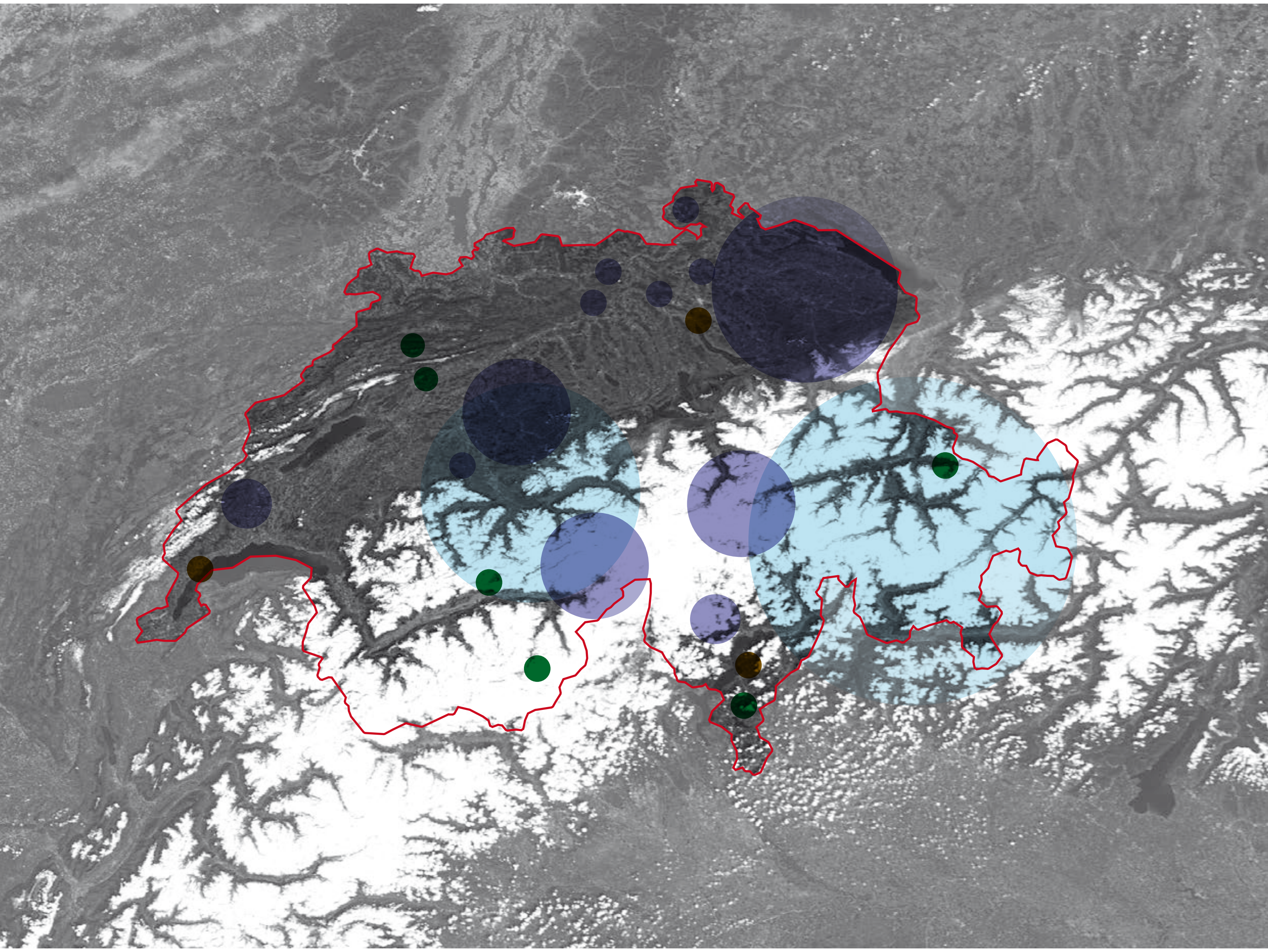
CH2014 – IMPACTS

TOWARD QUANTITATIVE SCENARIOS OF CLIMATE CHANGE IMPACTS IN SWITZERLAND



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Review process

The report was reviewed by 35 national and international reviewers including scientists and stakeholders. Of these, 22 reviewers were invited to comment on a specific chapter within their expertise or on the overarching sections. Additionally, a call for an open review was distributed to potentially interested communities via ProClim. In response, 13 reviews were submitted. In total 900 comments have been received and answered individually. The invited reviewers were given the opportunity to review the revised version of the report.

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Dissemination of the impact data

The quantitative impact data presented in the CH2014-Impacts report are available from the website www.ch2014-impacts.ch. The data are either hosted directly on this website or made available by a link provided by the institution owning the data. The data are provided for use in research, education, and commercial work unless further restrictions are imposed by the owner institutions. No redistribution of the data for commercial use or reselling is allowed. Publication of any form, based fully or in part on data provided by the CH2014-Impacts initiative, must include the following acknowledgment "The data were obtained from the CH2014-Impacts initiative (www.ch2014-impacts.ch)." or must acknowledge the institution providing the data directly, and must include a citation of this report.

Data disclaimer

Although all possible care has been taken in the preparation of the data and related information, the correctness, accuracy, reliability and completeness of the data and the descriptions presented cannot be guaranteed. The participating institutions are responsible for the linked content on their websites.

How to cite this report

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INDICES
- summer days
- tropical nights
- frost/ice days
- growing season length
- heating/cooling degree days

CRYOSPHERE
- snow cover
- winter tourism
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- permafrost

HYDROLOGY
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BIODIVERSITY
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- tree species
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Foreword

Bruno Oberle
Director of the Federal Office for the
Environment (FOEN)

Climate change is altering our environment. In Switzerland, too, rising temperatures and changing precipitation are affecting surface water, terrestrial ecosystems and biodiversity: the glaciers are melting, steep mountain slopes in the Alpine valleys are becoming unstable, dry periods in summer are becoming more frequent and longer, foreign animal and plant species from the south are spreading to Switzerland and displacing native species. The habitat of Switzerland is changing, and with it, our livelihoods.

Thanks to science, we now know the causes of many changes and, vice versa, many impacts of our actions. Science reveals how human activity influences climate change and thereby enables us to avert the harm that can be averted and to prepare for consequences that are inevitable. The present report examines the effects of global climate change on Switzerland and thus provides important information for the further development of our climate policy, both in tackling the causes of climate change and in initiating and coordinating measures to adapt to its impacts.

Observations and projections of these impacts are of key importance to adaptation to climate change. Changes must be recognized, anticipated and interpreted correctly, appropriate measures must be planned and initiated at the right time and to the right degree. Interaction between science and policy is essential to this process, to which the CH2014 initiative makes an important contribution.

Further steps, however, must follow. Only if we manage to limit climate change by effectively addressing its causes, will adaptation be technologically and economically feasible. We must therefore be conscious of our responsibility toward future generations and reduce greenhouse gas emissions, both globally and in Switzerland.

‹ Protection from rockfall is an important ecosystem service supplied by forests, and may deteriorate in a changing climate in many places across Switzerland (protection forest at Bilten, Glarus; photo: Georg Ledergerber, BAFU).

Summary

The CH2014-Impacts initiative is a concerted national effort to describe impacts of climate change in Switzerland quantitatively, drawing on the scientific resources available in Switzerland today. The initiative links the recently developed Swiss Climate Change Scenarios CH2011 with an evolving base of quantitative impact models. The use of a common climate data set across disciplines and research groups sets a high standard of consistency and comparability of results. Impact studies explore the wide range of climatic changes in temperature and precipitation projected in CH2011 for the 21st century, which vary with the assumed global level of greenhouse gases, the time horizon, the underlying climate model, and the geographical region within Switzerland. The differences among climate projections are considered using three greenhouse gas scenarios, three future time periods in the 21st century, and three climate uncertainty levels (Figure 1). Impacts are shown with respect to the reference period 1980-2009 of CH2011, and add to any impacts that have already emerged as a result of earlier climate change.

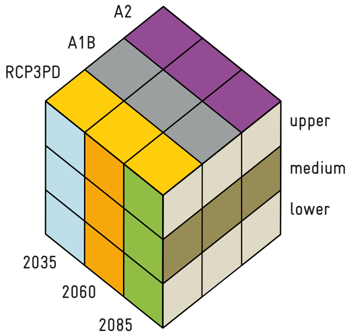

Figure 1: "Scenario cube" mapping the CH2011 scenario space. Scenarios of anthropogenic greenhouse gas emissions include A2 (high emissions, no intervention to reduce climate change), A1B (intermediate emissions, no intervention), and RCP3PD (low emissions due to an effective mitigation policy; referred to as RCP2.6 in the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, here RCP3PD is used for consistency with CH2011). Time periods are 30-year averages centered on the years 2035, 2060, and 2085. Climate projections of temperature and precipitation with respect to the reference period 1980-2009 include a medium estimate, and an uncertainty range from upper to lower estimates, with an estimated 2/3 chance of covering the true temperature change, and an estimated 1/2 chance of covering the true precipitation change.

‹ Snowmaking may allow high-elevation ski resorts to mitigate the impact of climate change on the duration of the business season (artificially snowed ski run at Savognin on January 9, 2011; photo: Keystone).

MORE TROPICAL NIGHTS AND LONGER GROWING SEASON

The implications of climate change for Switzerland are first depicted using derived statistics (climate indices) such as “tropical nights” or “growing season length”. CH2014-Impacts projects a roughly twofold increase in the number of “summer days”, and the common occurrence of “tropical nights” for the lower parts of Switzerland in non-intervention scenarios (A1B and A2, period 2085; Figure 2). This suggests opportunities for tourism and recreation, but poses challenges for health, agriculture, forestry, and biodiversity. In the same scenarios, the domain of frequent “frost days” retreats to higher elevations, highlighting the hazards of permafrost thawing, while “ice days” become rare in the low elevations, potentially benefitting traffic safety and human health. An increase in the “growing season length” holds promise for agriculture, but has uncertain consequences for ecosystem biodiversity. A lower number of “heating degree-days” contrasts with a higher number of “cooling degree-days”, in a shift that may deeply affect the important energy demand for space heating and cooling.

○
● summer days
● tropical nights
● frost/ice days
● growing season length
● heating/cooling degree days
○
○

CH2014-Impacts complements this general picture with detailed quantitative results on specific impacts from a range of fields: cryosphere, hydrology, biodiversity, forests, agriculture, energy, and health. The diverse geography of Switzerland is examined by a combination of local to regional case studies and Switzerland-wide analyses (Figure 3).

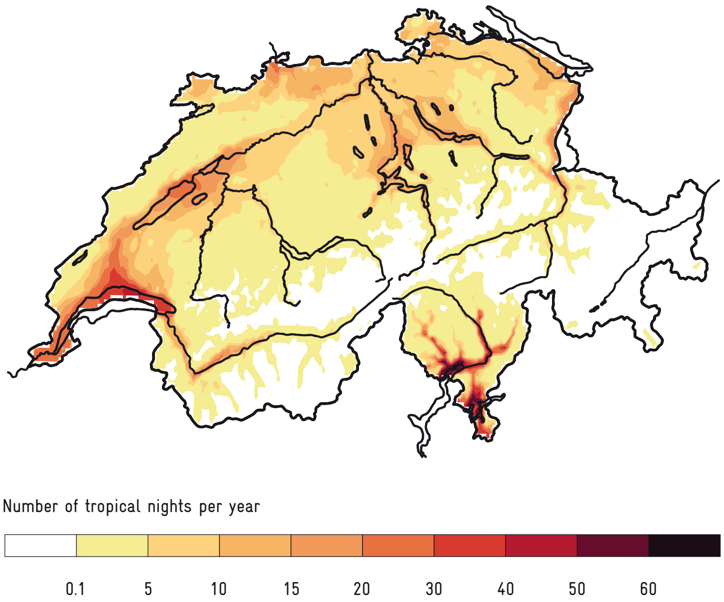

Figure 2: Number of tropical nights per year projected for the end of the 21st century (period 2085, medium estimate) under the A1B climate scenario without intervention to reduce climate change.

LOSS OF GLACIAL ICE AND CHANGES IN RIVER RUNOFF REGIMES

According to non-intervention scenario projections (A1B or A2, medium estimate), snow on the Swiss Plateau will seldom last for several days by the end of the century (Figure 3). Mountain ski resorts face shorter business seasons in all scenarios and time periods considered. Artificial snow mitigates this impact to a considerable extent. Unless constraints on resources and social acceptance prove too limiting, snowmaking may even allow high-elevation resorts to enhance their competitiveness under moderate climate change as projected for the mitigation scenario RCP3PD, or until the mid-century for the non-mitigation scenarios A1B and A2. Based on the simulation of a representative selection of 50 Swiss glaciers, a near-complete loss of glacial ice by the end of the century is projected under the A1B scenario (Figure 3).

● snow cover
● winter tourism
● glaciers
● permafrost

In catchments with little glacial influence, runoff regimes are projected to shift from snow controlled to rain controlled. This results in a change in seasonality, with lower summer runoff and higher winter runoff, but little change in the annual sum (Figure 3). Effective climate change mitigation (scenario RCP3PD) avoids about half of the potential impact as projected under non-mitigation scenarios (A1B and A2). Decreasing summer runoff may lead to an increasing need to manage the competing uses of this resource.

● river runoff
● groundwater temperature

The temperature of groundwater is projected to rise, especially where groundwater is recharged by river water (Figure 3). This warming may lead to the deterioration of groundwater quality. For the strongest warming considered (scenario A2, period 2085), the projections range from a marginal cooling to a warming of up to 7°C. This large uncertainty results mainly from impact modeling.

MIXED IMPACTS ON BIODIVERSITY, FORESTS, AND AGRICULTURE

Throughout Switzerland, the diversity of widespread bird and plant species is projected to change under the non-intervention scenario A1B. Losses of currently common species occur on the Swiss Plateau, with its comparatively small altitudinal range. Conversely, species richness increases at intermediate elevations. Both trends imply a “turnover” as species assemblages change in composition (Figure 3), and signal the importance of the management and conservation of biodiversity and ecosystem services.

● bird and plant species

The growth of many major tree species is projected to suffer from drought. Under unmitigated climate change (scenario A1B), the Swiss Plateau may become climatically unsuitable for the now widespread spruce and beech. Moderate warming (period 2035 or mitigation scenario RCP3PD up to period 2085) can benefit forests in terms of biomass at locations where low temperatures currently limit growth and where precipitation is abundant enough to satisfy the increased water demand resulting from higher temperatures. Forests at high elevations

● tree species
● forest properties
● ecosystem services

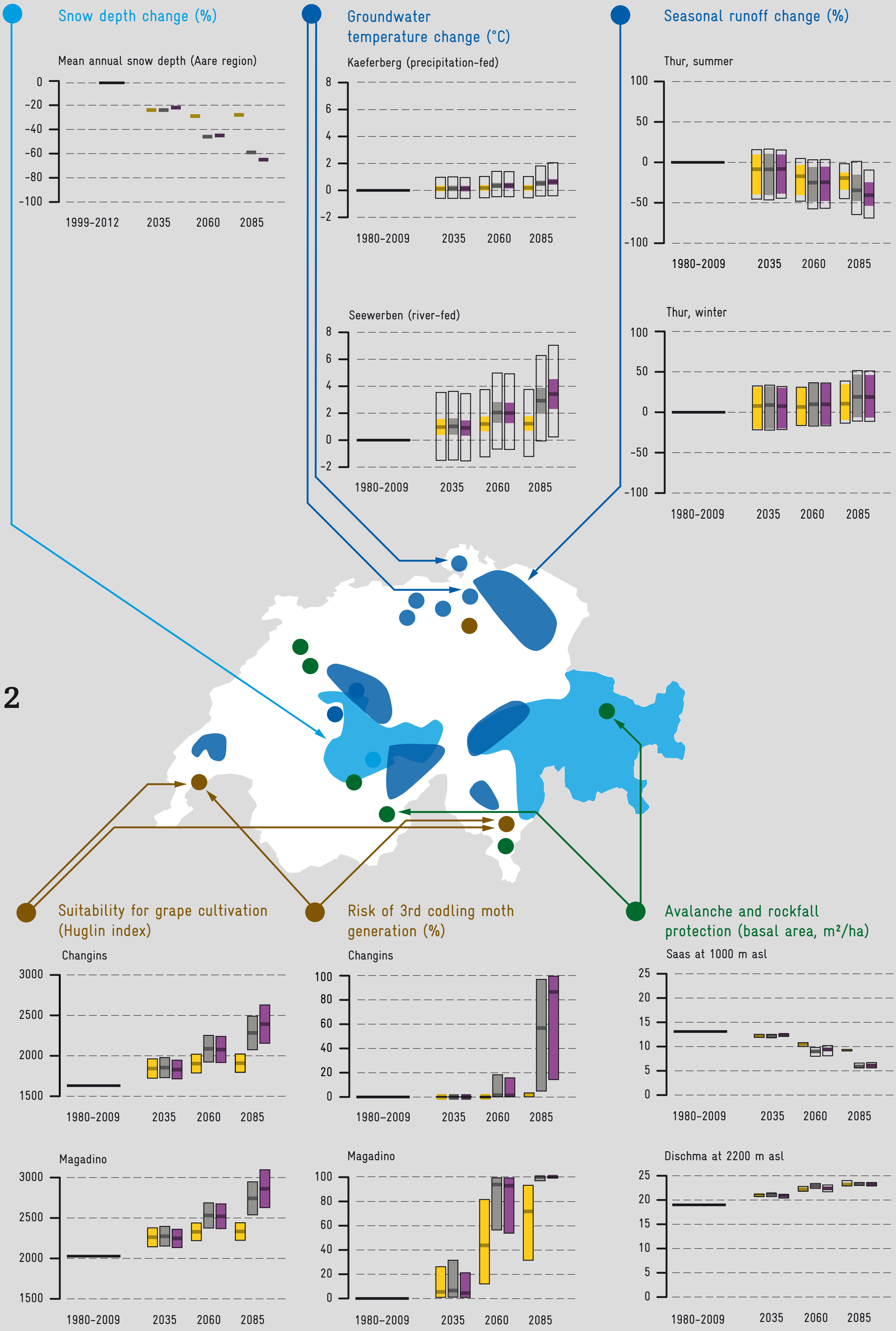
Snow depth change (%)
Mean annual snow depth (Aare region)
0
-20
-40
-60
-80
-100
1999-2012
2035
2060
2085
Groundwater temperature change (°C)
Kaeferberg (precipitation-fed)
8
6
4
2
0
-2
1980-2009
2035
2060
2085
Seewerben (river-fed)
8
6
4
2
0
-2
1980-2009
2035
2060
2085
Seasonal runoff change (%)
Thur, summer
100
50
0
-50
-100
1980-2009
2035
2060
2085
Thur, winter
100
50
0
-50
-100
1980-2009
2035
2060
2085
Suitability for grape cultivation (Huglin index)
Changins
3000
2500
2000
1500
1980-2009
2035
2060
2085
Magadino
3000
2500
2000
1500
1980-2009
2035
2060
2085
Risk of 3rd codling moth generation (%)
Changins
100
80
60
40
20
0
1980-2009
2035
2060
2085
Magadino
100
80
60
40
20
0
1980-2009
2035
2060
2085
Avalanche and rockfall protection (basal area, m²/ha)
Saas at 1000 m asl
25
20
15
10
5
0
1980-2009
2035
2060
2085
Dischma at 2200 m asl
25
20
15
10
5
0
1980-2009
2035
2060
2085

Figure 3: Selected climate change impacts. Greenhouse gas scenarios are indicated in yellow (RCP3PD), grey (A1B), and purple (A2); bold colored lines correspond to the medium climate change estimate, and the low-high climate uncertainty range is shown as a colored bar where an estimate is available. Black outlines include the impact modeling uncertainty to the extent that it is considered in each study (2 standard deviations for statistical estimates). Time ranges slightly deviating from the standard scenario periods were used for bird species turnover (20-year means) and energy impacts (year 2050).

(Dischma valley) respond with stable or enriched tree species diversity and larger biomass across the full range of scenarios. Forests at low elevations in dry inner-Alpine valleys (such as the Saas valley) are, however, sensitive and deteriorate even under moderate warming. Timber production potential, carbon storage, and protection from avalanches and rockfall are forest ecosystem services that reflect differences in the response of forests to climate change. There is an overall tendency to deteriorate at low elevations and improve at high elevations (Figure 3). Climate change will also affect forests indirectly by increasing the risk of infestation by spruce bark beetles, as indicated by the number of potential generations per year (e.g., from currently two at most to three by 2085 for scenario A1B; Figure 4).

Adverse, but potentially manageable developments, are seen in temperature-related impacts such as the incidence of agricultural pests or heat stress suffered by cattle. The risk of the codling moth (an apple pest) developing a third generation is expected to become substantial toward the end of the century in non-intervention scenarios for locations on the Swiss Plateau, and earlier for any scenario in the Ticino (Figure 3). A potentially beneficial impact on agriculture is the wider range of cultivable grape varieties as a result of higher temperatures. These findings are in line with earlier assessments that found, on balance, beneficial impacts on agriculture under the moderate degree of climate change projected for the first half of the century. Negative effects are, however, expected to dominate in the long term as climate change progresses, except for the case of effective mitigation (scenario RCP3PD).

○
● heat stress in cattle
● pest phenology
● wine production
○

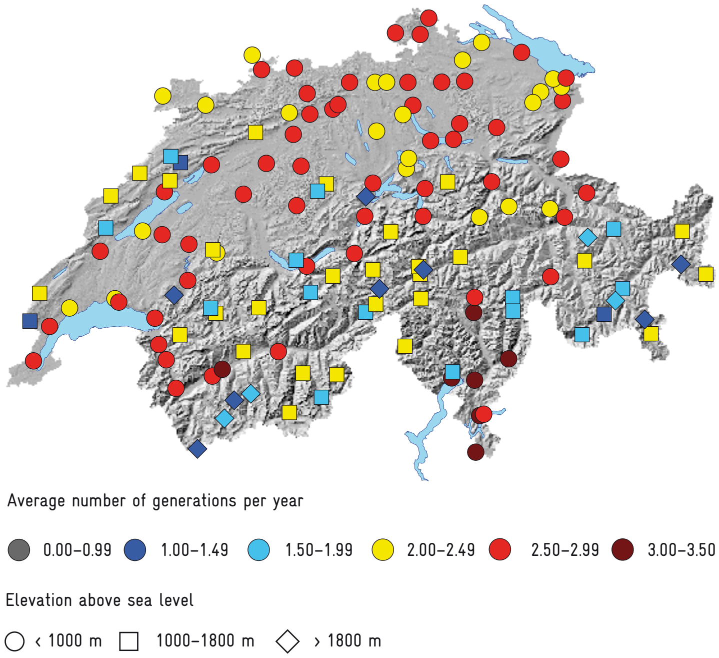

Figure 4: Potential generations of spruce bark beetles per year projected for the end of the 21st century (period 2085) under the A1B climate scenario without intervention to reduce climate change.

LESS ENERGY FOR HEATING BUT MORE FOR COOLING

Decreasing heating degree-days and increasing cooling degree-days indicate the heating energy saved, or cooling energy needed to maintain the indoor climate under changing ambient temperatures (Figure 3). The observed energy consumption for heating in households over the years 2000 to 2010, however, exhibits only 50% of the variation seen in heating degree-days (direct rebound effect). Applied to the future this means that only half of the potential energy saving is realized. A cross-sector analysis with a computable general equilibrium model suggests that the remaining 50% saving is largely absorbed by the consumption of other goods (indirect rebound effect), leaving a modest reduction in total energy consumption (<1%) and a small welfare gain (<0.25% of GDP) for the A1B scenario at mid-century. Increased need for space cooling, though economically detrimental, does not offset the saving from reduced heating.

○
● energy for heating/cooling
● effect on total energy use and GDP
○
○
○

Statistical analysis reveals a relationship between observed weather and indicators of human health for Switzerland (such as sales of registered health products or hospitalizations). By assuming that this relationship remains valid during long-term climate change, and neglecting potential adaption in physiology, behavior, etc., an upper bound estimate of the impact on human health indicators is obtained (Figure 3). The sales of registered health products in pharmacies increase in parallel with warming by up to about 3% (non-intervention scenarios A1B and A2 in period 2085). Hospitalizations show a complex relationship to climate change, increasing by about 4%, with little dependence on the greenhouse gas scenario and time period considered.

○
○
○
● health indicators
○

IMPORTANCE OF MANAGING CLIMATE CHANGE IMPACTS IN SWITZERLAND

In summary, CH2014-Impacts presents a picture of predominantly adverse consequences of climate change in Switzerland. These include examples of potentially deleterious changes, which can be mitigated and sometimes turned to an advantage if properly managed. This highlights the role of foresight and management in dealing with climate change impacts in Switzerland. Beneficial effects tend to be limited to moderate climate change, underscoring the importance of greenhouse gas emission abatement. Adverse short-term impacts appear limited with respect to the reference period 1980-2009, but will add to any impacts already experienced today as a consequence of climate change over the previous decades.

The impact of severe climate change emerges toward the end of the century, when the scenarios of unabated greenhouse gas emissions (A1B and A2) lose their moderate appearance. Due to the inertia of the socio-economical and physical climate systems involved, an increase in the severity of climate change appears inevitable for these non-intervention scenarios in the 22nd century. In particular, elevated CO_2 concentrations in the atmosphere persist over centuries, as CO_2 is only partially absorbed by the ocean and natural land sinks. Unless it proves feasible to remove a considerable fraction of the emitted CO_2 from the atmosphere by technological means, long-term impacts will continue to intensify in the 22nd century.

There are several areas of overlap between the separate impact studies: glacier melt affects river flow regimes, species turnover is related to forest composition, and surface and groundwater changes are relevant for health considerations, to name a few examples. The assessments of these topics are broadly consistent, though they do not interlock. Nevertheless, cross-cutting issues warrant closer investigation, and a tighter integration of impact models is desirable for the future.

TOWARD COMPREHENSIVE SCENARIOS OF CLIMATE CHANGE IMPACTS

This report provides quantitative insights from the physical to the human environment, though its scope is limited due to the challenge of producing quantitative data on Switzerland within a tight time frame, and with the tools and resources at hand. The coverage of impacts, scenario space, and impact uncertainty is thus not yet comprehensive nor representative. Current limitations also stem from the CH2011 climate scenarios. Thus, the report focuses on the impacts of mean changes in temperature and precipitation provided by CH2011, and does not cover impacts related to other variables or to extreme weather events, which are not quantified in CH2011.

○
● INDICES
● CRYOSPHERE
● HYDROLOGY
● BIODIVERSITY
● FOREST
● AGRICULTURE
● ENERGY
● HEALTH
○

The intention of the CH2014-Impacts initiative is to provide a pilot report on quantified impacts along the full cascade of the implications of climate change in Switzerland; from the physical environment and ecosystems to socio-economic consequences, based consistently on a common foundation of quantitative climate scenarios, which are publicly available. This collection of studies, though not comprehensive in itself, is intended to stimulate an ongoing process toward the consolidation of scenarios that depict potential impacts of climate change in Switzerland in a multidisciplinary, integrated, and comprehensive way. Impact scenarios will serve the interests of stakeholders, and aid politicians and decision makers in developing effective Swiss mitigation and adaptation strategies. The present report is only a step on the path to this goal, and continued advancements in impact studies and underlying climate data will be needed to proceed.

1 — Introduction to the CH2014-Impacts initiative

Climate underpins our existence and well-being in subtle, yet important ways. It is an essential ingredient for the identity of any country and its people. If the name "Switzerland" brings to mind snow-capped mountains and cows grazing on green meadows, this image also echoes the climate peculiar to the country.

Awareness of climate change is widespread today, as global warming of the climate system is unequivocal and the observed warming since the mid-20th century is "extremely likely" to be due to human influence (IPCC, 2013). In Switzerland, the warming trend over the last three decades has been about 1.6 times greater than the Northern Hemispheric mean (Begert et al., 2005; Ceppi et al., 2012) and is clearly perceptible.

With global emissions of greenhouse gases steadily rising, climate change in Switzerland and elsewhere is set to continue. The long-term future depends on the political choice between increasingly larger changes in the climate system as a consequence of unabated emissions and the chance to keep change at a moderate level by a speedy trend reversal in emissions. The main greenhouse gas, CO_2, once emitted accumulates in the atmosphere and is only partly absorbed by ocean and land sinks, even on centennial time scales. Therefore, only an eventual phase out of fossil emissions will stabilize the climate system. Given the past and ongoing emission of greenhouse gases, this implies that some further climate change is unavoidable (IPCC, 2007a).

The impacts of climate change are manifold and anthropogenic warming has had a discernable influence on many physical and biological systems (IPCC, 2007b). Glaring evidence of ongoing climate change is the melting of our mountain glaciers. Rising greenhouse gas levels will lead to an increasing number of severe impacts across many sectors and geographical regions, and are very likely to impose net annual costs that will increase over time as global temperature increases (IPCC, 2007b). Additional costs will accrue due to adaptation to climate change impacts (Stern et al., 2006).

Still, present understanding of the consequences of climate change is fraught with uncertainty, originating from policy decisions, societal and technological development, and the climate system. There is already uncertainty concerning the global scale of warming and this amplifies as the focus is set on associated variables such as precipitation, and on regional to local spatial scales, in particular in areas with complex topography such as Switzerland. Further uncertainties are involved in the step from climate change to specific impacts. These difficulties notwithstanding, a sound understanding of climate change and its impacts, both adverse and beneficial, is a crucial prerequisite for dealing adequately with climate change.

An overview of previous efforts to assess climate change including the institutions involved internationally and in Switzerland is described in the Box on page 20. Since the mostly qualitative national assessment "Climate Change and Switzerland 2050 – Impacts on Environment, Society and Economy" (OcCC, 2007) was published, a new set of climate projections from the European project ENSEMBLES (van der Linden and Mitchell, 2009; with the participation of ETH Zurich; ETHZ and Federal Office of Meteorology and Climatology; MeteoSwiss) has become available and innovations in statistical methods have been made (partly by the National Centre of Competence in Research on Climate; NCCR Climate). Based on these developments, the new "Swiss Climate Change Scenarios CH2011" were elaborated (CH2011, 2011; Chapter 3). The

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‹ Dairy cows will increasingly suffer from heat stress, which could affect milk production (photo: imago/ Geisser).

Box: Institutions and previous assessments related to climate change

At the **global level**, the need for a comprehensive assessment of scientific knowledge on climate change to advise international policy was recognized already in the 1980s. The World Climate Research Programme (WCRP), the International Geosphere-Biosphere Programme (IGBP) and an international programme of biodiversity science (Diversitas) were launched to organize scientific activities related to global change. In 1988, the Intergovernmental Panel on Climate Change (IPCC) was established to assess "the scientific, technical, and socioeconomic information relevant for the understanding of the risk of human-induced climate change". The IPCC's role is defined as providing a policy relevant but not policy prescriptive basis for the decision making process.

IPCC's First Assessment Report (FAR; IPCC, 1990) inspired the formation of the United Nations Framework Convention on Climate Change (UNFCCC). Since 1995 – when it entered into force – the UNFCCC continues to provide the essential policy framework for addressing climate change at the international level. The Second Assessment Report (SAR; IPCC, 1995) became the basis for the Kyoto Protocol adopted in 1997 and in force since 2005. The Kyoto Protocol is the only international treaty that sets legally binding obligations on industrialized countries to reduce emissions of greenhouse gases. Subsequent IPCC findings from the Third (TAR; IPCC, 2001), and in particular the Fourth Assessment Report (AR4; IPCC, 2007a;b), informed the negotiations of the 16th Conference of the Parties in Cancun, Mexico in December 2010, which agreed on a warming limit of 2°C above preindustrial levels.

Today, the scientific results assessed by the IPCC again provide the basis for the UNFCCC international negotiations to act on climate change. In addition, the new Structured Expert Dialogue communicates the latest scientific findings such as the IPCC Fifth Assessment Report (AR5; IPCC, 2013). The goal of the ongoing negotiations is to agree on a new, comprehensive binding treaty by the end of 2015 as a successor to the Kyoto Protocol. This instrument is expected to foster reductions in greenhouse gas emissions and subsequently limit the scale of impacts in accordance with the agreed upon long-term target of 2°C warming.

In **Switzerland**, research contributing to IPCC findings has a long and strong tradition. Many academic institutions have been involved, such as the universities, the ETHs, and not least the Swiss Academy of Sciences (through ProClim and the OcCC), catalyzing progress in climate change science through their early support. Already in 1997, the final report of the National Research Programme "Climatic Changes and Natural Hazards (NRP 31)" linked climate change, natural hazards, ecology, and society and highlighted the possible future challenges. In the same year, the Priority Programme Environment (SPPU) dedicated an entire module to climate change (CLEAR – Climate and Environment in an Alpine Region) that communicated its results to the general public and policy makers in several publications.

The National Centre of Competence in Research on Climate (NCCR Climate) established in 2001, further strengthened climate research in all disciplines and all major aspects of climate research, including impacts of climate change. The results of such activities are reflected in the report "Climate Change and Switzerland 2050 – Impacts on Environment, Society and Economy" (OcCC, 2007). This report addresses stakeholders and the general public, and offers an extensive and mostly qualitative assessment of impacts expected around the year 2050, based on existing literature and on climate projections from the PRUDENCE project (Christensen et al., 2002). The ongoing National Research Programme "Sustainable Water Management (NRP 61)" focuses on the capacity of natural systems to absorb the effects of changes in environmental conditions, including climate conditions, as a basis for forward-looking strategies for sustainable and integral water resources management.

Within the national administration, the Federal Office for Environment (FOEN) is in charge of national climate change related activities. This includes the coordination of Swiss mitigation efforts, as well as the development of a national adaptation strategy (FOEN, 2012a). Over the past years, national and cantonal administrations together with the private sector have supported various research activities that focus on issues related to climate change impact and adaptation (e.g., FOEN, 2012b; Holthausen et al., 2011). The CH2014-Impacts report extends these recent activities with a snapshot of the currently available quantitative impact information based on a common set of climate scenarios (CH2011, 2011).

CH2011 scenarios are used as an up-to-date basis for the CH2014 impact studies. On the impact modeling front, major progress was made in representing impact relevant systems and processes quantitatively.

One of the conclusions of the OcCC report (OcCC, 2007) is that "[...] there are no precise estimates of the costs for the adaptations and measures mentioned, which, for some fields, may be of economic relevance." This statement shows that climate change is a cross-cutting issue with natural, societal, and economic aspects. It also implies a need for more quantitative research to fill some of the still remaining gaps in the scientific basis for strategies to address climate change. The advancements in climate data and impact models present an opportunity for multi-sectoral studies that are both quantitative and coherently based on a common foundation of climate data.

Acting on this opportunity, the Oeschger Centre for Climate Change Research (OCCR) of the University of Bern initiated CH2014-Impacts as a community effort to quantify climate change impacts over the 21st century, with support from the Federal Office for the Environment (FOEN), MeteoSwiss, and NCCR Climate (now concluded). An open call was issued through the Forum for Climate and Global Change (ProClim) in December 2011, inviting experts from all relevant fields to participate. The condition for participation was the ability to quantify impacts based on the CH2011 Swiss climate change scenarios. Accordingly, the goal of the CH2014-Impacts initiative is to compile results from currently available impact models, applied to a common set of climate scenarios for Switzerland. This approach is specific to CH2014-Impacts and complementary to existing studies (see Box). It should not be seen as a comprehensive assessment of climate change impacts, which would have to be founded on multiple lines of evidence and a review of the existing literature.

Thanks to the great response to the call for participation in CH2014-Impacts, a broad collection of studies was included in the report. The contributions reach from the physical environment and ecosystems to socio-economic consequences, quantifying selected impacts of climate change related to aspects of the cryosphere, the hydrosphere, biodiversity, forests, agriculture, energy, and health. The result is a "sample of opportunity", based on what has been offered by the Swiss science community. It reflects the current state of the art and present gaps in quantitative impact methods.

The report compiles quantitative information from multiple fields, based on common climate scenarios. As yet limited in scope, it aims to contribute to a future comprehensive quantitative depiction of potential climate change impacts in Switzerland, which the impact community can draw on to inform and support stakeholders and policymakers. This report is thus an effort toward building a set of quantitative scenarios of climate change impacts in Switzerland, in analogy to the CH2011 climate scenarios.

In order to be relevant for a robust assessment of climate risks and opportunities, the report considers the full range of projected outcomes from CH2011, including time horizons from the short term (around the year 2035) to the end of the current century (around 2085), greenhouse gas levels from soaring emissions to stringent climate change mitigation, and the uncertainty originating from the underlying climate models and natural climate variability as quantified in CH2011.

The CH2014-Impacts report was made possible through the enthusiasm of the authors, who contributed their work without additional funding. Over 20 research groups from 15 institutions were involved, including the OCCR of the University of Bern, the Center for Climate System Modeling (C2SM) at ETHZ, MeteoSwiss, the Swiss Federal Institute for Forest, Snow and Landscape Research (WSL), the Agroscope institutes, the WSL Institute for Snow and Avalanche Research (SLF), the Swiss Federal Institute of Aquatic Science and Technology (EAWAG), the Ecole polytechnique fédérale de Lausanne (EPFL), the Research Institute of Organic Agriculture (FiBL), the University of Applied Science Chur (HTW Chur), and the Universities of Innsbruck (Austria), Fribourg, Luzern, and Zurich. Additionally, the process was accompanied by the Swiss Academy of Sciences via ProClim and the Organe consultatif sur les changements climatiques (OcCC).

2 — The CH2014-Impacts approach to scenario-based impact quantification

2.1. INTRODUCTION

Quantifying climate change impacts requires a model of the linkages by which climate affects the environment, the economy, and society. Of the multitude of relevant linkages considered in this report, each is treated with a dedicated **impact model**. Common to this variety of tools is the need for an equally quantitative description of the evolution and future states of climate as an input. The CH2011 **climate scenarios** provide such information for the key variables mean surface air temperature and precipitation (CH2011, 2011), derived from climate simulations with a spatial resolution capturing Switzerland's main topographic features.

Climate simulations are encumbered by substantial uncertainty due to the limited understanding of climate change, under-representation of physical processes, and largely unpredictable natural variability. Such **climate uncertainty** concerns the simulation of global change and is further accentuated in the local assessment for Switzerland. CH2011 (2011) represents the climate uncertainty range by an upper, a lower, and a medium estimate each for temperature and precipitation changes.

The appropriate time horizon for an impact assessment varies with the topic considered, the stakeholders concerned, and the nature of the planning and management decisions involved. The climate system itself limits the choice of time periods for which impacts can be reliably quantified, as shorter periods or periods closer in time would be dominated by natural variability. The three **time periods** provided by CH2011, each representing a 30-year average, are a compromise between these limits and needs in order to allow for a short-, mid-, and long-term perspective over the 21st century.

The scale of future anthropogenic climate change is governed by the amount of CO_2 and other greenhouse gases and pollutants emitted to the atmosphere. This great unknown depends on socio-economic dynamics as well as political choice about greenhouse gas emission reduction (commonly referred to as climate change mitigation). In the context of the Swiss impact assessment of CH2014-Impacts, global climate policy is largely an external factor, and may be best considered in terms of political uncertainty. Uncertainty along these lines is bracketed by **three greenhouse gas scenarios**, which range from unrelenting emission growth to ambitious climate change mitigation.

In summary, the full impact assessment process presents itself as a sequence of steps along a causal chain of greenhouse gas levels, climate change, and impacts. With each step, new dimensions of the problem come into play. The complexity common to all impact assessments is structured using the heuristic concepts of greenhouse gas scenarios, time periods, and climate uncertainty levels.

Moreover, estimating an impact of a given climate change is also subject to uncertainty, because reality is represented incompletely in the impact models, and unknown non-climatic factors can play a role. This **impact uncertainty** is expressed in a spread of results when different impact models are applied to the same question.

The choice of a greenhouse gas scenario is fundamental to this kind of impact assessment, as each end result is conditional on it. Any such result makes no claim to predict future events as, e.g., a weather forecast would. To express this conditionality, these results are called **projections**, following an established convention (e.g., IPCC reports). A projection

‹ During summer 2013, melting reduced the ice thickness at the tongue of the Rhone glacier by 3-5 m even with protective cover (entrance of the fleece-covered ice cave of the Rhone Glacier; photo: David Volken, BAFU).

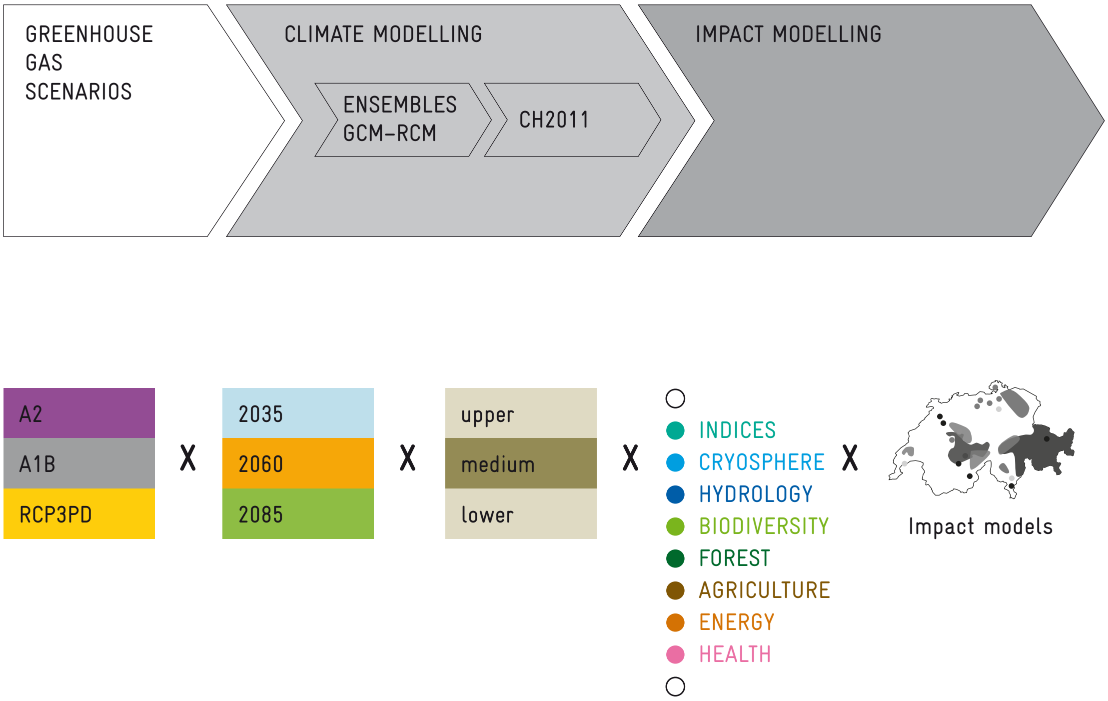


Figure 2.1: Flowchart of the quantitative assessment of climate change impacts showing the stages of an impact projection in the form of an arrow (top), and the heuristic concepts of greenhouse gas scenarios, time periods, and uncertainty levels (bottom).

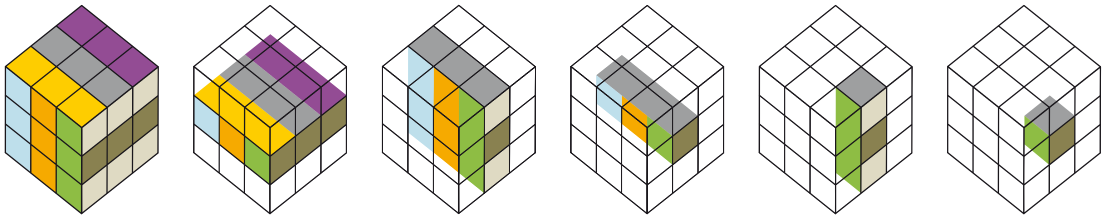


Figure 2.2: The "scenario cube" illustrating the 27 possible combinations of greenhouse gas scenarios, time periods and climate uncertainty levels, and subsets showing possible selective simulation protocols.

can be visualized as an arrow spanning from the greenhouse gas scenario to the final impact assessment (Figure 2.1).

As the collection of climate projections based on a greenhouse gas scenario is called a climate scenario following the usage of the CH2011 report, the projection of impacts can eventually form an **impact scenario**. To justify this term, an impact scenario would need to be representative enough to inform a comprehensive assessment of, in this case, all major climate change impacts in Switzerland. The studies of this report do not yet constitute an impact scenario in this sense, but can serve as building blocks of future scenarios that are yet to be completed.

The dimensions of greenhouse gas scenario, time period, and climate uncertainty, broken down into three levels each, are schematically represented by a **scenario cube** (Figure 2.2). The 27 blocks of the scenario cube illustrate the complete simulation protocol for the impact models. While each individual impact study in this report rests on a similar projection, not all studies take into account the full range of eventualities, exploring, as it were, only a fraction of the scenario cube (Figure 2.2). This limitation is mostly due to limited computational resources, data restrictions, and the tight time frame of the project.

In the following sections, the essential concepts of the CH2014-Impacts assessment approach are discussed in more detail, to guide the reader in the interpretation of the report's results. More specific information about the CH2011 climate scenario data is presented in Chapter 3.

2.2. GREENHOUSE GAS SCENARIOS

CH2011 (2011) considers three greenhouse gas scenarios widely used for climate projections and broadly representative of the literature. These scenarios are based on diverging assumptions about future socio-economical, technological, and political developments, which translate into a range of future greenhouse gas emissions and atmospheric concentrations that are used to force climate models. These scenarios also specify secondary anthropogenic drivers of climate change such as aerosols or land use changes.

- The **A2** scenario (Nakicenovic and Swart, 2000) projects high emissions as a consequence of unchecked population growth and continued reliance on fossil fuels without intervention to reduce climate change. The A2 scenario corresponds in emissions and underlying assumptions to the strongest warming scenario of the Representative Concentration Pathways (RCPs) on which most climate simulations of the IPCC's recent fifth assessment report are based (IPCC, 2013).

- The **A1B** scenario (Nakicenovic and Swart, 2000) represents the midrange of the greenhouse gas scenarios. Lower emissions in comparison to A2 result from a turnaround in global population in mid-century, combined with rapid economic growth and technological development, which lead to a diminishing role of fossil energy. Like A2, A1B does not assume specific climate policy intervention.

- The **RCP3PD** scenario is the lowest of the RCP scenario set (IPCC, 2013) and represented the most stringent climate change mitigation scenario of the literature when it was developed. RCP3PD is originally defined as a path of atmospheric greenhouse gas and aerosol concentrations. It offers an estimated 2/3 chance of limiting global surface temperature to 2°C above the preindustrial average (IPCC, 2013; RCP3PD is referred to as RCP2.6 in the IPCC report, after the level of radiative forcing reached in 2100; here we adhere to the name used in CH2011, 2011). While the underlying assumptions are not part of the scenario definition, they include both moderate increases in driving factors such as population and energy use, and an ambitious and effective mitigation policy.

In the figures of this report, the three greenhouse gas scenarios are color-coded by yellow (RCP3PD), grey (A1B), and purple (A2), respectively (Figure 2.1).

2.3. CLIMATE DATA BASE, REFERENCE PERIOD, AND SCENARIO HORIZON

The common set of input data for the impact models consists of the „Swiss Climate Change Scenarios CH2011" published in 2011, and its later extensions (Chapter 3). The CH2011 scenarios in turn are developed on the basis of the regional climate model simulations from the European-wide ENSEMBLES project (van der Linden and Mitchell, 2009). Some impact models require data extending beyond the Switzerland-specific scope of CH2011, such as the biodiversity study (Chapter 7), or require transient scenarios with high temporal and spatial resolution, such as the study on beech and fir distribution (Chapter 8). In these cases, CH2011 data is augmented by interpolating the scenario periods or by using climate model output directly, after applying appropriate processing steps such as spatial downscaling, etc.

CH2011 (2011) specifies the change in climatological 30-year means of surface air temperature and precipitation with respect to an observational reference period. The 30-year mean is used to represent a climate state as the period is long enough to remove year-to-year variations, but still short enough to capture longer climatic trends (definition by World Meteorological Organization; WMO, 1967).

The reference period used in this report spans the years 1980–2009. This period was chosen for CH2011 scenarios over the widely used standard reference period 1961–1990, in order to enhance comparability with recent observations. This choice implies a difference in the annual reference temperature of about 0.8°C with respect to the period 1961–1990 (Figure 2.3). Any impacts having occurred due to climate change during the two decades separating the different reference periods will not show up in the results of this report. Similarly, the impact of warming since the preindustrial period, which amounts to roughly 1.5°C for Switzerland (Begert et al., 2005), is not included. Comparison of the presented result with earlier studies also requires comparability in the reference periods. This applies, e.g., to comparisons with the CH2050 scenarios (OcCC, 2007), which use a similar reference year (1990).

The time horizon of the scenarios covers the current century in three 30-year averaged periods around the central years 2035 (near term), 2060 (mid-term), and 2085 (long term). The periods partly overlap and are mainly selected for practical reasons to provide projections relevant for near-, mid- and long-term decisions, respectively.

2.4. QUANTIFYING UNCERTAINTY

Science strives to reduce uncertainty by expanding knowledge (although some uncertainties are irreducible). An equally important scientific task is to quantify uncertainty so as to faithfully reflect the bounds of our current knowledge. The ability to show the "uncertainty" of a result is a strength rather than a weakness of any study. The existence of an uncertainty range allows one to devise robust responses by prudent selection of the central, upper or lower estimates depending on whether the focus is on the likely outcome or a less likely but potentially more momentous outcome. In other words, uncertainty ranges allow one to hedge against risks that a best-guess approach might overlook.

The CH2011 climate uncertainty range spanned by "upper", "medium", and "lower" values formally corresponds to the 95% confidence interval inferred from the spread of the underlying climate model ensemble simulations and observed natural climate variability. However, this range captures true climate uncertainty incompletely, due to the limited number of climate models used and incomplete coverage of the relevant processes in the climate system and their respective scientific uncertainties.

Based on expert judgment informed by the current state of climate science, CH2011 (2011) recommends the following interpretation of the climate uncertainty range: the expected chance that actual observed values will fall between the upper and the lower values is two in three for temperatures, and one in two for precipitation. This interpretation is important for comparison with other assessments, for example OcCC (2007), which used uncertainty ranges corresponding to 19 out of 20 cases (i.e., a 95% interval).

Impact uncertainty is quantified as the range of estimates that is consistent with what is known about the underlying influence of climate. This concerns process knowledge, the availability of observations, and the influence of random factors such as natural variability. The impact uncertainty range results either from applying different models to the same process (e.g., in the studies of Chapter 6), or from considering the uncertainty of the model's parameters (e.g., Chapters 11–12).

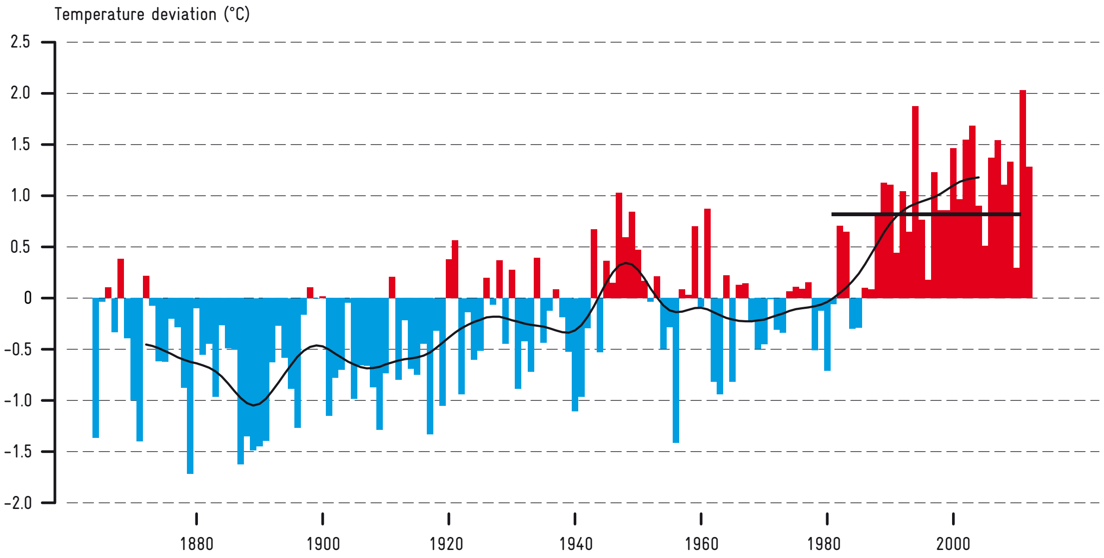


Figure 2.3: Mean annual temperature over Switzerland with respect to the period 1961–1990. The impacts presented in this report are presented with respect to the reference period 1980–2009. The figure shows the mean temperature over the closely corresponding period 1981–2010 (bold black line). The fine black line shows the smoothed (20-year Gaussian filter) mean annual temperature (Begert et al., 2013).

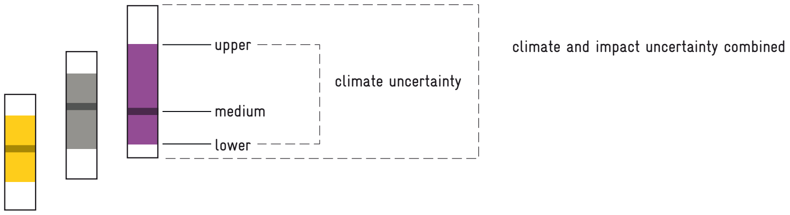


Figure 2.4: Illustration of uncertainty: climate uncertainty which represents the upper, medium, and lower estimates of the CH2011 climate scenarios, and impact model-related uncertainty. Colors identify the greenhouse gas scenarios RCP3PD (yellow), A1B (grey), and A2 (purple).

The quantification of impact uncertainty is relatively detailed in some studies of this report, and partial or missing in others according to the resources at hand. Additionally, non-climatic factors may have a large potential influence on the impact of climate change (e.g., the role of technological development for energy demand in Chapter 10), but are not generally considered in this report.

The CH2011 climate uncertainty levels are illustrated in the scenario cube with olive green shading (Figure 2.2). In the graphical presentation of results, climate uncertainty corresponding to the CH2011 upper/lower levels is shown by colored bars extending from the central estimate (Figure 2.4). The combined range of climate and impact model uncertainty is indicated by an outline, which extends beyond the colored climate uncertainty range when separate information on impact uncertainty is available.

2.5. LIMITATIONS

Apart from the uncertainties introduced above, any impact study faces specific limitations which arise from its methodological approach and affect its implications. Additionally, there are limitations that are common to all assessments and are related to the climate scenarios on which the report rests. According to the definition of climate as the (long-term) statistics of weather, designing a climate scenario involves the specification of the frequency and intensity of all possible weather events in the future, covering in principle all relevant variables.

The approach taken for the CH2011 climate scenarios makes this challenging problem tractable by resorting to strong simplifications: only the mean change in the main variables surface air temperature and precipitation is specified, and the day-to-day fluctuation of weather is borrowed from observations over a reference period (so-called delta change approach, Chapter 3). This approach does not account for possible systematic changes in the occurrence of extreme weather events that would not affect the average climate. Changes in extremes such as heat waves, heavy precipitation, etc., are expected to occur in a warming climate, but cannot be reliably projected based on the CH2011 scenarios (Chapter 3). As a consequence, only the impact of average climate changes can be assessed, while great caution must be exercised where extreme events come into play. This general limitation is discussed further in Chapters 3 and 4.

Further limitations are inherent in the general approach of the CH2014-Impacts initiative, and need to be taken into account when interpreting the results. One limitation arises because the different impact studies, although based on the same data sets, are independent from each other. For example, the results of the glacier study (Chapter 5) are not directly incorporated in the study of river discharge (Chapter 6), which in turn is not part of the agricultural assessments (Chapter 9). Similarly, there is no coupling between the climate and impact modeling, which are treated as sequential stages. Additionally, each impact model has its own assumptions and specific restrictions. For these reasons, derived quantities cannot be expected to be fully consistent across the chapters of the report. However, an agreement between methodologically independent results is a measure of confidence and robustness, whereas inconsistencies or disagreement may indicate process complexity and intricacies that are at present not fully understood scientifically.

The number of impact models for such a comparison is still very limited owing to the national character of the CH2014-Impacts initiative. Finally, the comparability of different impact studies presented in this report is limited by the use of climate data beyond the CH2011 datasets in a few cases, and the incomplete exploration of the scenario cube by some of the impact models. These deviations are discussed in the corresponding chapters and the synthesis (Chapter 12).

3 — Data basis of CH2014-Impacts – The Swiss Climate Change Scenarios CH2011

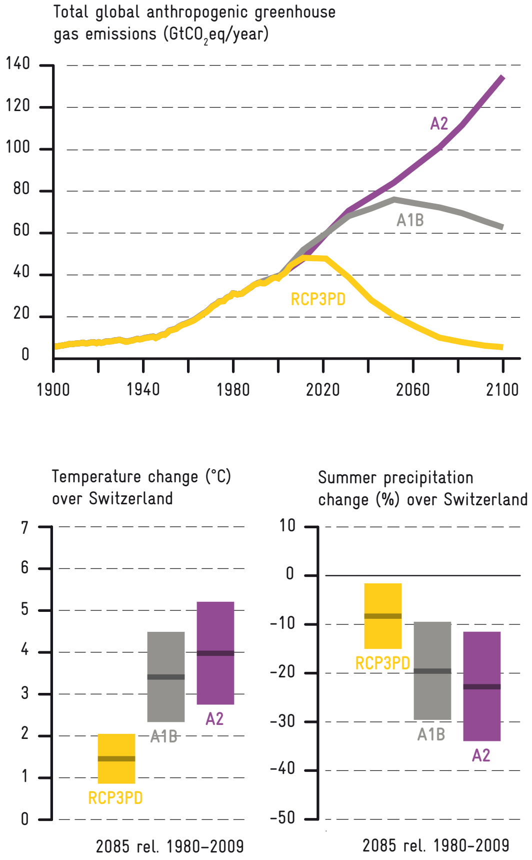


Figure 3.1: The three pathways of past and future anthropogenic greenhouse gas emissions, along with projected mean annual warming and projected summer precipitation change for Switzerland for the 30-year average around 2085 and averaged over all five CH2011 regions (CH2011, 2011; Zubler et al., 2014a). The (seasonal) changes for different future scenario periods and for individual regions can be found in CH2011 (2011).

‹ Warming across Switzerland brings more "summer days", along with opportunities for tourism and recreation (Aare near Bern-Aarwangen; photo: Anaïs Elisa Kohler).

3.1. INTRODUCTION

Regional climate projections with a methodologically sound treatment of the different sources of uncertainty (Chapter 2) are scientifically challenging. The CH2011 initiative addresses this challenge with the Swiss Climate Change Scenarios (CH2011, 2011) and the upcoming CH2011 Extension Series, which are both developed on the basis of the regional climate simulations of the European ENSEMBLES project (van der Linden and Mitchell, 2009). The CH2011 initiative is a multi-institutional collaboration between the Center for Climate Systems Modeling (C2SM), MeteoSwiss, ETH Zurich, the National Centre of Competence in Research (NCCR) on Climate, and the Organe consultatif sur les changements climatiques (OcCC). CH2011 (2011) provides projections of changes in temperature and precipitation relative to the reference period 1980–2009 for three greenhouse gas scenarios (RCP3PD, A1B, and A2) and for three 30-year projection periods centered around 2035, 2060, and 2085.

The main results show that in the course of the 21st century and under the non-mitigation scenarios A2 and A1B, it is very probable that temperature will increase in all seasons over Switzerland compared to the mean observed temperature of past decades. The annual mean warming for Switzerland by the end of the century is 0.9–2.0°C for the stabilization scenario (RCP3PD), 2.3–4.5°C for the A1B scenario, and 2.7–5.2°C for the A2 scenario (Figure 3.1). The projected warming is largest in summer and more pronounced in the Alpine region than on the Swiss Plateau (Figure 3.2). Summer precipitation averaged over Switzerland is projected to decrease by the end of the century by 2–15% for RCP3PD, by 10–30% for the A1B scenario, and by 12–34% for the A2 scenario (Figure 3.1). In all other seasons precipitation could either increase or decrease. Summer drying appears to be more pronounced in western Switzerland and Switzerland south of the Alps (Figure 3.3).

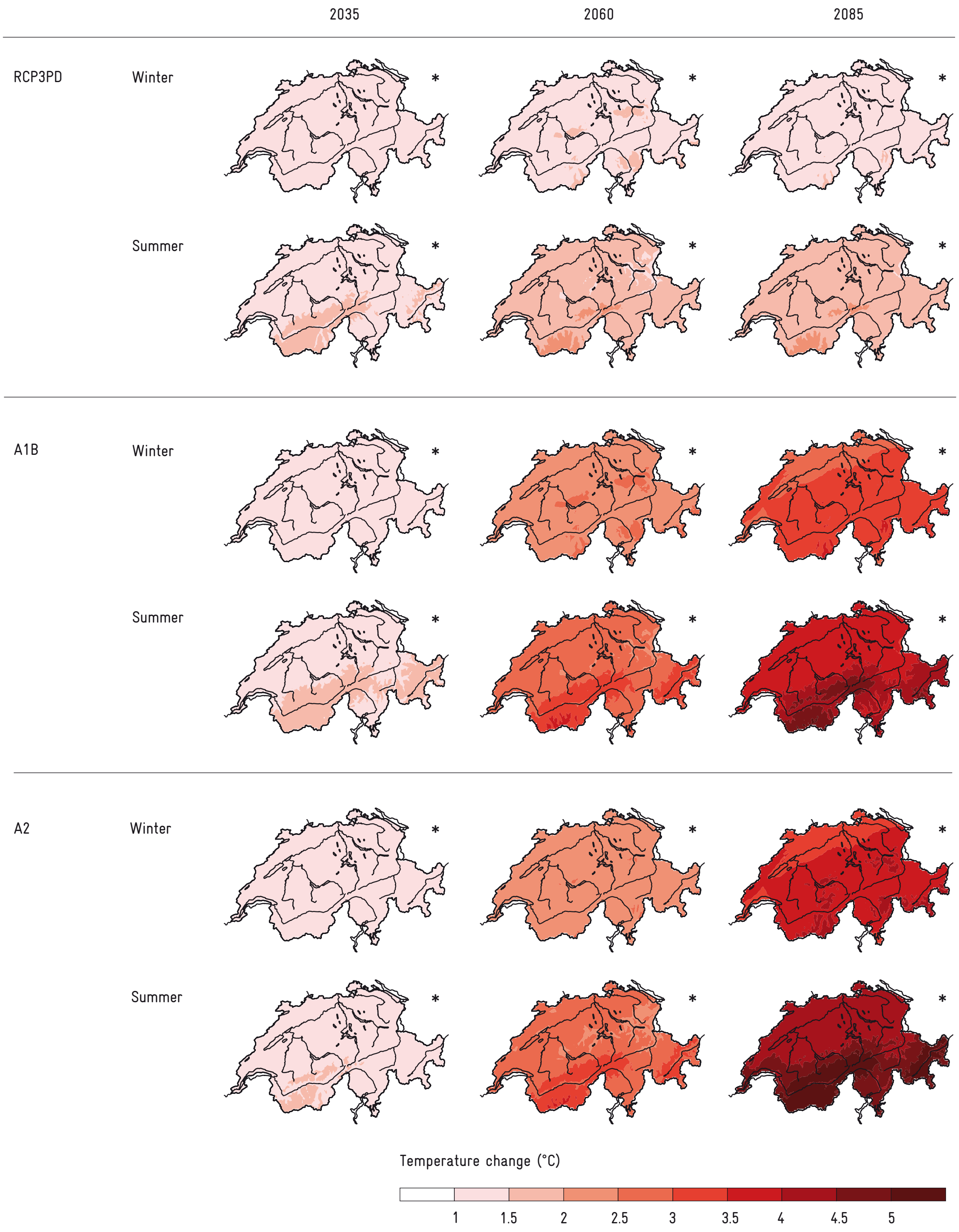


Figure 3.2: DAILY-GRIDDED projected temperature change (medium estimate changes with respect to the reference period, 1980–2009; Figure based on Zubler et al., 2014a). The range between lower and upper estimate only contains positive values. This implies that projected temperature changes exceed the natural decadal variability irrespective of the scenario, season, or projection period (denoted by *). The corresponding maps of absolute temperature observed in 1980–2009 are presented in CH2011 (2011, Figure A1).

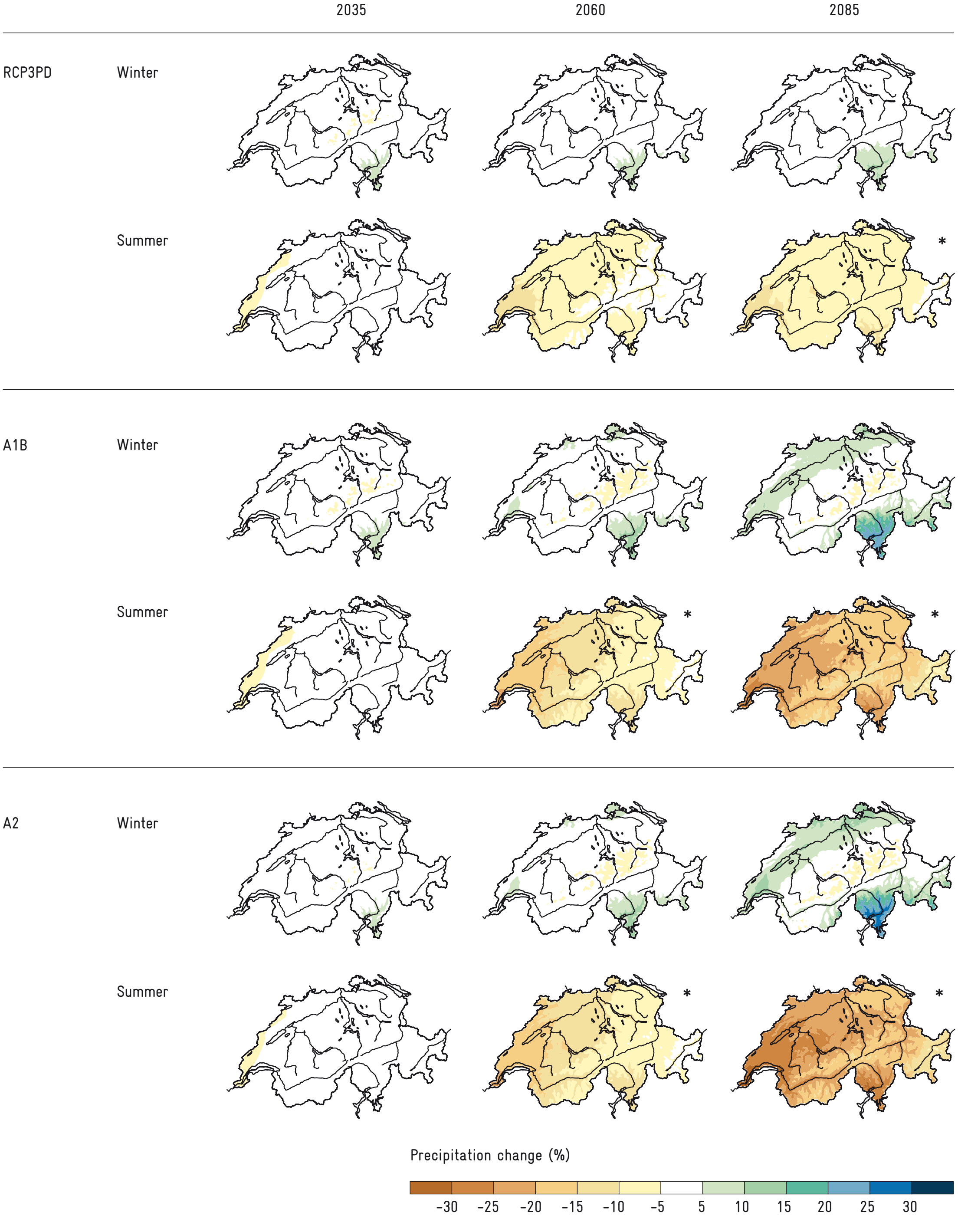


Figure 3.3: DAILY-GRIDDED projected precipitation change (medium estimates relative to the reference period, 1980–2009, Figure based on Zubler et al., 2014a). Summer drying is a robust signal emerging with proceeding climate change. This signal eventually exceeds natural decadal variability for all greenhouse gas scenarios, and the climate uncertainty range (lower to upper) only contains negative values (denoted by *). In all other seasons precipitation could either increase or decrease. The corresponding maps of absolute precipitation observed in 1980–2009 are presented in CH2011 (2011, Figure A1).

The CH2011 projections are used as input for most of the individual impact studies in CH2014-Impacts (Chapter 2). They are comprised of different data products with varying levels of aggregation. They are consistent among each other and are released in a consolidated and reviewed form, which makes them readily applicable for numerous climate change impact studies. In this chapter a summary of the salient features of the CH2011 datasets (CH2011, 2011) and of the upcoming CH2011 Extension Series is provided. Particular attention is given to uncertainties, limitations and constraints that arise from the underlying climate model simulations, as well as from the statistical methods that are applied to the raw regional climate model output.

3.2. OVERVIEW OF THE CH2011 SCENARIO DATASETS

Since their release in 2011, the CH2011 scenario datasets have been subject to continued extensions to meet the manifold requirements of the end-user community. Currently, four distinct datasets exist that describe projected future changes in air temperature at 2 m above ground and in precipitation, both relative to the reference period (Table 3.1):

SEASONAL-REGIONAL provides estimates of mean changes for each season and for each of five disjoint regions covering Switzerland. Lower, medium, and upper estimates indicate an uncertainty range derived from the joint assessment of 20 climate model chains (Section 3.4).

DAILY-REGIONAL is derived from SEASONAL-REGIONAL by disaggregating the seasonal mean changes into a daily resolved mean annual cycle (Section 3.5).

DAILY-GRIDDED is based on the SEASONAL-REGIONAL estimates of temperature and precipitation changes, downscaled to a horizontal 2-km grid, which covers all of Switzerland. The gridded data describe a daily resolved mean annual cycle, which is derived using the same disaggregation method as in DAILY-REGIONAL (Section 3.6).

DAILY-LOCAL is derived from the output of 10 climate model chains that is individually downscaled to measurement stations of MeteoSwiss. The downscaled data provide projections of the daily resolved mean annual cycle of changes in temperature and precipitation. The DAILY-LOCAL projections differ from the other datasets in two fundamental aspects: They are based only on a subset of the available ENSEMBLES model chains, and they are not the result of a probabilistic assessment (Section 3.7).

In all datasets, temperature changes are expressed as differences with respect to the reference period 1980–2009, and precipitation changes are expressed as ratios with respect to the reference period. To obtain projections in absolute terms, the user has to add the projected temperature change to, or in case of precipitation multiply with, the corresponding observations in the reference period.

Table 3.1: Overview of CH2011 datasets. Extensions to the original report in 2011 are marked with *.

Name	Temporal resolution	Spatial resolution	Greenhouse gas scenarios	Short name
Climate scenarios of seasonal means	seasonal	CHNE, CHW, CHS, CHAE*, CHAW*	A1B, A2, RCP3PD	SEASONAL-REGIONAL
Regional scenarios at daily resolution	daily	CHNE, CHW, CHS, CHAE*, CHAW*	A1B, A2, RCP3PD	DAILY-REGIONAL
Gridded scenarios at daily resolution*	daily	2 km × 2 km horizontal resolution	A1B, A2, RCP3PD	DAILY-GRIDDED*
Local scenarios at daily resolution	daily	temperature: 188 stations precipitation: 565 stations	A1B, A2*, RCP3PD*	DAILY-LOCAL

3.3. COMMON DATA BASIS OF THE CH2011 PROJECTIONS

Different climate models simulate different magnitudes of climate change, in particular at the regional scale. To account for this uncertainty, all CH2011 climate projections are based on a multi-model ensemble of simulations. The multi-model simulations originate from the ENSEMBLES project (van der Linden and Mitchell, 2009) that comprises 20 combinations of 6 different general circulation models (GCMs) with 14 different regional climate models (RCMs). The combination of a GCM with an RCM, which is nested into the low-resolution GCM (about 100–300 km grid spacing), is referred to as a "model chain", in which the large-scale information from the GCM is used to drive the RCM at its lateral boundaries. All simulations cover the period from 1950–2050, and a subset of 14 simulations extends to 2100. The ENSEMBLES simulations only comprise model runs under the A1B greenhouse gas scenario. Climate projections for A2 and RCP3PD are derived with the pattern-scaling method (Section 3.4).

3.4. SEASONAL-REGIONAL

For the SEASONAL-REGIONAL scenarios, 20 ENSEMBLES model chains together with the observed historical data are jointly assessed to derive estimates of regionally and seasonally averaged changes in temperature and precipitation for the three projection periods. The changes are assessed separately for each region, season, projection period, and variable. They are based on a probabilistic method, but the results are not interpreted in terms of probabilities (see below).

The five representative regions used for the spatially aggregated products SEASONAL-REGIONAL and DAILY-REGIONAL are: northeastern Switzerland (CHNE), western Switzerland (CHW), Switzerland south of the Alps (CHS), western Alps (CHAW), and eastern Alps (CHAE; Figure 3.4). Their delineation is based on a combination of expert judgment and pairwise correlations between grid-cells, to yield climatologically homogeneous regions of similar size.

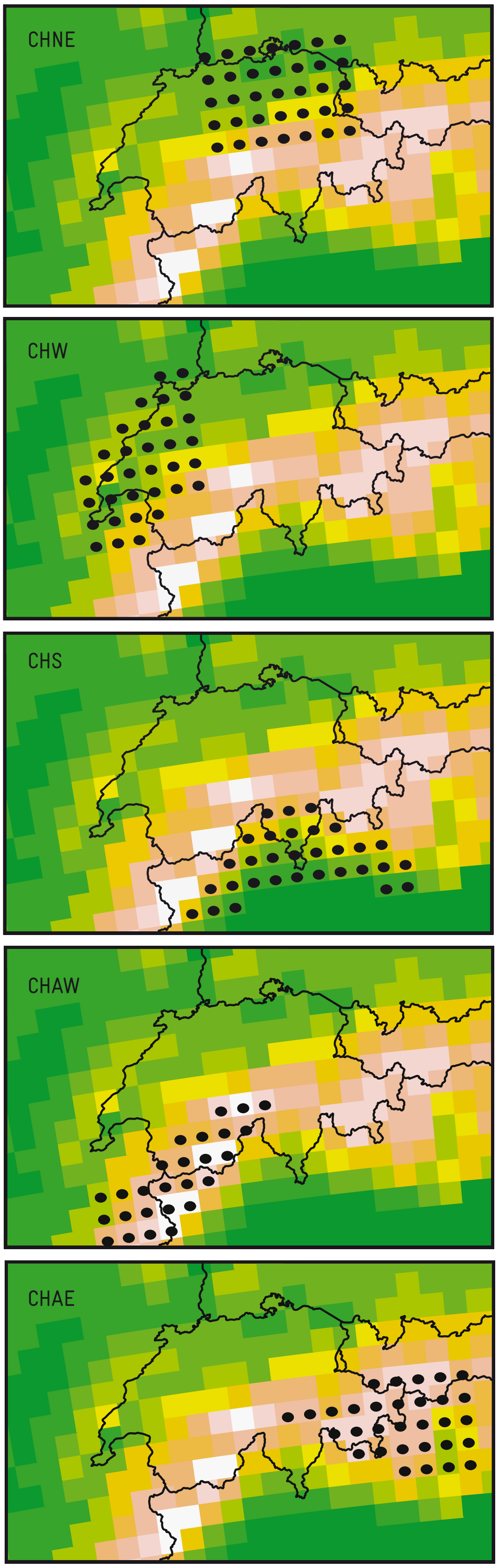


Figure 3.4: The five CH2011 regions used for the scenario calculations of SEASONAL-REGIONAL and DAILY-REGIONAL (CH2011, 2011; Zubler et al., 2014a).

At the time when the CH2011 report (CH2011, 2011) was written, confidence in the capabilities of regional climate models to simulate the Alpine climate was not high enough for a robust assessment. Therefore, the entire Alpine region was excluded. However, recent studies have shown that model simulations over this area are meaningful (Im et al., 2010; Kotlarski et al., 2012), leading to the extension of the CH2011 scenarios for the Alpine regions CHAW and CHAE (Zubler et al., 2014a).

In CH2011 (2011) the Bayesian algorithm of Buser et al. (2009) is adapted and applied to derive probability distributions of expected climate changes from the ensemble of individual model chains (Fischer et al., 2012a). The resulting probability distributions reflect climate uncertainty, which includes model uncertainty and an estimate of the internal decadal variability of the climate system (Section 2.4). The Bayesian framework makes it possible to decompose the complex interrelationships between observations, model projections, and unavoidable subjective prior assumptions in a systematic and transparent way.

Since the ENSEMBLES model chains are all run under the A1B greenhouse gas scenario, the widely used "pattern scaling approach" is applied to extend the projections to the greenhouse gas scenarios A2 and RCP3PD (Fischer et al., 2012a). For a specific scenario period, this approach consists of multiplying the lower, medium, and upper estimates for the A1B scenario with a scaling factor. This factor represents the global average temperature change under the A2 and RCP3PD scenario, respectively, divided by global average temperature change under the A1B scenario.

3.5. DAILY-REGIONAL

To obtain the DAILY-REGIONAL scenarios, the estimates of SEASONAL-REGIONAL (i.e., "lower", "medium", and "upper" estimates) are interpolated in time by fitting a third-order trigonometric polynomial to the seasonal averages in a way that preserves the seasonal means (Bosshard et al., 2011).

3.6. DAILY-GRIDDED

Based on the SEASONAL-REGIONAL multi-model estimates (for all three greenhouse gas scenarios) and based on the ensemble mean pattern over Switzerland (for A1B), temperature and precipitation changes are downscaled to a regular grid with a mesh size of about 2 km × 2 km. The downscaling procedure for the localized climate change signals of temperature and precipitation is based on the geostatistical interpolation method "kriging with external drift". This method combines a trend estimate for the target variables as a function of the geographical coordinates (latitude, longitude, and altitude) with a spatial interpolation of the resulting residuals (Zubler et al. 2014a).

This product relies on the same methodology as DAILY-REGIONAL, i.e., fitting a third-order trigonometric polynomial through the season means at the gridpoint level. Further details are given in Zubler et al. (2014a).

3.7. DAILY-LOCAL

The DAILY-LOCAL projections represent changes in the mean annual cycle at the local scale and at daily resolution, derived by applying a statistical downscaling technique to individual GCM-RCM chains. The method involves the spatial interpolation of daily climate model data to the measurement sites (188 temperature and 565 precipitation sites) and a spectral smoothing to derive changes in the mean annual cycle (Bosshard et al., 2011).

CH2011 (2011) provides DAILY-LOCAL projections for the A1B greenhouse gas scenario only. To extend this product to the two alternative greenhouse gas scenarios (A2 and RCP3PD), a pattern scaling procedure, similar to the one described in Section 3.4, is used (Figure 3.5). The method is presented in more detail in the upcoming CH2011 Extension Series and a preliminary version of this dataset was made available to the participants of CH2014-Impacts.

3.8. LIMITATIONS

While the different datasets presented here can be recommended for a large number of applications, some important limitations need to be taken into account:

a) The CH2011 scenarios provide no information about the probability of different combinations of temperature and precipitation changes within their respective uncertainty ranges, as both variables are considered separately. Hence, it is not clear, whether for instance a realization of an upper estimate of temperature change occurs more likely in combination with an upper, medium, or lower estimate of precipitation change.

The correlation between temperature and precipitation is investigated in the upcoming CH2011 Extension Series based on raw climate model data. This analysis suggests a weak negative correlation between temperature and precipitation changes in summer (Figure 3.6). This means that models showing stronger summer warming have a slight tendency to show stronger precipitation reduction. However, taking into account all CH2011 regions, projection periods and seasons, the model data reveal that a firm conclusion about the correlation structure is hampered by model uncertainty and possibly by the complex climate regimes in Switzerland. Therefore, for a comprehensive impact study, it is recommended to sample all combinations of changes in precipitation and temperature.

b) There is currently no guidance on the combinations of upper, lower, or medium estimates in temperature or precipitation from one season to the next, as the climate change signal of SEASONAL-REGIONAL is assessed separately for each season. In other words, future climate cannot be expected to follow the medium estimate throughout the entire year, nor the upper or lower estimate, nor any other specific quantile in between. The seasonal cycle of the climate change signal as actually simulated by the model chains is not considered in the analysis. This caveat applies also to the temporally disaggregated datasets DAILY-REGIONAL and DAILY-GRIDDED.

c) All CH2011 datasets provide the climate change signals in the form of change factors, i.e., differences (for temperature) or ratios (for precipitation) between the climate model simulations for the future projection periods and for the reference period. To obtain the actual projections for a future climate, these change factors are added to (for temperature) or multiplied with (for precipitation) recent baseline observations. This method is also referred to as the "delta change method". It is a robust and widely used technique, which has several benefits. It partly corrects for model biases (i.e., systematic errors) under the assumption that biases and inter-annual variability are constant over time. Another benefit of the delta change method is that the correlation structure in space and time is at least physically reasonable because it reflects observed conditions. This makes the method very appealing for applications that need data at several locations or for several parameters at the same time at high temporal resolution. On the other hand, this approach is questionable if the assumptions mentioned above are not justified, or if the correlation structure in space and time of temperature or precipitation changes in a future climate. In particular, changes in lengths of dry and wet spells and changes of the shape of the

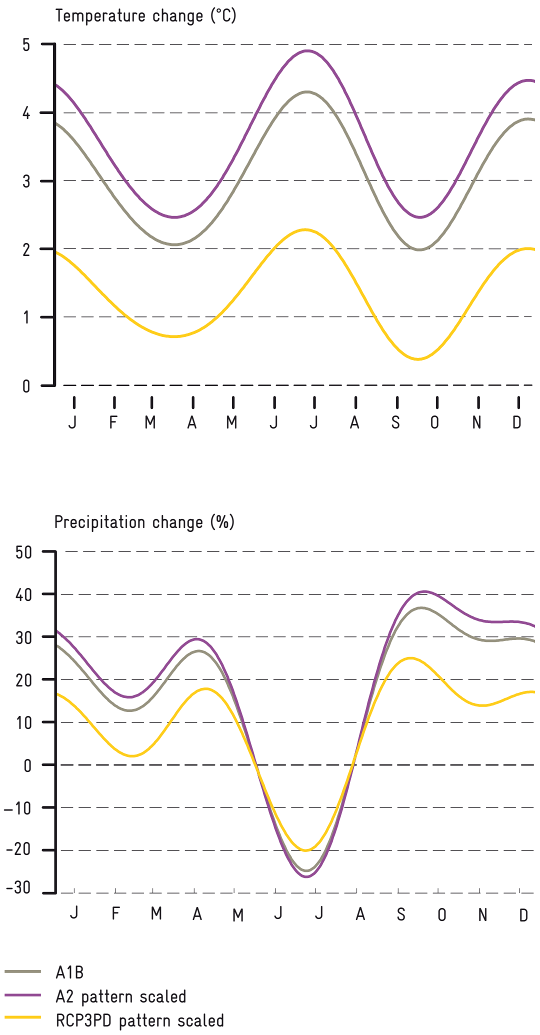


Figure 3.5: Example of the application of pattern scaling to the DAILY-LOCAL scenarios for the 2085 projection period obtained with the GCM-RCM chain KNMI-ECHAM5-RACMO for Zurich. Non-scaled (A1B) and pattern-scaled (A2 and RCP3PD) mean annual cycles of the climate change signal are shown on the top for temperature and on the bottom for precipitation (CH2011, 2011; and upcoming CH2011 Extension Series).

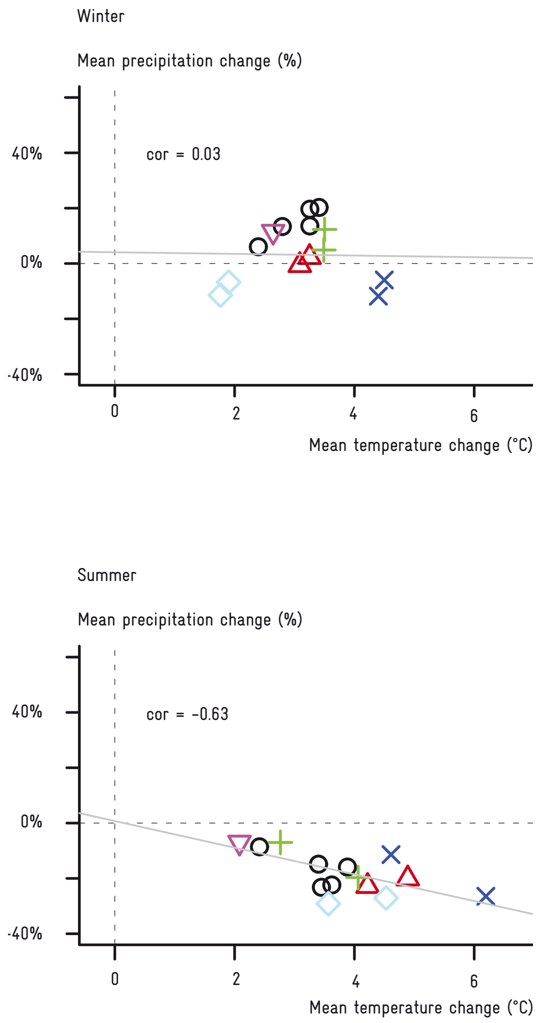


Figure 3.6: Scatter-plots of absolute changes in seasonal temperature (x-axis, in °C) and relative changes in seasonal precipitation (y-axis) during winter (top) and summer (bottom) for the CHNE region and the 2085 period. Data are grouped according to the driving GCMs (colors). The correlation coefficient (cor) is given as inset. Figure from the upcoming CH2011 Extension Series.

statistical distributions are not represented by these data sets. Therefore, care must be exercised in using these data for applications that are sensitive to such changes, e.g., some agricultural impact studies. Similarly, the delta change approach will not reflect a potential change in the occurrence of extreme precipitation or temperature events.

d) The assessment of model uncertainty from a finite set of currently available models (as in CH2011) most likely substantially underestimates the full range of uncertainty resulting from model imperfections (Knutti, 2008; Knutti et al., 2010; Masson and Knutti, 2011; Fischer et al., 2012a). Therefore the uncertainty ranges spanned by the "lower" and the "upper" estimate should not be interpreted in the sense of probabilistic uncertainty estimates, but rather as ranges of plausible outcomes that are consistent with the data and information at hand (Section 2.4).

e) Although the DAILY-GRIDDED dataset describes future changes at a resolution of 2 km × 2 km, care is needed when working with changes at individual grid-cells because the underlying climate change information only has a resolution of 25 km × 25 km and therefore a too smooth topography. This means for instance that micro-climatic features in Alpine valleys and local-scale feedback mechanisms are not accounted for in the downscaled data.

f) The pattern scaling approach used to extend results beyond the A1B greenhouse gas scenario is developed to scale the greenhouse gas induced signal only, while the natural variability remains unscaled. The pattern scaling approach assumes that any local-to-regional climate change in the long-term trend is linearly related to the long-term signal of the global mean temperature change. The pattern-scaled projections are therefore not meant to fully replace dynamically modeled projections for other emission scenarios. Such simulations were not available for the CH2011 assessment.

3.9. IMPLICATIONS

The use of the CH2011 datasets in impact assessments offers the advantages of consistency, transparency, and scientific credibility, since the data is based on the most recent models, observations, and statistical methods, and is carefully assessed and reviewed before publication. The provision of climate change projections is a continuous process that heavily relies on exchange between the climate modeling and climate impacts community. Since the publication of CH2011 (2011), user feedbacks have promoted the continuing development of related datasets. Despite these recent advances, there is still a large gap between available information and end-users' needs. For instance, up to now, projections are available for temperature and precipitation only and do not include variables such as wind speed, solar radiation, or relative humidity, which are often needed as input to impact models. Further examples concern the availability of quantitative and robust estimates of changes in extreme events or of probabilistic multivariate projections. It is expected that some of these limitations will be overcome by the ongoing improvement of climate models, by the development and application of new statistical techniques, and by a deeper understanding of the climate system.

To make these developments available to the impact community, regular updates and a continuous extension of national climate change scenarios are needed. The establishment of formal and informal sustainable structures to foster the exchange between climate modelers and end-users is important. Recently, the concept of a 'translator community' formed by scientists from all involved disciplines has been put forward by Salzmann et al. (2013). Sustainable bodies are needed to secure continuity and maintenance services for users. For Switzerland, an implementation of these needs could for instance be envisaged in the context of a national framework for climate services (NFCS; WMO, 2012).

4 — Temperature-based climate indices for sector-specific impact assessment

○
● summer days
● tropical nights
● frost/ice days
● growing season length
● heating/cooling degree days
○
○

– Climate indices facilitate the interpretation of expected future climate change for specific sectors and stakeholders.

– In the projections for the 21st century, trends toward more tropical nights and summer days, a longer growing season, but fewer frost and ice days are seen. Heating degree days are projected to decrease, cooling degree days to increase.

– The magnitude of the projected changes is strongly dependent on the considered greenhouse gas scenario. Under the mitigation scenario RCP3PD, the expected changes are much less pronounced than in the non-intervention scenarios A1B and A2.

– In the Swiss Alps, climate indices and their changes vary greatly with elevation.

‹ By the end of the century, the growing season may start as early as mid-February in the lower parts of Switzerland (flower buds opening on a cherry tree near Geneva; photo: Dorothée Baumann).

4.1. INTRODUCTION

Many expected climate change impacts are related to fixed temperature thresholds through physical processes. For instance, the frequency of temperatures below the freezing point has an impact on Alpine glaciers, permafrost and runoff hydrology (Chapters 5 and 6); similarly, distinct biophysical temperature thresholds limit agricultural production (Chapter 9) or may affect the development of various ecosystems (Chapter 7 and 8). Furthermore, a wide range of socio-economic sectors may suffer from impacts caused by extreme events rather than from average seasonal changes (Rahmstorf and Comou, 2012; Hansen et al., 2012; Klein Tank et al., 2009; IPCC, 2012). A prominent example is the record-breaking hot summer of 2003, which had substantial socio-economic and ecological impacts in Switzerland (OcCC, 2003), and increased mortality by ten thousands of heat-related deaths across Europe (e.g., Vandentorren et al., 2004; Schär and Jendritzky, 2004, Garcia-Herrera et al., 2010, Robine et al., 2008). Similarly, unusually cold winter temperatures may lead to travel disruption, cold-related enhanced mortality and increased energy consumption (e.g., Cattiaux et al., 2011).

In this chapter, changes in climate indices are presented to facilitate the interpretation of climate change and its impact for specific sectors. A climate index is a statistic typically calculated from daily temperature or precipitation series. A common type of index is the number of days on which a certain threshold is exceeded. Due to methodological limitations (Section 4.2) the analysis is limited to indices based on temperature thresholds. They are defined mostly following the recommendations of the World Meteorological Organization (WMO; Klein Tank et al., 2009) and include:

- Number of **summer days**: average number of days per year with maximum temperatures ≥ 25°C.
- Number of **tropical nights**: average number of days per year with minimum temperatures ≥ 20°C.

- Number of **frost days**: average number of days per year with minimum temperatures < 0°C.
- Number of **ice days**: average number of days per year with maximum temperatures < 0°C.
- **Thermal growing season length**: average number of days in a year between the first occurrence of a 6–day period with daily mean temperatures > 5°C and the first occurrence after July 1 of a 6–day period with daily mean temperatures < 5°C.
- **Heating degree-days**: annual average sum of differences between outside daily mean air temperature and the base temperature inside the building (20°C) on days with mean temperatures < 12°C (SIA, 1982).
- **Cooling degree-days**: annual average sum of differences between outside daily mean air temperature and the base temperature of 18.3°C, above which cooling is assumed to be needed.

Projected changes in summer days and tropical nights inform heat-related impact assessments, while frost and ice days quantify the conditions relevant to cold-sensitive impacts. Growing season length is relevant for the agricultural sector and plant ecology, heating degree-days, and cooling degree-days are indices tailored to the economic and energy sector.

4.2. METHODS

The projection of future fixed-threshold indices from climate simulations is challenging since small temperature biases (systematic differences between model simulation and observations) may lead to large biases in fixed-threshold indices. Therefore, the most robust approach to date is to impose the climate change signal onto observed temperatures (delta-change approach; Chapter 3).

The basis for the calculation of the indices listed above are the CH2011 scenarios "DAILY-GRIDDED" (Chapter 3) and km-scale observational temperature data from MeteoSwiss (Frei, 2014). The temperature change projections are based on daily mean temperatures, but are applied to minimum or maximum temperatures also, depending on the climate index. The indices are calculated for all uncertainty estimates (lower, medium, and upper), all greenhouse gas scenarios (A1B, A2, and RCP3PD) and all scenario periods (2035, 2060, and 2085) corresponding to the full "scenario cube" (Chapter 2, Figure 2.2). The indices are expressed as an annual mean for a 30-year period. The reference period covered by observational data is 1980–2009. More details are provided in Zubler et al. (2014a; b). Only long-term projections (2085) are discussed here because the intermediate periods do not add qualitatively new information.

A considerable limitation of the delta change approach is that the statistical distribution of climate variables is just shifted by the mean change value and its shape is assumed to be constant in time (Chapter 3). For this reason, caution is needed when the delta change approach is applied in the context of very rare events. For example, both a shift and a broadening of the distribution of summer temperatures could increase the frequency of events like the heat wave of 2003 (Schär et al., 2004; Scherrer et al., 2005; Fischer et al., 2012b). However, recent studies demonstrated that within certain bounds, changes in the exceedance of moderate temperature thresholds can be well approximated by a simple uniform shift in the temperature distribution (Fischer and Schär, 2010; Ballester et al., 2010; Lustenberger et al., 2014). Fischer et al. (2012b) suggest that the variability of temperatures increases for summer and decreases for winter. Under this assumption the delta change approach tends to underestimate the changes in indices such as tropical nights or ice days.

The delta change approach was not extended to precipitation-based indices since a mean shift does not sufficiently capture the possible changes in precipitation amount or frequency (Rajczak et al., 2013). In addition, there are regions on the globe where precipitation extremes increased although mean precipitation shows a decrease (Frich et al., 2002; Alexander et al., 2006).

4.3. RESULTS

All of the investigated temperature-based indices show clear imprints of the overall warming in Switzerland. However, based on the different thresholds and definitions, the projected changes in indices strongly depend on elevation and geographical region.

Today, the largest number of **summer days** in Switzerland is found in the valleys of the Ticino and along the northern shore of Lake Geneva. In these regions, about 60–70 summer days occur in an average year of the reference period, while typical values in the Swiss Plateau range from 20 to 60 days (Figure 4.1 a). By the end of the 21st century, the increase for RCP3PD over these regions is about 15–25 summer days (Figure 4.1 b). An average increase by about 30–70 summer days, or roughly a doubling, is projected for A1B (Figure 4.1 c) in the lower parts of Switzerland. Scenario A2 is very similar to A1B and therefore not shown.

Tropical nights are rare today in Switzerland. The only regions where tropical nights occur occasionally are the lowest section of the Ticino valley, the northern shore of Lake Geneva and some Föhn valleys (Figure 4.1 e). However, during the extremely hot summer 2003, seven tropical nights were recorded in Basel. Toward the end of the century, tropical nights are expected to occur in most parts of the Swiss Plateau, except for RCP3PD (Figure 4.1 f). In A1B (Figure 4.1 g) and A2, an average of 10–30 tropical nights are projected along the Aare and Rhine rivers, and up to two entire summer months with tropical nights in the Ticino and on the northern shore of Lake Geneva.

The increase in summer heat-related indices is largest in valleys even though the warming is not more pronounced there. Owing to the spatially rather homogeneous warming pattern, the increase in summer heat-related indices mirrors topography. A similar pattern is also seen on the European scale (Fischer and Schär, 2010). The upper elevation limit for summer days rises by about 400 m toward the end of the 21st century in A1B and A2, such that summer days may occur even above 1700 m asl (Figure 4.1 d). Tropical nights, currently not experienced above 500 m asl, may appear at elevations above 1400 m asl toward the end of the 21st century (Figure 4.1 h).

Warming is expected to cause a reduction in the number of frost days and ice days and to prolong the growing season (Frich et al., 2002). The fraction of the Alps experiencing **frost days** on more than one third of the year is projected to shrink considerably in the non-intervention scenarios A1B and A2 (Figure 4.2 c, blue colours). In the lower part of Switzerland, the corresponding number of frost days is projected to decrease from about 60 days to less than 30 days in some areas, while the number of **ice days** decreases from currently 25–45 to about 0–10 days (Figure 4.2 f–h). Thus, in the A1B and A2 scenario ice days disappear almost completely along the Ticino river and the shores of Lake Geneva based on the delta change approach (Figure 4.2 g). The strongest decrease of frost days is found at elevations above 3000 m asl (Figure 4.2 d). For ice days the strongest decrease of more than two entire months for the A1B and A2 scenario is found at similar elevations (Figure 4.2 h).

In A1B and A2, the **thermal growing season length** increases considerably in most parts of Switzerland. An extension by about 2 months is projected for the medium estimate of A1B in the lower part of Switzerland (Figure 4.2 k,l). Thus, according to the thermal index used here the growing season may start already in mid-February in these regions. In RCP3PD the increase of the thermal growing season length is projected to be limited to about 2–4 weeks until the end of the century (Figure 4.2 j).

Rising ambient temperatures are expected to reduce heating and increase the cooling demand in Switzerland (Chapter 10). A reduction of **heating degree-days** by 25–27% is found for the A1B scenario on the Swiss Plateau (Figure 4.3 a–d), where most of the population lives (medium temperature projection). The reduction decreases with higher elevation to about 15–20%.

At current temperatures, there is only little demand for cooling, with 50–200 **cooling degree-days** in an average year of the reference period (Figure 4.3 e). Toward the end of the century, however, cooling demand may increase to more than 400 cooling degree-days in some of the most populated areas in the scenarios A1B and A2 (Figure 4.3 g,h). This corresponds to an increase of the demand by a factor of two to eight. In the south of Switzerland, more than 1000 cooling degree-days are projected under the scenarios A1B and A2 (Figure 4.3 g,h). Above 1500 m asl, cooling degree-days are zero in the reference period (Figure 4.3 e), but the scenarios A1B (Figure 4.3 g,h) and A2 indicate a potential cooling need by the end of the century even at these elevations.

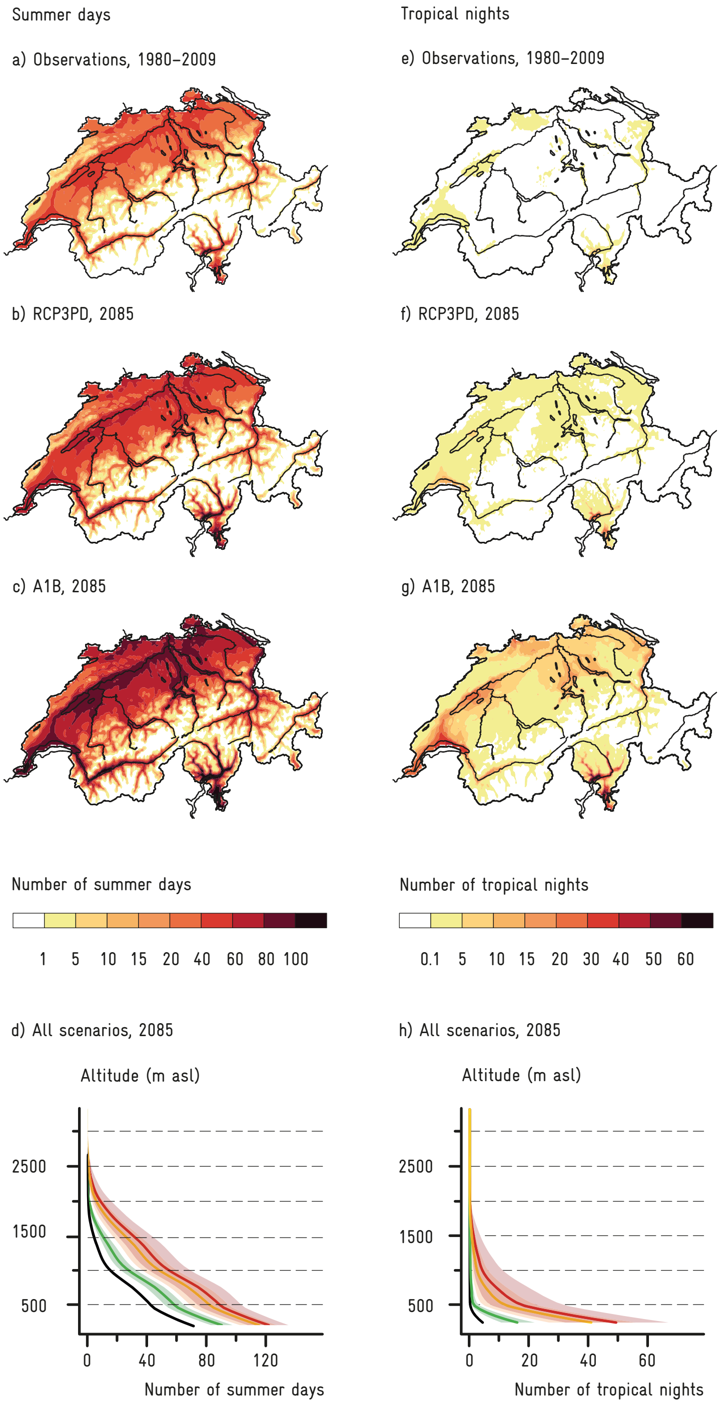


Figure 4.1: Number of summer days (left) and tropical nights (right): (a, e) 30-year mean over observations in the reference period 1980–2009, medium estimates of (b, f) the RCP3PD scenario (2085), and (c, g) the A1B scenario (2085). A2 is similar to A1B and is not shown as a map. (d, h) Vertical structure for all scenarios: In (d, h) the black line indicates the observations. The scenarios are displayed as follows: RCP3PD (green), A1B (yellow), and A2 (red). The lines in (d, h) correspond to mediums of height bins of 100 m over all grid points within Switzerland. Shading indicates the range from the lower and the upper estimate of each greenhouse gas scenario, respectively. Spatial variability is not displayed in the bottom panels.

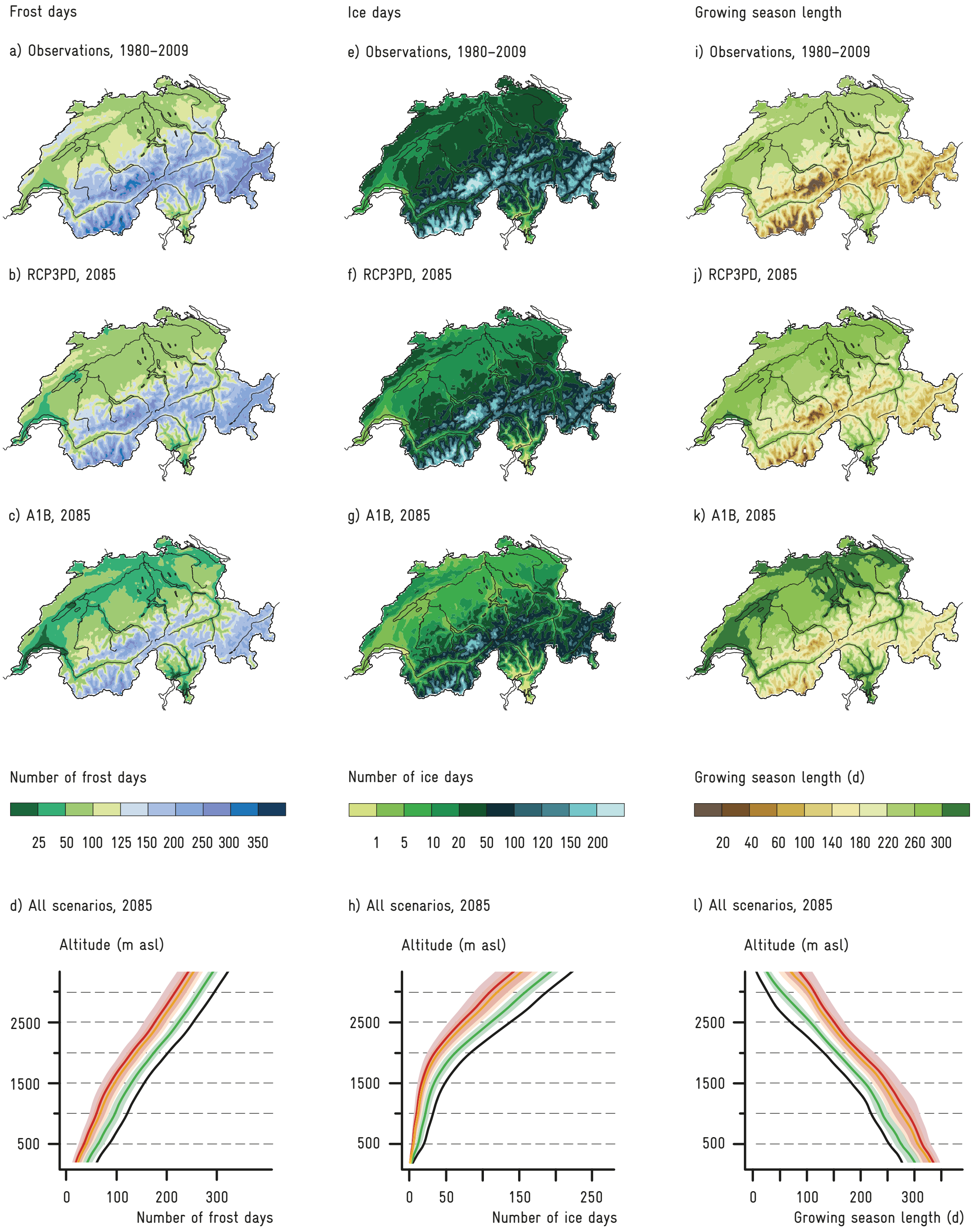


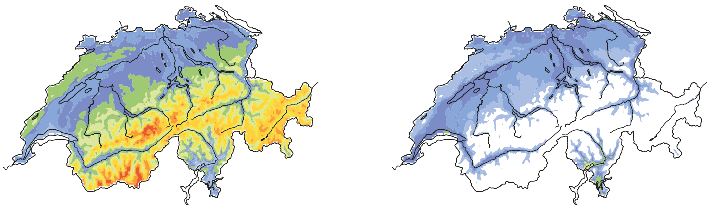
Figure 4.2: Number of frost days (left), ice days (middle), and growing season length (right): (a, e, i) 30-year mean over observations in the reference period 1980–2009, medium estimates of (b, f, j) the RCP3PD scenario (2085), and (c, g, k) the A1B scenario (2085). A2 is similar to A1B and is not shown as a map. (d, h, l) Vertical structure for all scenarios: In (d, h, l) the black line indicates the observations. The scenarios are displayed as follows: RCP3PD (green), A1B (yellow), and A2 (red). The lines in (d, h, l) correspond to mediums of height bins of 100 m over all grid points within Switzerland. Shading indicates the range from the lower and the upper estimate of each greenhouse gas scenario, respectively. Spatial variability is not displayed in the bottom panels.

Heating degree-days

Cooling degree-days

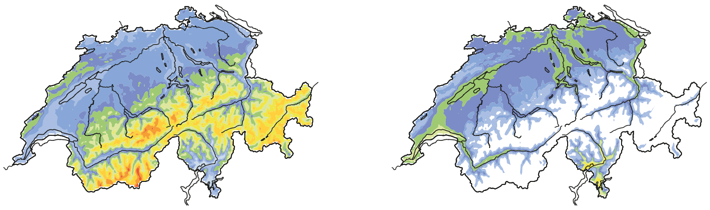
a) Observations, 1980–2009

e) Observations, 1980–2009



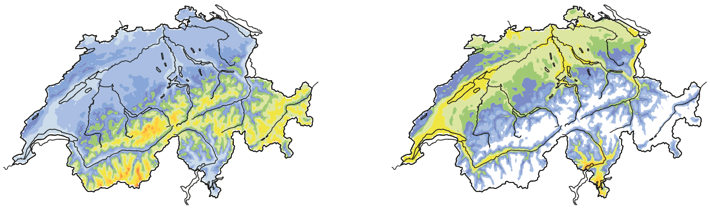
b) RCP3PD, 2085

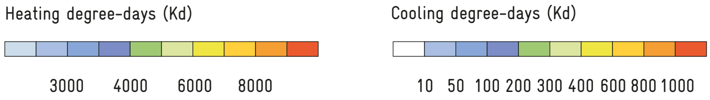
f) RCP3PD, 2085



c) A1B, 2085

g) A1B, 2085





d) All scenarios, 2085

h) All scenarios, 2085

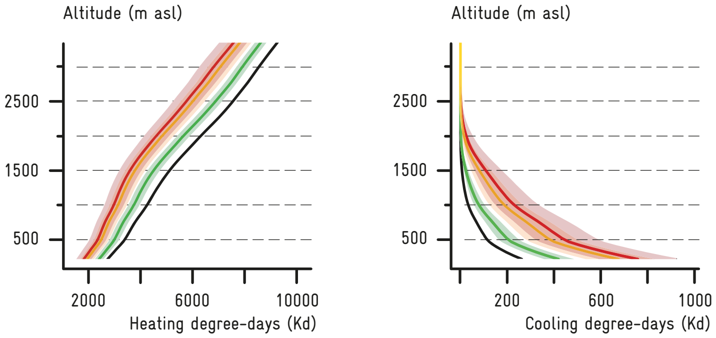
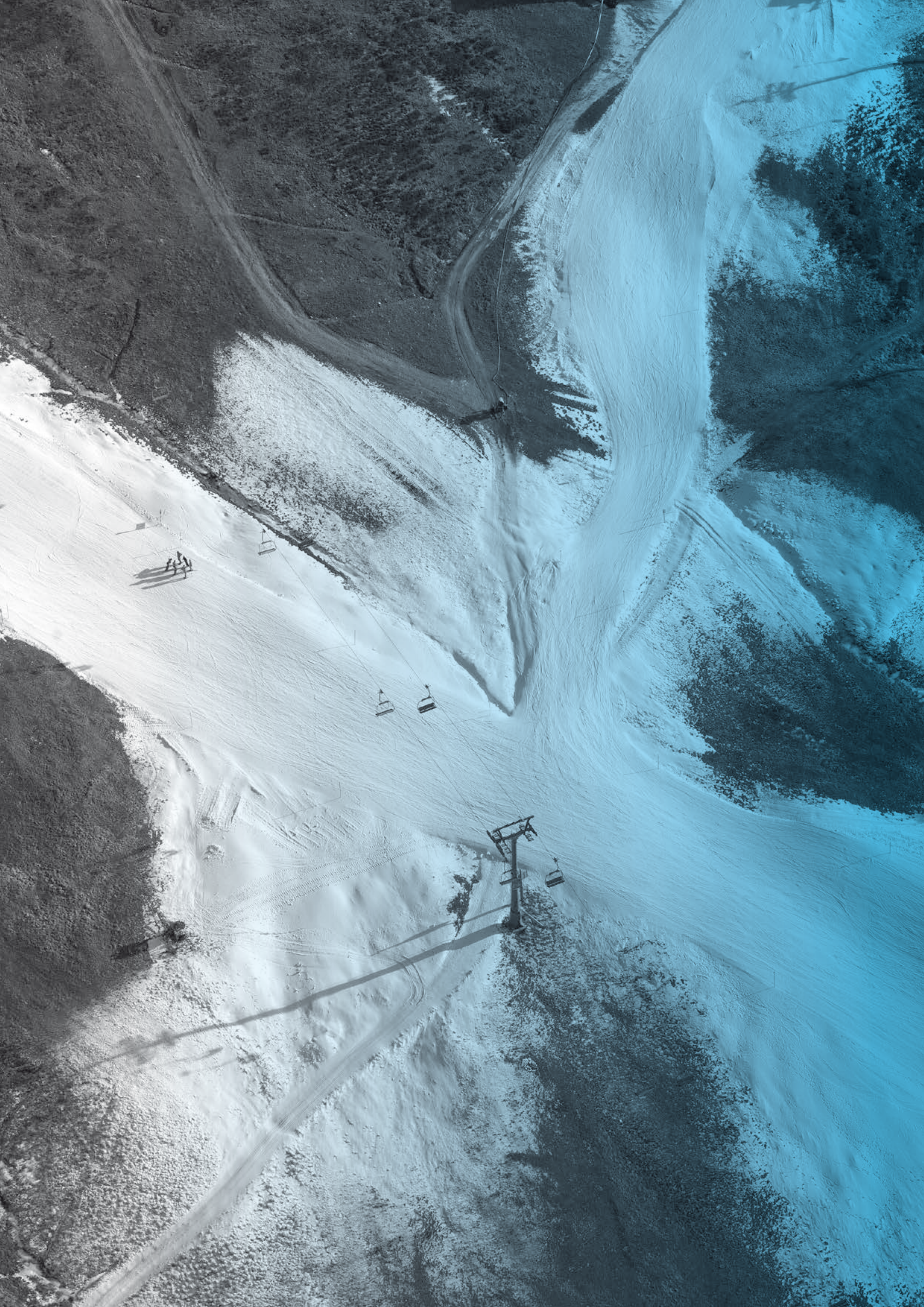


Figure 4.3: Heating degree-days (left) and cooling degree-days (right) in units of Kelvin-days (Kd): (a, e) 30-year mean over observations in the reference period 1980–2009, medium estimates of (b, f) the RCP3PD scenario (2085), and (c, g) the A1B scenario (2085). A2 is similar to A1B and is not shown as a map. (d, h) Vertical structure for all scenarios: In (d, h) the black line indicates the observations. The scenarios are displayed as follows: RCP3PD (green), A1B (yellow), and A2 (red). The lines in (d, h) correspond to mediums of height bins of 100 m over all grid points within Switzerland. Shading indicates the range from the lower and the upper estimate of each greenhouse gas scenario, respectively. Spatial variability is not displayed in the bottom panels.

4.4. IMPLICATIONS

The projected future changes in climate indices show a robust picture of more tropical nights and summer days, increasing cooling demand but reduced heating degree days, longer growing season, and fewer frost and ice days in a future climate. The changes in the investigated indices are highly sensitive to the greenhouse gas scenario considered and much larger for the two non-intervention scenarios than for the mitigation scenario. Although the evaluated indices are based on moderate temperature thresholds that are not related to highly damaging extreme events, a change in their value may still have substantial implications for related socio-economic sectors. They are relevant for the impacts discussed in the following chapters, e.g., for agriculture, biodiversity, permafrost and glacier melt, heating/cooling energy demand, health and human comfort indices, etc. Many of the changes that are highlighted by these indices reflect the Alpine topography, affecting high elevations more in some cases, and the densely populated Swiss Plateau in others.



5 — Cryospheric aspects of climate change – impacts on snow, ice, and ski tourism

○
○
○
● snow cover
● winter tourism
● glaciers
● permafrost
○

– A multi-day snow cover is projected to become a rare phenomenon in the Swiss Plateau by the end of the century assuming that the future climate is evolving according to the non-intervention scenarios A1B or A2, whereas the depth and duration of the snow cover will be significantly reduced at higher elevations.

– Ski tourism is projected to face serious challenges under the scenario A2 for 2060, but ski areas at high elevations might benefit from climate change by increasing their share of the skiing market.

– Around 90% of the glacier ice volume is projected to melt and large areas are deglaciated by the end of this century under the A1B scenario.

– Permafrost is expected to degrade due to increasing air temperatures but will be less affected by changes in precipitation.

‹ Snowmaking may be an effective adaptation option but is also costly and controversial (Jakobshorn, Davos in winter 2010/2011; photo: Helmut Steck).

5.1. INTRODUCTION

The cryosphere comprises ice and snow environments that are vulnerable to climate change, and its glaciers are compelling indicators of ongoing climate change (IPCC, 2013). The cryosphere plays a crucial role in many climate processes that directly affect human societies. This chapter describes the impact of climate change on four aspects of the cryosphere, i.e., snow cover, glaciers, permafrost, and ski tourism in Switzerland. The presented results are in line with former investigations but quantitatively demonstrate the impact of climate change in Switzerland according to the CH2011 scenarios (Chapter 3).

Mean winter temperatures in the Swiss Plateau have changed during the last decades from just below to slightly above the freezing point. Snow is very sensitive to this threshold of 0°C. As a consequence, precipitation as snow fall has been decreasing (Serquet et al., 2011) and, together with the concurrent snow melting, is responsible for the observed reduction of the snow cover, especially at lower elevations (Scherrer et al., 2004; Marty, 2008).

Ski tourism has been repeatedly identified as being particularly vulnerable to climate change (Abegg et al., 2007). While first generation impact studies considered natural snow only, second generation studies also incorporated snowmaking as an adaptation measure to climate change (Scott et al., 2012). In Switzerland, the impact of climate change on the ski tourism industry including current snowmaking technology has so far only been addressed in a few case studies (Rixen et al., 2011).

The increasing temperatures, especially in spring and summer, affect the glaciers by shortening the time period with a protecting snow cover. Therefore, the bare ice is exposed to the summer sun earlier, which thus has more time to melt the glacier ice. This process has caused major mass loss and a decrease in length of alpine glaciers over the past century (e.g., Bauder et al., 2007; Lüthi et al., 2010). The continued strong warming during the last decades has led to an accelerated volume loss in all glaciers of the Swiss Alps (Huss et al., 2010).

Permafrost, defined as lithospheric material with temperatures below the freezing point during at least two consecutive years (French, 2007), is widespread in Switzerland. It occupies about 6% of the territory, typically at elevations above 2400 m asl (PERMOS, 2010). The impact of recent climate change on alpine permafrost is still difficult to measure due to the shortness of the measurement period and the strong influence of the insulation by the snow cover (Haeberli et al., 2010).

5.2. METHODS

For each of the topics investigated, different models are applied, using selected data from the DAILY-LOCAL (winter tourism, glaciers, and permafrost) and DAILY-GRIDDED scenarios (snow cover) from CH2011 (Chapter 3). For snow cover, winter tourism, and permafrost, typical Alpine regions are studied. The glacier study covers 50 selected glaciers representing at present approximately 50% of the glacierized area and holding about 70% of the estimated total stored ice volume in the Swiss Alps (Farinotti et al., 2009). The data set includes the whole range of different glacier types from the largest valley glaciers to small mountain and cirque glaciers.

Future **snow cover** changes are simulated with the physics-based model Alpine3D (Lehning et al., 2006). It is applied to two regions: The canton of Graubünden and the Aare catchment. These domains are modeled with a Digital Elevation Model (DEM) with a resolution of 200 m × 200 m. This defines the simulation grid that has to be filled with land cover data and downscaled meteorological input data for each cell for the time period of interest at hourly resolution. The reference data set consists of automatic weather station data. All meteorological input parameters are spatially interpolated to the simulation grid. The reference period comprises only thirteen years (1999–2012), because the number of available high elevation weather stations for earlier times is not sufficient to achieve unbiased distribution of the observations with elevation. The model uses projected temperature and precipitation changes for all greenhouse gas scenarios (A1B, A2, and RCP3PD) and CH2011 time periods (2035, 2060, and 2085).

Impacts on **ski tourism** are assessed using the ski season and snowmaking simulation model "SkiSim 2.0". The current and future natural and technical snow-reliability of 34 ski areas in the Canton of Graubünden (Eastern Switzerland) is calculated using daily temperature and precipitation data as input. Snow production is activated if (i) the day lies within the snowmaking period (Nov 1–March 31), (ii) the air temperature is below –5°C, and (iii) modeled snow depth of the previous day is below the critical threshold. Details on the model procedures are presented in Steiger (2010). Each ski area is assigned to a climate station (nearest neighbor principle). Temperature and precipitation are extrapolated to the mean elevation of the ski area (average height between the lowest and the highest point of a ski area) using empirically derived lapse rates. The study covers all greenhouse gas scenarios (A1B, A2, and RCP3PD) and CH2011 time periods (2035, 2060, and 2085).

Two indicators are used to address the ski areas' sensitivity to climate change: the 100-day rule and the Christmas indicator. The 100-day rule states that in order to successfully operate a ski area, a snow cover sufficient for skiing (snow depth > 30 cm) should last at least 100 days per season (Dec 1–April 15). The Christmas indicator is defined by a minimum snow depth of 30 cm, maintained throughout the Christmas-New Year's period (Dec 22–Jan 4). This period is of particular interest because of high visitation and revenue levels (Steiger and Abegg, 2013).

For a representative sample of **glaciers** in the Swiss Alps, future ice evolution is simulated with two complementary modeling tools developed at VAW (ETHZ): The first approach uses GERM, a distributed mass balance model with geometry adaption (Huss et al., 2008; 2010). The second approach uses the LV-model, a 2-variable macroscopic glacier model dynamically calibrated with past glacier length changes (Lüthi, 2009; Lüthi et al., 2010).

Required input data for GERM are a detailed bedrock and surface geometry at a reference time. The model is calibrated for each glacier separately using past ice volume changes, and mass balance measurements if available. The LV-model requires records of glacier length changes and climate. Both models are driven with time series of temperature and precipitation variations in daily (GERM) or seasonal (LV) resolution. While GERM provides a detailed picture of the glacier mass distribution and three-dimensional geometry evolution, the LV-model yields length and volume change. Glaciers are integrative systems that sample the sum of climate variations, such that time-transient modeling is required. The CH2011 scenarios specify shifts of the climate parameters for three future scenario periods. To obtain continuous time series, temperature and precipitation is linearly interpolated between the centers of the reference and scenario periods. In addition, year-to-year fluctuations from the past are superimposed on the linear trend. An ensemble of realizations is constructed by 10 randomly sampled fluctuations for each of the 10 climate model chains included in the DAILY-LOCAL data set. This yields 100 individual model runs representing uncertainty from climate simulation and day-to-day weather fluctuations. Only scenarios based on the SRES A1B greenhouse gas scenario are used.

To simulate the response of a typical Alpine **permafrost** site to future climate changes, the fully-coupled one-dimensional heat and mass transfer model COUP (Jansson, 2012) is used, and parameterized here for a site located at 2900 m asl on the Schilthorn, Bernese Alps (Scherler et al., 2010). The permafrost there is at least 100 m deep and the mean seasonal thaw depth is around 5 m. The reference run is driven using observed air temperature and precipitation data. Projections use DAILY-LOCAL data for the neighboring station of Mürren, with a correction for the elevation difference, and consider all greenhouse gas scenarios (A1B, A2, and RCP3PD) and the scenario period 2085. A sensitivity study using the delta change approach (Chapter 3) is carried out with multiple pairs of delta values for air temperature and for precipitation, covering the CH2011 uncertainty range. Delta values are applied throughout the year for annual sensitivity, and to selected seasons for seasonal sensitivity.

5.3. RESULTS

Snow cover changes are projected to be relatively small in the near term (2035) (Figure 5.1 top), in particular at higher elevations above 2000 m asl. As shown by Bavay et al. (2013) the spread in projected snow cover for this period is greater between different climate model chains (Chapter 3) than between the reference period and the model chain exhibiting the most moderate change. In the 2085 period much larger changes with the potential to fundamentally transform the snow dominated alpine area become apparent (Figure 5.1 bottom). These changes include a shortening of the snow season by 5–9 weeks for the A1B scenario. This is roughly equivalent to an elevation shift of 400–800 m. The slight increase of winter precipitation and therefore snow fall projected in the CH2011 scenarios (with high associated uncertainty) can no longer compensate for the effect of increasing winter temperatures even at high elevations. In terms of Snow Water Equivalents (SWE), the projected reduction is up to two thirds toward the end of the century (2085). A continuous snow cover will be restricted to a shorter time period and/or to regions at increasingly high elevation. In Bern, for example, the number of days per year with at least 5 cm snow depth will decrease by 90% from now 20 days to only 2 days on average.

Ski tourism in the Canton of Graubünden is sensitive to climate change. In the reference period (1981–2010), nearly all investigated ski areas (mean elevation between 1200 and 2500 m asl) are snow-reliable. Without snowmaking, the number of snow-reliable ski areas (100-day rule fulfilled in at least 7 out of 10 years) will markedly decrease over time, e.g., in the A2 scenario from 100% (reference period) to 88% (2035), 71% (2060) and 47% (2085). Natural snow-reliability in the Christmas-New Year's period will be even more affected (Figure 5.2).

With snowmaking, the number of snow-reliable ski areas (100-day rule fulfilled in at least 7 out of 10 years) will also decrease over time, but to a much lesser extent, e.g., in the A2 scenario from 100% (reference period 1980–2009 and future period 2035) to 97% (2060) and 75% (2085). Again, the Christmas-New Year period is more sensitive to the projected climate changes. To secure the future

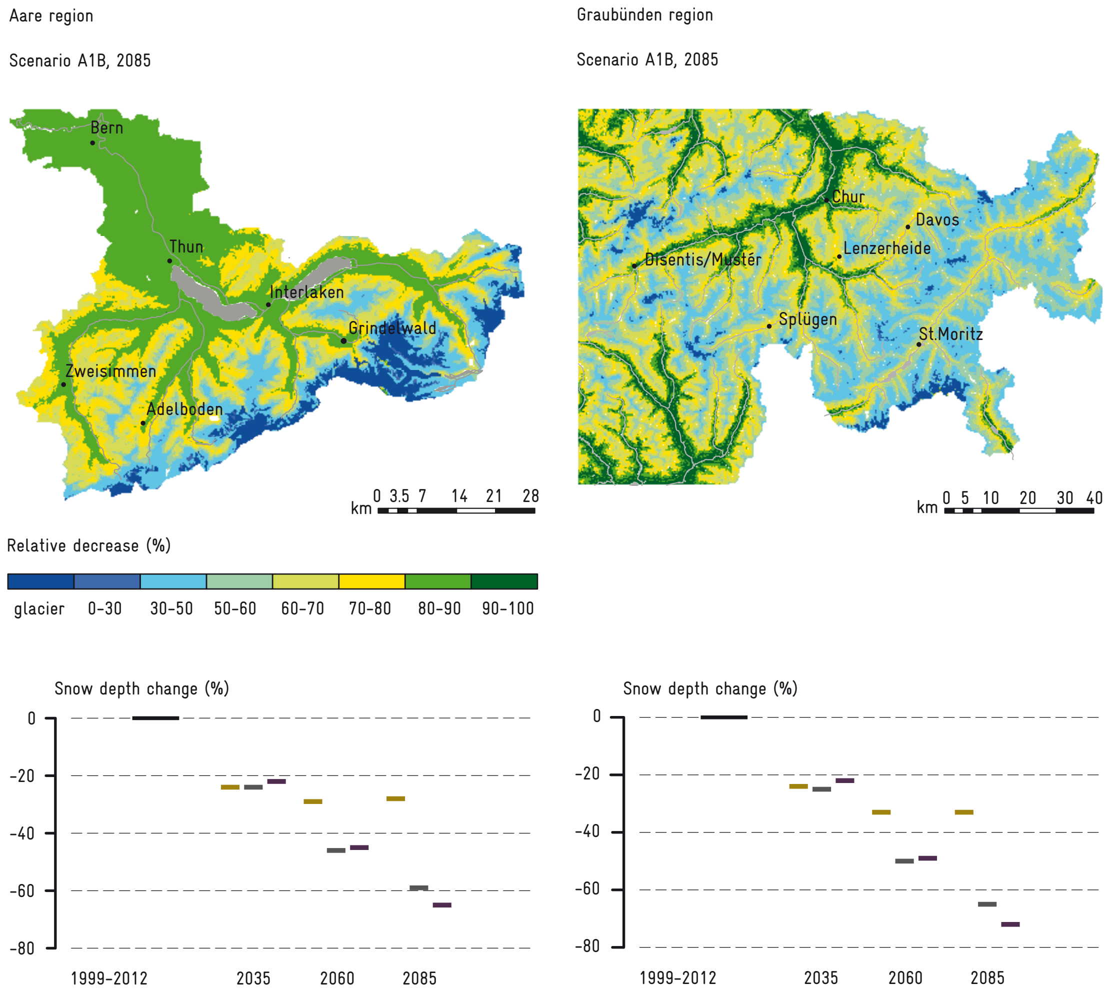


Figure 5.1: Relative decrease of annual mean snow depth compared with the reference period (1999–2012) for the Aare region (left) and the Graubünden region (right) for different scenarios (yellow: RCP3PD, grey: A1B, and purple: A2) and time periods (bottom) and for February 1 snow depth of the last time period (2085) and the A1B greenhouse gas scenario (top).

technical snow-reliability of the ski areas, the production of technical snow has to be substantially increased, i.e., doubled or tripled depending on the ski area and scenario. Ski tourism would benefit from climate change mitigation, as model results for the RCP3PD scenario show reduced impacts and stabilize after 2035.

The analysis of 50 **glaciers** with detailed measurements yields an area of 443 km^2 and a volume of 44 km^3 in 2010. Despite the very different approaches, both modeling methods yield very similar results (Figure 5.3), which gives confidence in the robustness of the conclusions. The simulated results for the A1B scenario show persistent negative mass balances resulting in large ice volume losses (Figure 5.4). Of the 50 glaciers analyzed in detail, among them the largest of the Alps, almost 90% of the ice volume is melted between the reference period and the last scenario period (2085) of A1B (Figure 5.4). This corresponds to the deglaciation of large areas. Remaining ice masses are limited to elevations above of 3000 m asl, and are clustered in the western Swiss Alps.

Permafrost reacts to an increase in air temperature in a complex and spatially heterogeneous manner due to the insulating influence of snow cover and an inhomogeneous distribution of surface and subsurface parameters such as heat conductivity, ice content, etc. Thus, temperature below ground does not necessarily reflect mean air temperature. Figure 5.5 demonstrates this by showing the

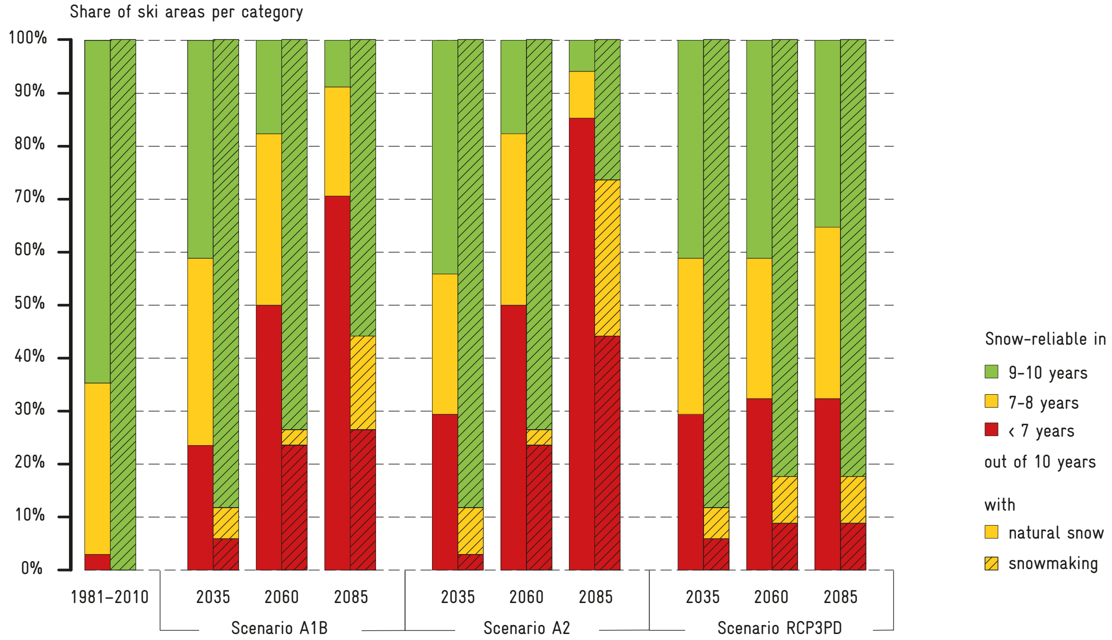


Figure 5.2: Natural and technical snow-reliability of ski areas in the Canton of Graubünden during the economically important Christmas holidays for all three scenario periods and greenhouse gas scenarios.

sensitivity of ground temperatures to annual and seasonal changes in air temperature (△T) and in precipitation (△P) for Schilthorn, Bernese Alps. For the annual change, the vertical pattern indicates that permafrost has a low sensitivity to changes in the amount of precipitation on the long term, as for a given △T, the soil temperature is independent of △P. Changes in seasonal precipitation have a larger influence (Figure 5.5). The presence of snow in autumn decouples the ground thermal regime from the atmosphere. Thus, a negative △P in fall will have a cooling effect on the soil as the reduced snow cover allows the negative air temperature to cool the ground. By the end of the 21st century, the greenhouse gas scenario A1B projects a △T of about 3.2°C and a △P of –2% in the medium estimate; the corresponding simulated soil warming for Schilthorn at 5 m is 2.5°C. These values can vary from site to site depending on factors such as substrate, ice content in the ground and influence of snow cover. Changes at larger depths (within the permafrost layer) will be much smaller within the same time period, although the thermal signal will propagate to larger depths for longer time periods.

5.4. IMPLICATIONS

If the non-intervention scenarios A1B or A2 are characteristic for future changes, a multiday snow cover in the Swiss Plateau will become an unusual phenomenon in the future. This will save millions of francs in costs associated with snow removal or traffic accidents, but may also decrease the revenue of winter tourism since the great majority of the prospective customers will not have the possibility to learn to ski close to where they live.

In comparison to other Alpine regions, destinations with a high share of high elevation ski areas such as Graubünden and the Valais will be less affected by climate change. These ski areas might even benefit from climate change (at least in periods 2035 and 2060) assuming a constant number of future skiers. The results of this study clearly demonstrate that snowmaking is an important option to mitigate economic losses due to climate variability and climate change, in line with the findings of IPCC (2007b). To get a broader picture, however, potential limitations must be considered concerning, e.g., the supply of resources (in particular water and energy), financial constraints (e.g., additional

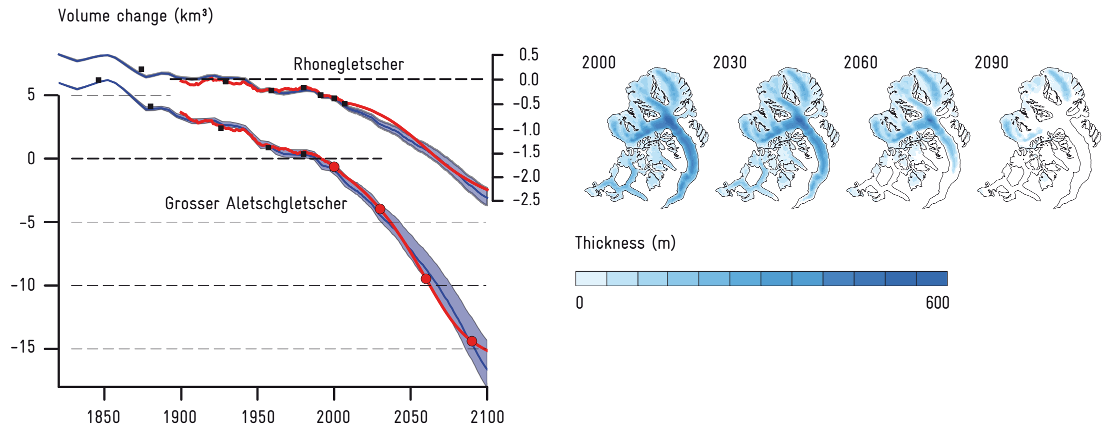


Figure 5.3: The future volume changes (A1B scenario) for the glaciers Grosser Aletsch and Rhone (left), as simulated with the LV-model (blue) and GERM (red). The blue shaded area is the envelope of the 100 model runs and the black squares indicate measured glacier volume changes. Red dots mark the times for which the simulated area and ice thickness distribution of the Aletsch glacier and its tributaries is shown (right). Estimated total ice volume of the two glaciers in the reference period: Grosser Aletschgletscher 16.8 km^3, and Rhonegletscher 2.2 km^3.

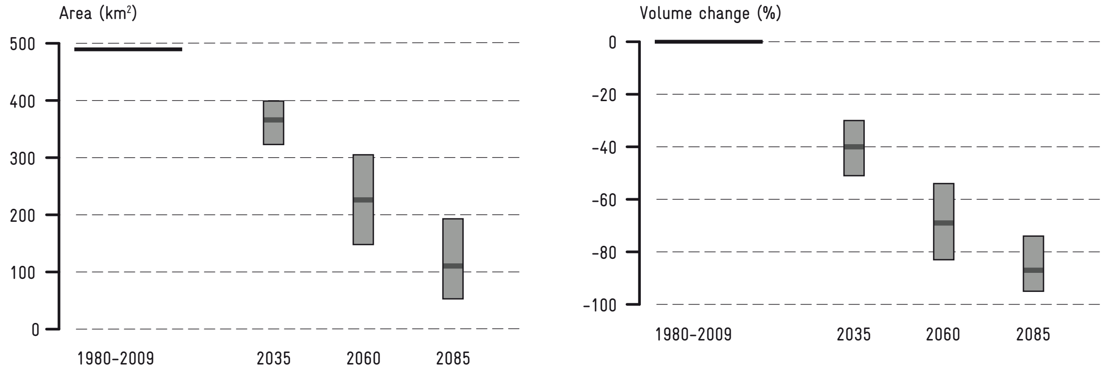


Figure 5.4: Glacier area (left) and ice volume change (right) with respect to the reference period (1980–2009) for 50 glaciers in the Swiss Alps as simulated with GERM for the greenhouse gas scenario A1B (average and range of all individual simulations).

investment and higher operating costs), and social acceptance. Another question mark is the potential impact of climate change on the demand side (skier market). Further research is needed to address the relative vulnerability of ski destinations, i.e., to extend this kind of analysis to other regions in Switzerland and in neighboring countries using comparable model parameters. Furthermore, climate change is only one factor influencing the future of ski tourism. Its interaction with other factors such as economic development and demographic change is yet poorly understood. Future research should therefore also address additional stressors in order to identify potential future pathways for sustainable tourism development.

A declining snow and ice reservoir in the Alps will prolong periods of low river flow in summer in many parts of Europe toward the end of this century (IPCC, 2007b; Farinotti et al., 2012, Chapter 6). Furthermore, a significant reduction of winter snow cover as simulated

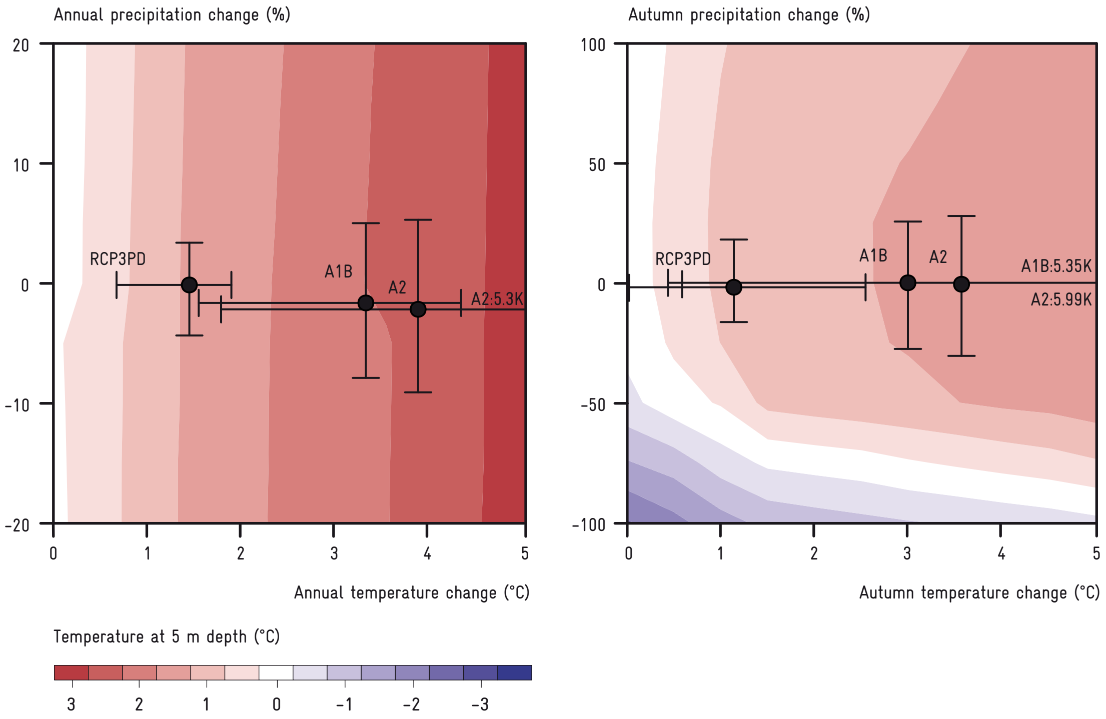


Figure 5.5: Sensitivity of simulated ground temperature at Schilthorn, Bernese Alps, to changes in surface temperature and precipitation applied over (left) the whole year and (right) the autumn months only (September–November). Panels show the difference in mean annual temperature at 5 m depth between the reference run (1980–2010) and the end of the 21st century (shading). Overlaid are the CH2011 projections for the three greenhouse gas scenarios (dots) and the ranges of the 10 DAILY-LOCAL model chains (error bars). Note the different scales on the precipitation axes.

especially for the mid- (2060) and long term (2085) will reduce soil moisture during dry springs and thus exacerbate the impact of hot summers. Together with the decreasing glacier melt, this can have severe consequences for several economic sectors including agriculture, hydropower generation, water supply and river navigation. Furthermore, increasing river and lake temperatures may present a problem for parts of the aquatic ecosystem (Wedekind and Küng, 2010). The bare rock and debris underneath the retreating glaciers and perennial snow patches will affect the typical Swiss landscape, whose green meadows and white mountains attract summer tourism. On the other hand, newly forming landscapes may provide new opportunities, as for example the emergence of new lakes represents for hydropower and tourism (IPCC, 2013; Haeberli et al., 2012).

The projected warming of permafrost at the Schilthorn can be interpreted as close to the upper bound for Switzerland, as the permafrost at this site is among the most sensitive due to its low ice content and the low albedo of the surface material (Scherler et al., 2013). More specific information on many permafrost sites in the Swiss Alps will become available with the ongoing analysis of site-specific factors conducted within the SNF-funded Sinergia project TEMPS "The Evaluation of Mountain Permafrost in Switzerland". Decreasing back-pressure by ice masses of melting glaciers or thawing of permafrost are expected to lead to ground instabilities and destabilization of slopes (Stoffel and Huggel, 2012). This can increase the frequency and magnitude of rock falls and debris flows, which in combination with floods from mountain lakes can affect residental areas far downstream (Huggel et al., 2012). Ground instability can also affect the safety and maintenance of infrastructure at high elevations. Therefore, special precautionary measures are recommended for any construction in potential permafrost areas (Bommer at al., 2010).

6 — Hydrological responses to climate change: river runoff and groundwater

○
● river runoff
● groundwater temperature
○
○
○

– For all greenhouse gas scenarios, a shift in runoff regime type is projected to occur in most catchments in Switzerland, with lower summer runoff and higher winter runoff, but little change in the total annual volume.

– Limiting emissions to RCP3PD levels would reduce the impacts on mean winter and summer runoff by approximately half in comparison with scenario A2 for the period 2085 – but even under scenario RCP3PD runoff seasonality is likely to be altered.

– For groundwater temperature change, the medium estimates for the period 2085 under the three greenhouse gas scenarios range from +1 to +3°C. The warming, which could pose problems for groundwater quality and drinking water production, is accentuated in certain aquifers, especially in the mid- to long term (periods 2060 and 2085). Situations of no change in groundwater temperature, however, cannot be excluded given the assessed levels of uncertainty in the projections.

‹ Seasonal redistribution and increasing variability of runoff make water resource management challenging (Aare river after the dry spell in spring 2011; photo: Jérôme Wider, PLANAT).

6.1. INTRODUCTION

Due to its natural water storage capacity and its role as a source of water to its downstream neighbors, Switzerland is sometimes called the „water tower of Europe“. However, the effects of climate change, i.e., glacier melting (Chapter 5) and changes in precipitation (Chapter 3), are calling this role into question. Climate change also affects ecosystems and human well-being indirectly through impacts on water resources and water quality. River runoff and groundwater reservoirs are crucial for understanding and quantifying these impacts: runoff is essential for the functioning of ecosystems and for supplying water needed for hydropower production, irrigation, cooling, and other uses; groundwater provides Switzerland with 80% of its drinking water.

The impact of climate change on river runoff has recently been investigated as part of a comprehensive assessment for the whole of Switzerland (FOEN, 2012b). Here, this study is complemented by considering the effects of different greenhouse gas scenarios, by conducting a detailed and systematic assessment of the model uncertainties in runoff projections, and by performing simulations for an intermediate mid-century time period.

Studies addressing the impact of climate change on groundwater and groundwater quality in Switzerland are rare. Groundwater quality is crucially dependent on its temperature, and warming may affect groundwater biogeochemistry in a way that reduces its quality and suitability as a source of drinking water. Since the 1980s, at least some aquifers in Switzerland have shown a marked increase in groundwater temperature (on the order of 1°C) associated with a change in climate forcing (Figura et al., 2011). Here, groundwater temperature projections based on the CH2011 scenarios are presented for a limited selection of aquifers to provide a preliminary assessment of potential future groundwater warming.

6.2. METHODS

In a first step, **runoff** from 186 mesoscale catchments from all parts of Switzerland (20 – 1760 km^2 in size) is simulated under today's climate and under projected future climate conditions to determine overall hydrological changes and to delineate regions of similar hydrological response. Based on the A1B scenario, these Switzerland-wide simulations are performed for a reference period (1984–2005, slightly shorter than the CH2011 reference period) and two time periods in the near (2035) and far (2085) future using the downscaled DAILY-LOCAL dataset (Chapter 3). The hydrological model used is PREVAH-GIUB (Viviroli et al., 2009a; b). Resulting changes in runoff, precipitation, and air temperature are classified by applying a cluster analysis to group regions of similar runoff response. Seven different types of region with similar runoff responses are identified, here referred to as response types C1–C7 (Figure 6.1; Köplin et al., 2012). The discussion focuses on response types C1–C6, as C7 is strongly influenced by hydropower production, which follows economic rather than climate processes.

In a second step, this spatially comprehensive analysis is complemented by performing a more detailed analysis of six selected catchments (Rhone at Brig, Vorderrhein at Ilanz, Emme at Wiler, Thur at Andelfingen, Venoge at Ecublens, and Verzasca at Lavertezzo) representing four major response types with increasing degrees of glaciation (C2, C4, C5, C6, Figure 6.1). Three catchments (Emme, Thur, Venoge) classified mostly as belonging to the same response type (C2) are selected to account for within-type variability and to test the validity of the classification under different greenhouse gas scenarios. These six catchments are analyzed taking into account all greenhouse gas scenarios and time periods, the climate modeling uncertainties (Chapters 2 and 3), and partly the uncertainty in hydrological impact modeling. The analysis does not capture the uncertainties inherent to the impact model parameters, and only part of the downscaling uncertainty. For each catchment, the ensemble of 10 DAILY-LOCAL scenarios, as well as the lower, medium, and upper estimates of the DAILY-REGIONAL dataset (Chapter 3), are used to force four hydrological models of different complexity, structure, and parameterization. These hydrological models are, in order of increasing complexity: HBV (Seibert and Vis, 2012), two versions of the model PREVAH (PREVAH-GIUB, Viviroli et al., 2009a; b; PREVAH-WSL, Kobierska et al., 2013), and WaSiM-ETH 8.0.1 (Schulla and Jasper, 2007). Data on glacier extent is provided by Linsbauer et al. (2013). The scaling methodology applied for transient glacier simulation approximates the scenarios RCP3PD and A2 in a way that may bias the runoff projections for the highly glaciated Rhone catchment. Consequently these greenhouse gas scenarios are not used for the Rhone catchment. Analysis of variance is used to distinguish between climate uncertainty (including natural variability) and impact uncertainty associated with the hydrological models (Chapter 2; climate uncertainty is not estimated for the Rhone catchment due to the incomplete coverage of the scenario range). The assessment focuses on changes in the annual cycle, as the available climate scenarios do not adequately capture changes in extremes.

Groundwater temperature projections are calculated for seven aquifers on the Swiss Plateau based on the empirical relationship between groundwater temperature and air temperature (Figure 6.2). Four of the aquifers studied are recharged mainly by riverbank infiltration (henceforth river-fed aquifers), and three by precipitation only (precipitation-fed aquifers). Two linear regression models are employed. One of these focuses on year-to-year correlations and yields separate estimates of annual mean groundwater temperature and monthly anomalies, whereas the other focuses on seasonality and yields direct estimates of monthly mean temperature. Both regression models are calibrated on historical measurement data that were only recently obtained (Schürch, 2011). The end of the calibration period is set at 2007 for all data sets, while the beginning of the calibration period varies depending on the length of the data available: for the three precipitation-fed aquifers (Kaeferberg, Laeufe, and Vorem Haag), the calibration periods begin in 1989, whereas for three of the the four river-fed aquifers they begin earlier (1971 for Seewerben, 1978 for Signau, 1972 for Weieracker, and 1989 for Distelmatten).

Other factors such as the influence of river discharge on the temperature of infiltrating water are not accounted for and are treated as statistical uncertainty. Model performance

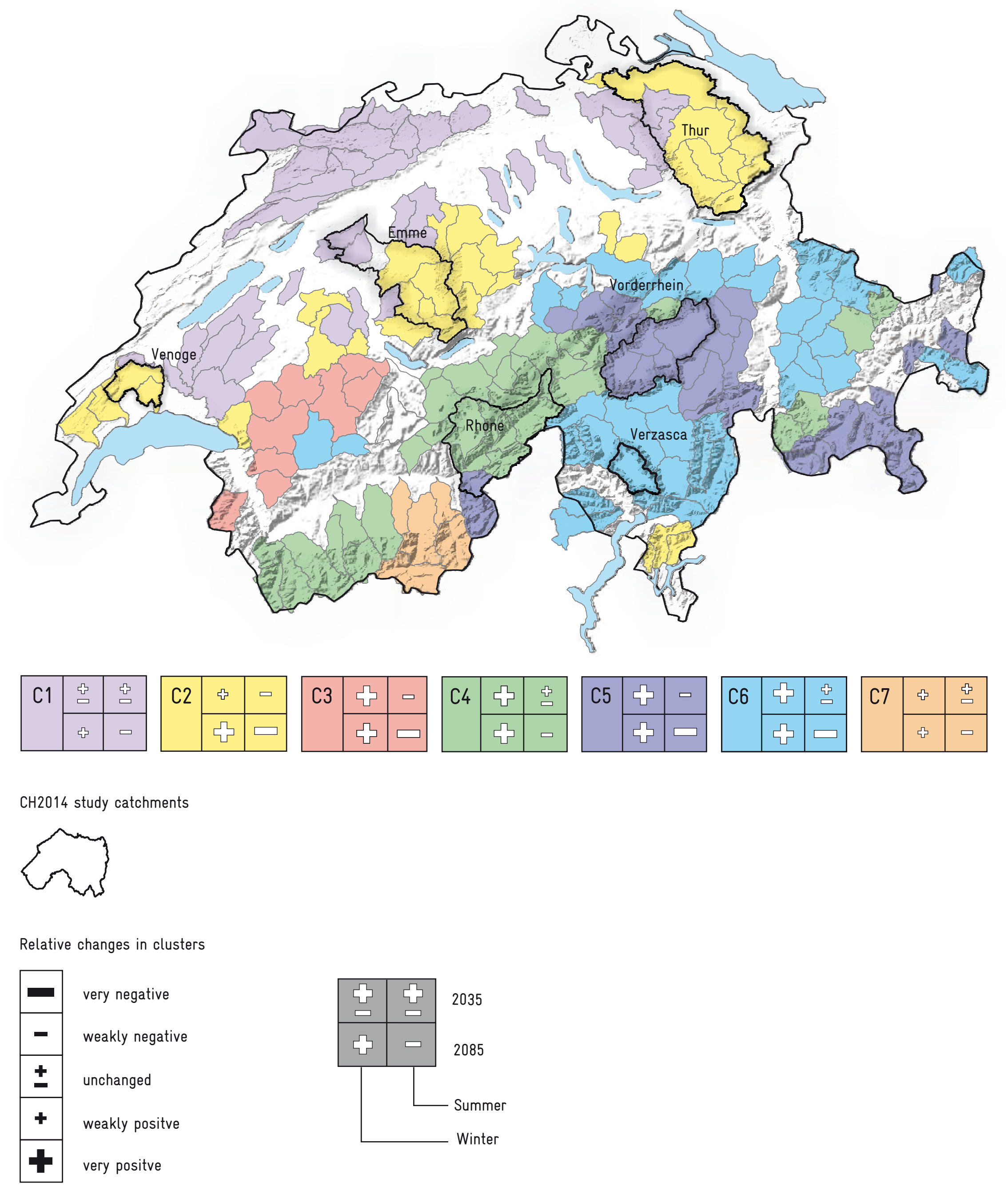


Figure 6.1: The seven runoff response types identified under the A1B scenario using the hydrological model PREVAH-GIUB (Köplin et al., 2012). Cluster C1 (light purple) corresponds to the Jura Mountains, cluster C2 to the catchments of the Swiss Plateau (yellow) and Ticino, and cluster C3–C7 (red, green, blue, and dark purple) to the alpine region with different degrees of glaciation. The boxes indicate the relative change in runoff in summer and winter in the scenario periods 2035 and 2085. The black contours indicate the six catchments selected for the in-depth study.

is evaluated by the goodness of fit to subsamples of the measurement dataset (validation data), after calibration based on the rest of the data (training data). The models perform better for the river-fed aquifers than for precipitation-fed aquifers. This is either because the relationship between groundwater temperature and air temperature is tighter in river-fed aquifers, or because the relevant measurement data series are longer. Box and transfer function models were also tested, but performed poorly in comparison to the linear regression models. Projections are calculated based on monthly mean air temperatures computed from the CH2011 DAILY-REGIONAL scenarios (including all three greenhouse gas scenarios and time periods).

6.3. RESULTS

The changes in **runoff** in Switzerland induced by climate change can be grouped into seven different response types (C1–C7, Figure 6.1) that mainly reflect the major geographical regions of Switzerland. Cluster C1 corresponds to the Jura Mountains, cluster C2 to the catchments of the Swiss Plateau and Ticino, and cluster C3–C7 to the alpine region, with different degrees of glaciation. Changes in runoff can be summarized as an increase in winter and a decrease in summer, with the total annual volume of runoff remaining approximately the same. Changes in runoff in autumn and spring are far less pronounced. These hydrological responses are summarized for each cluster in Figure 6.1. For catchments in clusters C3–C7, the thermally controlled melting of glaciers and snow governs the seasonal runoff. Here, the projected warming affects seasonality by increasing the proportion of rain in winter precipitation, by resulting in earlier snow melt, and by decreasing the amount of snow and ice melted during the summer. Accordingly, these catchments shift from a snow-controlled (nival) regime to a more rain-controlled (pluvial) regime. This shift is less pronounced at higher elevations with a higher degree of glaciation (regions C4 and C7). The rainfall-controlled catchments in the Jura Mountains (C1) and on the Swiss Plateau (C2) show similar changes in seasonality, with the projected reduction of precipitation in summer and an increase of liquid precipitation in winter directly altering the runoff. In general, projected changes in Switzerland are more pronounced in alpine areas and in the distant future.

Figure 6.2: Map showing the location of the aquifers studied. Blue: river-fed aquifers. Green: precipitation-fed aquifers.

The robustness of the Switzerland-wide response signal is evaluated based on an uncertainty analysis for the six catchments selected for an in-depth study. Figure 6.3 presents the projected annual cycle and related uncertainty bands for these six catchments in comparison to the reference period for the A1B scenario in the distant future (2085). For all catchments, the uncertainty is large, but the salient hydrological responses described above remain valid: (i) earlier melting of snow and ice in both alpine catchments (Rhone and Vorderhein); (ii) less summer runoff; and (iii) greater winter runoff in most catchments. Although the projected changes in the peri-alpine catchments (Emme, Thur) and in the catchment on the Swiss Plateau (Venoge) are comparatively small in absolute terms, the relative changes are considerable (Figure 6.3, bottom row). In the alpine Rhone catchment, the melting of residual glaciers prevents the occurrence of a decrease in summer runoff until the end of the century under the non-intervention scenario A1B.

The effect of climate change mitigation on the projected runoff is seen by comparing the different greenhouse gas scenarios (excluding the strongly glaciated Rhone catchment, for which only the A1B projections are available; Figure 6.4). Changes in runoff are projected to appear by the first scenario period (2035) irrespective of the greenhouse gas scenario. Differences between the mitigation (RCP3PD) and the non-intervention (A1B and A2) greenhouse gas scenarios become clear in the mid-century period (2060), when the effects of climate change are also greater. For the end of the century

(2085), a further increase in the impacts of climate change is projected, and differences appear between A1B and A2. Limiting emissions to RCP3PD levels would reduce the impacts on runoff in summer and winter, when the change is strongest, by approximately a factor of two in comparison to the impacts projected for scenario A2 for 2085. This potential reduction of the impact is independent of the response type (Figure 6.4, bottom row).

The uncertainty in the runoff projections for the non-glaciated catchments is dominated by the uncertainties in the climate models and by the natural variability of the climate (Figure 6.5). Within high alpine catchments, differences in the complexity of the glacier and snow melt routines, as well as differences in the representation of reservoirs in the hydrological models, are crucial and associated with high uncertainties, but the sign of the change remains consistent across all model chains of the DAILY-LOCAL data set (Chapter 3). This finding is relevant for future studies and for the interpretation of past studies that rely on a single hydrological model. In the lowlands, the ensemble mean indicates an increase of winter runoff but high uncertainties make the sign of the change inconclusive. In the mountain catchments, low winter runoff implies high uncertainties in the relative runoff change. The uncertainties in the summer runoff projections remain relatively stable whereas uncertainties in the winter runoff tend to increase with time.

The three lowland catchments of the same response type show similar behavior. This finding supports the clustering derived from the spatial analysis (Köplin et al., 2012; Figure 6.1) and justifies the extrapolation from the selected set of six catchments to the response types identified in the Switzerland-wide study.

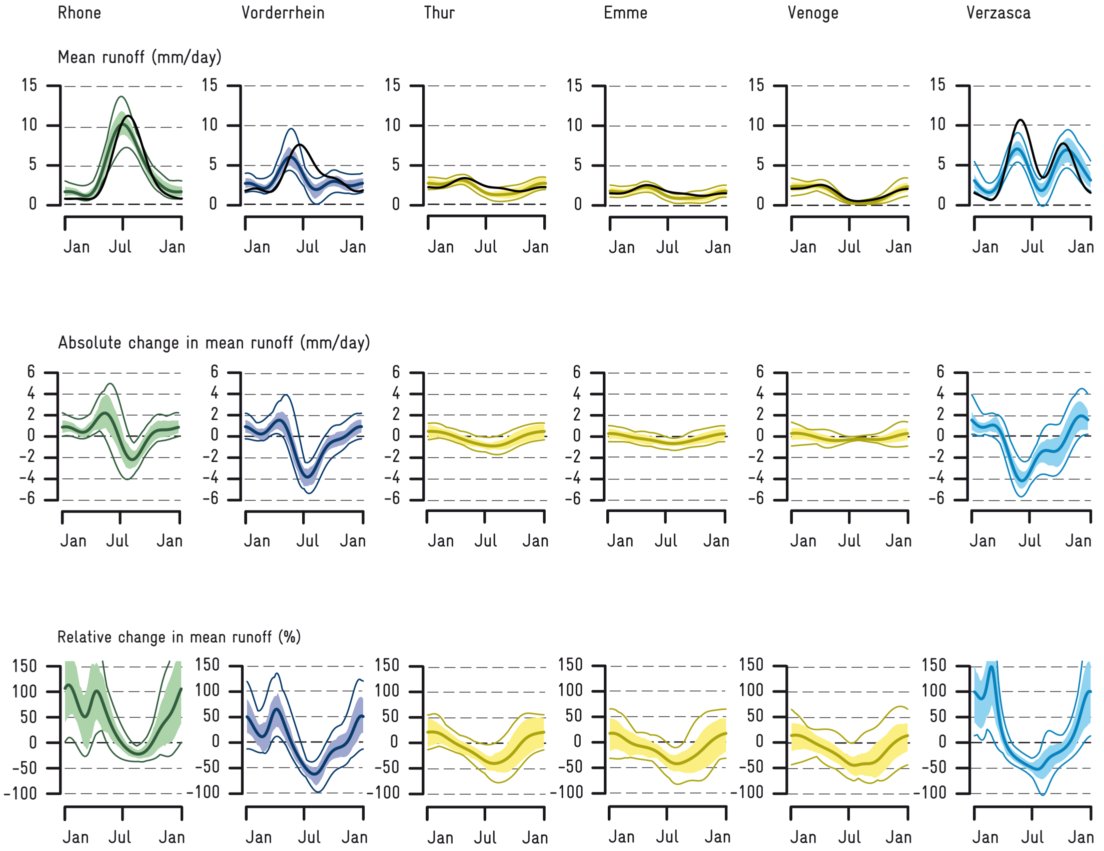


Figure 6.3: Mean runoff (top row) over the reference period (black) and the scenario period 2085 (colored) for scenario A1B, and the corresponding absolute change (middle row) and relative change (bottom row). For projected runoff, the mean over the uncertainty range is shown (bold colored line) along with the standard deviation (shaded) and the minima/maxima (thin lines). Colors indicate the runoff response types for each catchment according to Figure 6.2.

Based on the CH2011 climate projections, **groundwater warming** can be expected in all aquifers studied, but (with the exception of Distelmatten) there are marked differences between river-fed and precipitation-fed aquifers (Figure 6.6). According to the medium estimates, by the end of the century the latter are projected to warm by < 1°C on average while the former are projected to warm by 1–3.5°C. However, the results do not indicate clearly whether the relatively slight warming projected for precipitation-fed aquifers results from a weak coupling of groundwater temperature to air temperature or from the comparative shortness of the data sets. Taking into account the uncertainty in the projections, it is possible that groundwater temperatures will increase by up to 7°C in river-fed aquifers and by up to 2°C in precipitation-fed aquifers in any given year of the projection period 2085. However, as a result of the large uncertainties involved, the projections do not exclude a situation in which no warming, or even a slight cooling, might take place. Comparison of the groundwater temperature projections under the three different greenhouse gas scenarios shows that they are very similar for the 30-year period centered on 2035, but diverge later (Figure 6.6). With regard to seasonality, the two regression models are not always consistent; however, there is a clear tendency for warming to be strongest in summer and autumn. The uncertainty associated with the projections results mainly from the uncertainty inherent in the statistical predictability of groundwater temperature from air temperature, which is responsible for 70–80% of the total projection uncertainty. The remaining 20-30% of the total projection uncertainty results from the difference between the lower and upper estimates of the CH2011 projections. The impact uncertainty is larger in most river-fed aquifers than in precipitation-fed aquifers because of the stronger coupling with the naturally varying air temperatures.

6.4. IMPLICATIONS

The total annual **runoff** volume in Switzerland is projected to remain approximately the same as it is now. However, at the regional scale, e.g., in highly glaciated alpine valleys like the Rhone catchment, this will be partly at the expense of retreating glaciers. This general statement is especially true for the northern part of the Alps. In the Ticino and the southern Valais however, the annual runoff volume will decrease (FOEN, 2012b). The relative stability of the long-term annual runoff over time is related to the smallness of the projected changes in annual precipitation rates, supplemented by the contribution of glacier melt in glaciated catchments.

A seasonal redistribution of runoff is projected under all greenhouse gas scenarios, and will affect summer and winter runoff in all catchments. This confirms and corroborates previous findings (IPCC, 2007b; FOEN, 2012b) and has already been described qualitatively twenty years ago (VAW, 1990; OcCC, 2007). In the present study, the hydrological responses to climate change have been quantified using the latest and most comprehensive modeling approach. Furthermore, this study demonstrates that the response patterns are robust with respect to the considerable uncertainties that result from the choice of climate and hydrological models.

Although the long-term annual runoff will remain approximately constant, the year-to-year variability and the seasonal redistribution of discharge suggest some challenges for water resources management. Year-to-year variability, which may significantly affect water management, has not yet been investigated thoroughly because of the limitations of the downscaling method (Chapter 3). Concerning seasonal redistribution, the FOEN report (FOEN, 2012b) as well as Meyer (2012), showed for the Swiss Plateau that an increase in the duration of dry spells in summer might lead to water shortages like those that occurred in the summer of 2003. As shown in the present study, these water shortage situations are further exacerbated by the projected groundwater temperature increase, which can affect groundwater quality. In all regions of Switzerland, water scarcity in summer has additional implications for agriculture and ecosystems, drinking water supply and hydropower production (SGHL and CHy, 2011). For instance, Holzkämper et al. (2013a) showed that the positive effects of climate warming on agricultural yield are suppressed by water stress in extremely dry years like 2003. Still, in a continental context, the threat of drought stress is less for Switzerland than for southern and eastern Europe (IPCC, 2007b).

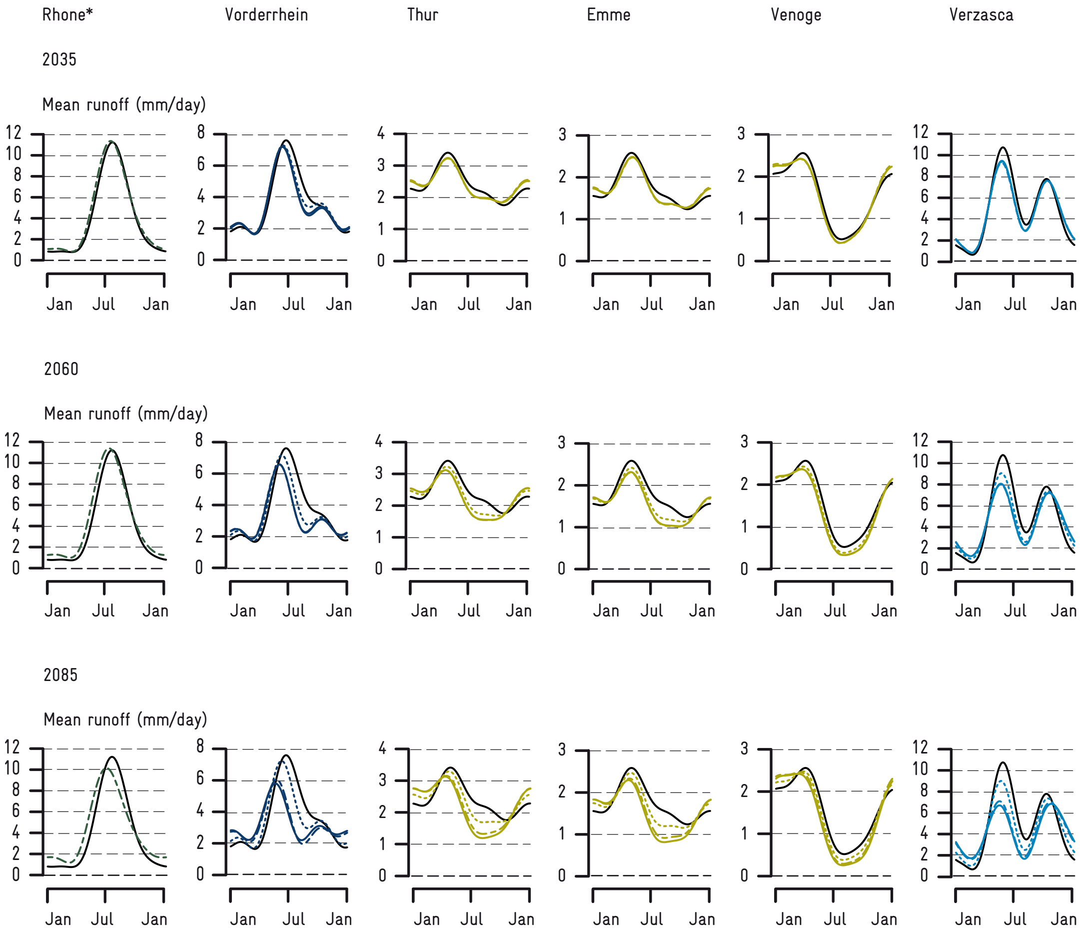
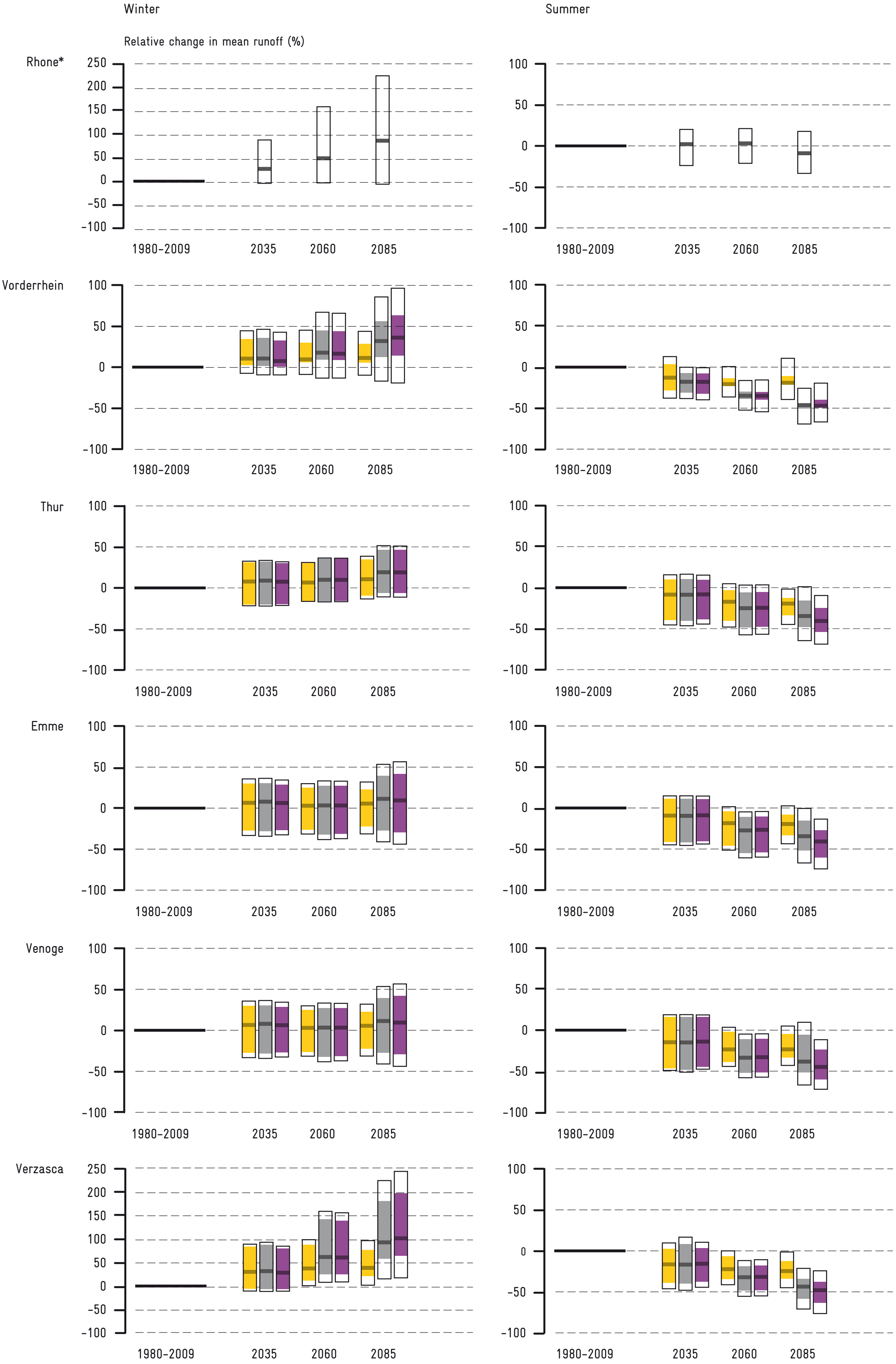


Figure 6.4: Mean runoff over the reference period (black) and the three CH2011 time periods (colored) and greenhouse gas scenarios A2 (solid), A1B (dashed), and RCP3PD (dotted). The lines represent means over 24 simulations; the uncertainty range is not shown. Colors indicate the runoff response types for each catchment according to Figure 6.2.
*Scenarios A2 and RCP3PD are not shown for the Rhone catchment due to potential bias (section 6.2).

Climate change, and especially the higher temperatures associated with climate change, will cause a shift in the runoff regime from nival to pluvial in catchments that are not strongly influenced by glacial meltwater. Accordingly, an increase in the variability of runoff throughout the year and from year to year, resulting in lower stability and lower predictability, is another challenge that will need to be met in the future. A more flexible and adaptive water management will be needed to deal with a more irregular and longer flood season (Köplin et al., 2014) and an expected increase in the frequency of occurrence of extreme events such as droughts and floods. Joint regional governance of water resources and water management across political boundaries can balance water demand and water availability at the local scale. Furthermore, multifunctional storage that – apart from hydropower production – can be used for drinking water supply, irrigation, artificial snow production, and flood retention might be a viable solution. Again, regional and multi-user agreements have to be established, which is not an easy task also from a political point of view.

The implications for hydropower production have been studied by Hänggi et al. (2011a; b). They considered the direct effect of changes in runoff on hydropower production across Switzerland from the reference period 1980–2009 to the period 2035 (under scenario A1B), assuming current production schemes and


Winter
Summer
Relative change in mean runoff (%)
Rhone*
Vorderrhein
Thur
Emme
Venoge
Verzasca
250
200
150
100
50
0
-50
-100
1980–2009
2035
2060
2085

electricity markets. For winter they find an increase of 10% in hydropower production, for summer a decrease of 4 to 6%, and overall for the whole year a slight increase of 0.9 to 1.9%. Despite these encouraging results, adverse impacts of climate change, especially in the mid- (2060) and long term (2085) for single hydropower stations, cannot be excluded.

Although this study presents detailed and comprehensive results, more research is needed to determine how changes in climate variability and climate extremes will affect runoff, as changes in climate variability are not captured in the climate change scenarios used (Chapter 3). Furthermore, uncertainties related to the internal model parameters and a broader spectrum of downscaling methods should be addressed in future studies.

It is worth emphasizing that the present study shows that mitigation of greenhouse gases can reduce the change in runoff in winter and summer by about a factor of two. With regard to the implications summarized above, mitigation can help considerably in attenuating the adverse effects of climate change. Still, some changes will occur and will require adaptation. Thus, future modeling studies should couple hydrological impact models with models for water resource management, irrigation, hydropower production, etc., to quantify the impact of hydrological change on society, the economy, and ecosystems.

Although the models do not perform equally well for all aquifers, the projections clearly indicate that **groundwater temperatures** in river-fed aquifers, which account for approximately 30% of Swiss drinking water production, will increase strongly. The main reason for this groundwater warming is the warming of the rivers that feed the aquifers. Various studies show that higher temperatures affect microbiological activity during the infiltration of river water (Sprenger et al., 2011; Figura et al., 2013), and in Switzerland during the unusually hot, dry summer of 2003, oxygen consumption was observed to increase with increasing groundwater temperature to such an extent that groundwater anoxia resulted (Hoehn and Scholtis, 2011). This could pose problems not only with respect to groundwater quality (Sprenger et al., 2011), but also with respect to drinking water production as a result of the possible clogging of pumping wells with manganese and iron precipitates (Hunt et al., 2002). To assess the impact of climate warming on oxygen concentrations and on the redox state of groundwater, monitoring at riverbank infiltration sites needs to be continued and intensified in the future. Furthermore, because the groundwater temperature projections rely solely on statistical relationships and are subject to relatively large uncertainties, further studies need to focus on constructing adequate models for groundwater temperature based on field experiments and long-term monitoring.

According to the present study, Switzerland will retain its role as Europe's water tower, but as summer runoff and drinking water become more vulnerable in the course of the next century, adaptation measures, such as improving the efficiency of water usage, storage, and distribution, will need to be implemented to prevent water shortages. Immediate reduction of greenhouse gas emissions as expressed in the RCP3PD scenario can greatly reduce these impacts.

‹ **Figure 6.5:** Relative change in mean runoff projected for winter (DJF, left) and summer (JJA, right). Greenhouse gas scenarios are indicated by the colors yellow (RCP3PD), grey (A1B), and purple (A2). The black boxes and the horizontal line in the middle of each box show the range and the mean of the ensemble, respectively. The shaded range indicates the climate uncertainty including the effect of natural variability. Note the wider scale of the y-axis for the Rhone and Verzasca for winter.
*Scenarios A2 and RCP3PD and the climate uncertainty range for A1B are not shown for the Rhone catchment because of potential bias (section 6.2).

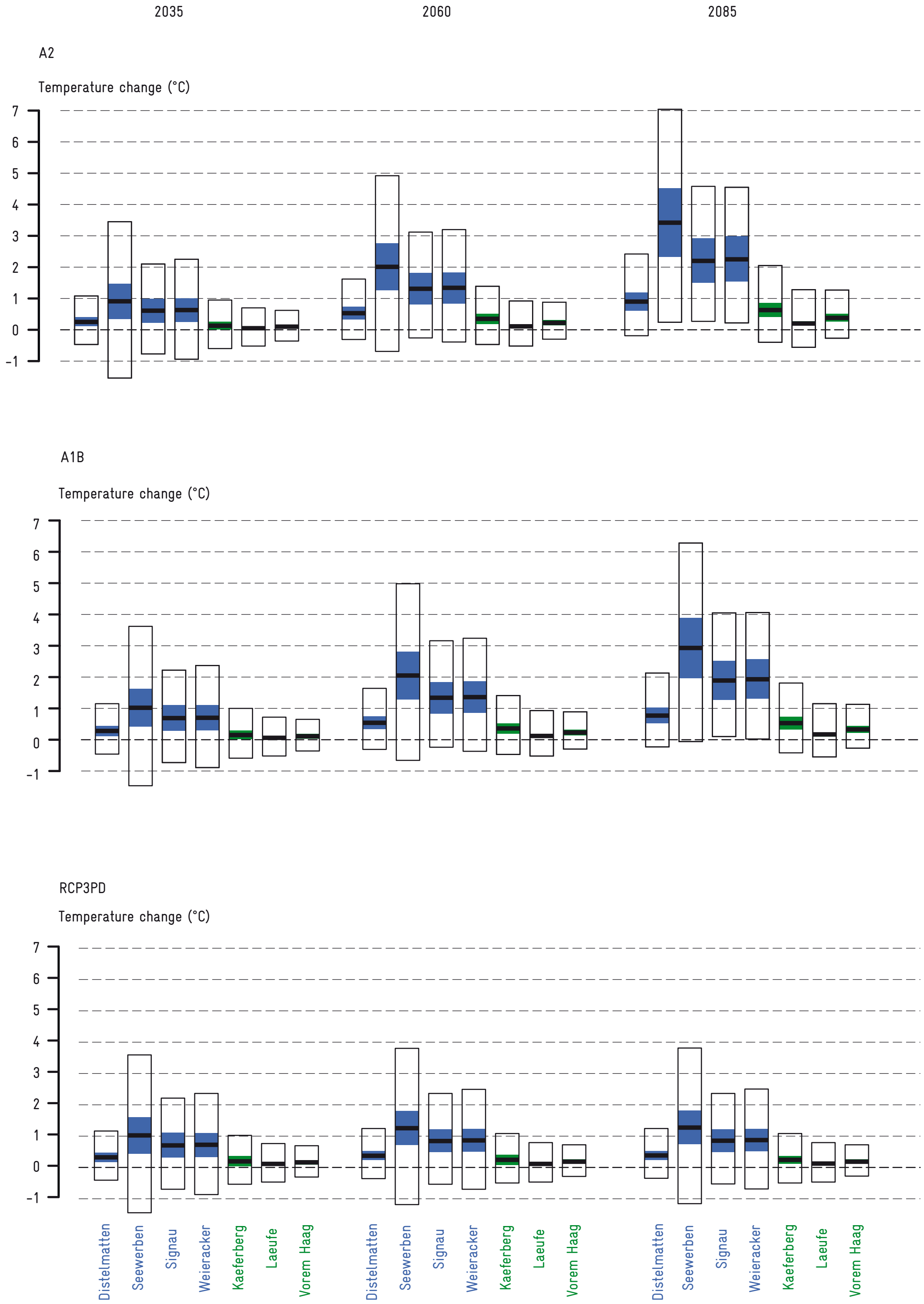


Figure 6.6: Projected groundwater temperature change for each of the three CH2011 climate scenarios and time periods. Shown are the averaged projections of the two linear regression models. Blue: river-fed aquifers. Green: precipitation-fed aquifers. The colored region of each box shows the uncertainty associated with the climate projections, and the black outline shows the combined uncertainty of the temperature change in any given year of the corresponding future period, including both climate and impact uncertainty.

7 — Impacts on the biodiversity of widely distributed birds and vascular plants: species richness and turnover

○
● bird and plant species
○
○

– Projected changes in species composition (i.e., turnover) of birds and vascular plants, two important components of biodiversity, are widespread across Switzerland, with especially strong turnover at both low and middle (~2000 m asl) elevations by the end of the century under the A1B scenario.

– Areas with large changes in number of species and turnover in composition do not completely coincide because areas initially with few species can experience high turnover with the influx of just a few species, as in Graubünden and Valais.

– Uncertainty in the turnover of species composition that is associated with different climate models decreases with increasing time as impacts become stronger. Uncertainty in turnover is initially found both in high and low elevations in the first simulation period (2020), but predominately in mountainous areas in the third simulation period (2090).

– By using an approach that should better capture the limits on species distributions imposed by warm, dry conditions, these projections suggest that low-elevation cantons will be among the most highly impacted by climate-driven changes in species distributions.

‹ Climate change alters the species composition of bird communities in Switzerland (wigeons rising from a marsh near Kerzers, March 2013; photo: Hansruedi Weyrich/weyrichfoto.ch).

7.1. INTRODUCTION

There is increasing concern regarding the effects of climate change on the survival and future distribution of animals and plants, since warming climate moves tolerable conditions to higher elevations, potentially increases ecosystem productivity, and can alter interactions among species. These effects may diminish or alter the distribution of ecosystem services that depend on key species. Some species, such as birds, might have relatively little difficulty tracking the changing climate conditions that they prefer. Other species that are not very mobile and do not disperse widely (some insects, many terrestrial vertebrates, and plants) face substantial challenges. The conversion of productive habitat to highways, settlement, and intensive agriculture and the fragmentation of remaining habitat impact biodiversity negatively and further exacerbate effects of climate change by presenting substantial barriers to successful dispersal of species to newly suitable areas.

Modeling studies conducted at coarse resolution suggest that, depending on dispersal ability, 15–37% of species in studied continental areas may be irretrievably on the path to extinction by 2050 (Thomas et al., 2004) and this number may increase to 50% for high mountain species in Europe (Engler et al., 2011, Dullinger et al., 2012). The distributions of some species are currently responding to climate change (Thomas and Lennon, 1999; Parmesan and Yohe, 2003), often in ways that are consistent with forecasts from species distribution models (Araújo et al., 2005; Chen et al., 2011). These changes suggest that management and conservation decision-making can benefit from assessments of climate change impacts, so as to facilitate policy adaptation to potential future climates. Conclusions from earlier modeling studies of climate change impacts on biodiversity in Switzerland are limited because wide-ranging species are modeled exclusively with distribution data from within

Switzerland (Pearman et al., 2011). Because this practice does not capture warm, dry conditions that limit species ranges, projected impacts on species distributions at low elevations are underestimated and estimates of impact intensity are biased toward high elevations where increasing numbers of species find future conditions suitable. In this chapter, updated projections of expected change in species assemblages are provided by focusing on wide-ranging species, using species distribution data of European extent, and incorporating the most recent regional climate models for Switzerland.

7.2. METHODS

State-of-the-art species distribution models (SDMs; Guisan and Zimmermann, 2000) are applied for selected species of **birds** and **vascular plants**. These two groups are often used in scientific study, management, and monitoring of biological diversity. Here these SDMs are calibrated with data on climate and known locations of occurrences of each species across Europe, and then validated with independent data from Switzerland. Validated models are applied to maps of projected future climate for Switzerland and the surrounding area. An ensemble approach (Araújo and New, 2007) is used for modeling each species individually. This includes calibration of models using four different algorithms. The European extent of the calibration data allows comprehensive capture of the relationship between climate and distribution limits of each species.

Species data for calibration come from the Atlas of European Breeding Birds (Hagemeijer and Blair, 1997) and from the Atlas Floreae Europaeae (Jalas and Suominen, 1972–2005), both at approx. 50 km × 50 km resolution. Independent validation data come from approximately 410 sites (1 km^2 in size) of the Swiss Biodiversity Monitoring Program (BDM; Weber et al., 2004). The climate data come from: (1) the WorldClim database (Hijmans et al., 2005) providing the current climate of Europe at 10 min and 30 sec resolution (approximately 1 km × 1 km) and (2) future climate simulations by six regional climate models (RCMs) covering Switzerland under the A1B scenario, and downscaled to a resolution of 1 km × 1 km, for the period 2010 to 2100 (Lautenschlager et al., 2009; Chapter 3). Five of six climate models are also used in CH2011 (2011). These additional sources (WorldClim data and additional RCMs) are used because of the need to calibrate models and project future species distributions outside of Switzerland. For this report, the assessment is restricted to species which already occur in Switzerland currently, and whose current distribution in Switzerland at a resolution of 1 km × 1 km is well represented by the European-scale models. This is done because it is only possible to validate model performance for currently resident species. Accordingly, immigration of new species into Switzerland, though likely, is not considered. Specifically, the selection of species comprises only those with at least 25 occurrences in the calibration data that are at the European extent, at least 10 occurrences in the BDM validation data set, and sufficient model performance on the validation data (AUC ≥ 0.7). For the projections, SDMs are applied to both the current climate and the six future RCM-simulated climates for the A1B scenario, averaged for the time periods 2011–2030, 2041–2060, and 2081–2100 over all of Switzerland. These periods deviate slightly from the standard CH2011 periods (Chapter 3) and are referred to by the central years 2020, 2050, and 2090, respectively. The 20-year period is selected to avoid averaging over a period that includes substantial climate change and, thus, could interact with modeled variability in the climate tolerances of species. The use of SDMs implies that equilibrium states are modeled, but convergence to equilibrium is species specific and not directly accounted for.

The susceptibility of current species assemblages to climate change is assessed by comparing simulated current and future species composition. Susceptibility is quantified for each 1 km^2 grid cell in terms of species turnover, a quantity calculated as 1–S where S is the Sorensen similarity index (S). This index quantifies the similarity between the lists of species at two different sites or, alternatively, at a single site at two distinct points in time. Turnover attains its minimum value 0 when the species assemblage persists unchanged; conversely, the maximum value 1 indicates that there are no species in common between the present and future period. Additionally, the uncertainty in turnover is considered. It is estimated from the variation among the six different RCMs by calculating for each square kilometer the standard deviation of turnover divided by its mean. The distribution of turnover values is examined on the canton level. The projected turnover here is a lower bound because only species already occurring in Switzerland are considered. As a consequence, invading species will further increase turnover.

7.3. RESULTS

Of the 395 **bird species** and 1943 **plant species** for which there are 25 or more occurrences in the respective atlases of European species distributions, 111 bird species and 218 plant species are recorded in at least 10 sites of the BDM monitoring program. Using this independent dataset, models for a total of 79 avian species and 135 plant species performed sufficiently well (AUC ≥ 0.7) to give reliable projections of species distributions. The simulated current distributions of the study species indicate that relatively few have suitable climate at high elevations. Change in the absolute number of analyzed bird and plant species that find suitable climate in the future is highest in the lowlands of Switzerland (Figure 7.1). The differences in simulated species composition between current and future time periods indicate substantial turnover of both bird and plant species (Figure 7.2 a, d). Species turnover is noticeable by 2020 and becomes strongest by the third simulation period, approximately 2090 (Figure 7.2 c, f), and is most pronounced in high elevation areas of the southern Valais and in easternmost Switzerland in the Canton Graubünden (Figure 7.2 c,f). In these areas current climate is classified as suitable for few or none of the study species. Thus, any increase in the potential number of species in the future implies substantial turnover. Additionally, some areas of low turnover are scattered throughout the highest elevations (>2000 m asl) of the Alps (Figure 7.2 c,f), where only few species find suitable climate under both current and simulated future climate conditions.

The relative uncertainty in turnover values, owing to variation among climate simulations, decreases with time. For both birds and plants the highest uncertainty in projected turnover occurs in mountainous areas. Overall, uncertainty in turnover due to uncertainty in climate models is somewhat greater for birds than for plants.

Species turnover depends strongly on elevation (Figure 7.3). For birds (Figure 7.3) and plants (Figure 7.3 b), maxima in turnover occur at multiple elevations, with a main peak centered at 2000 m asl. Low turnover is projected at about 1000 m asl and 3700 m asl for both birds and plants. This is likely because upward movement of the potential distribution of low-elevation species does not lead to great losses around 1000 m asl and few species move into areas around 3700 m asl because climate at these very high and exposed elevations does not become warm enough. Average projected turnover values for individual cantons also show large variation and some cantons have bimodal distributions of turnover values (Table 7.1 a, b). Some small cantons at low elevation and having relatively little elevation range appear to experience high projected species turnover, as do some larger cantons, suggesting that a number of factors influence mean turnover projections within cantons.

7.4. IMPLICATIONS

The results suggest that many of the most widely distributed species in Switzerland will be affected by changing climate by 2090. Turnover in species composition among these species will be substantial, both in the low-lying cantons and in mountain areas, and most pronounced at about 2000 m of elevation. Likely two processes are reflected in these patterns. First, at low elevations and in cantons with little elevation range, climate change results in the loss of suitable conditions for native species because of increased temperatures that exceed the conditions experienced by these species in the warmest areas within their European distribution. At higher elevations (~2000 m asl), climate becomes suitable for many species that were originally restricted to the lowlands, while the previous resident species still may escape to higher elevations. Above 2000 m asl, few of the study species have suitable climate during the original time period, so conclusions are limited. Nonetheless, these areas are already projected by more specialized studies to suffer high local extinction rates or show high turnover (Engler et al., 2011; Pearman et al., 2011). These elevations are high enough that only a few species will find suitable conditions by 2090. At approximately 2000 m asl the average turnover for birds and plants is ca. 0.5 and 0.4 respectively, meaning that ca. 50% and 40% of the study species are projected to differ between the current period and the end of the century.

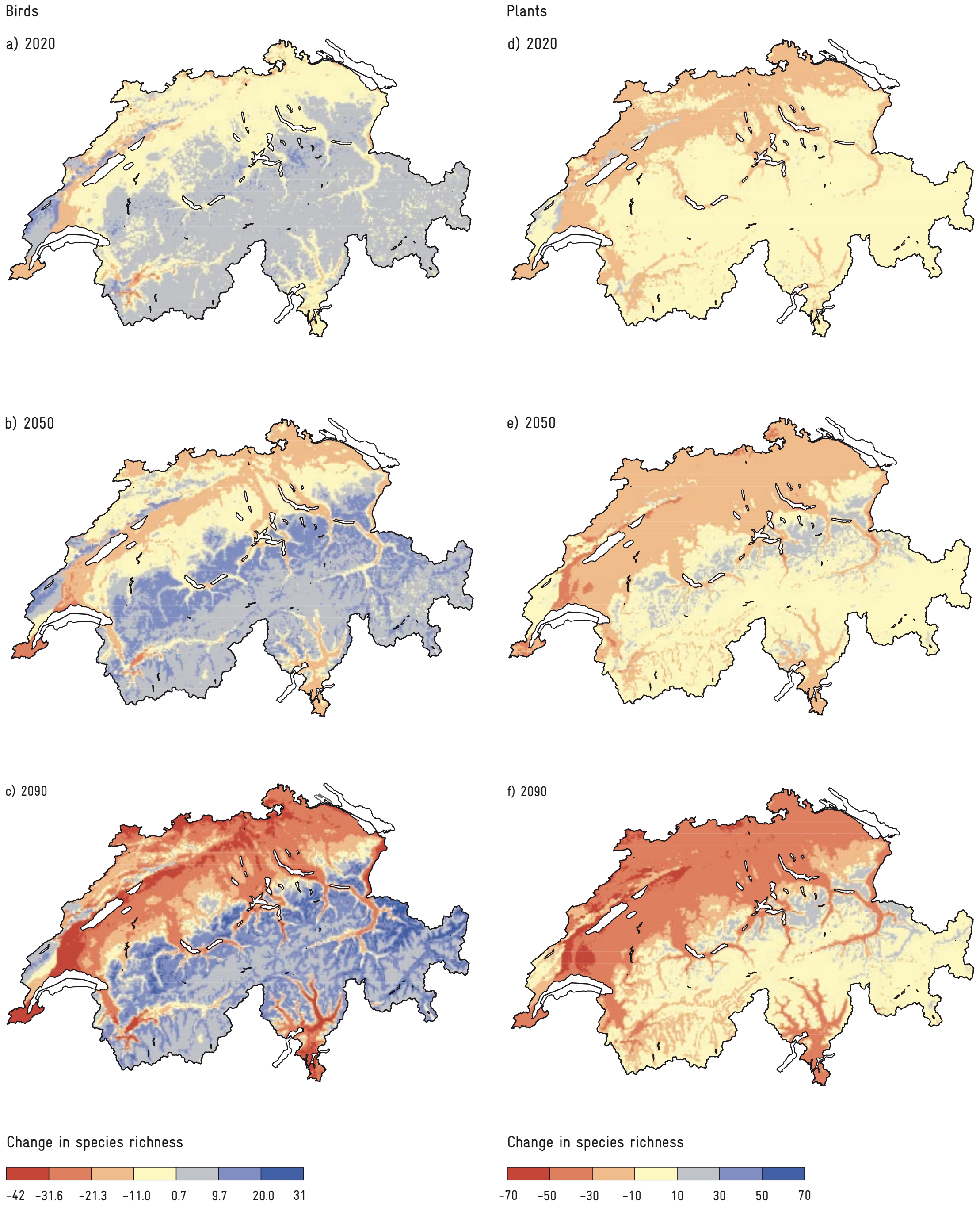


Figure 7.1: Mean change in the number of study species with suitable climate conditions under the A1B scenario at 2020 (a, d), 2050 (b, e), and 2090 (c, f). Results for birds (a, b, c) and plants (d, e, f) are shown. The resolution is 1 km × 1 km. The mean was calculated from application of the distribution models to current climate and to six regional models of future climate. Only the results for species that currently breed in Switzerland and have passed the selection criteria (see text) are shown. The potential arrival of species that might newly breed in Switzerland is not addressed because the models could not be validated at a resolution of 1 km × 1 km. The largest changes in terms of absolute numbers of breeding species occur in relatively low elevation areas because these areas originally have the largest number of species.

The general pattern of loss of suitable conditions for resident species at low elevations and increasingly suitable conditions for widely distributed species at high elevations likely carries over to additional species. The ones that are currently found at mid-elevations will likely lose suitable conditions at the bottom of their elevation range, while finding newly suitable areas nearby at higher elevations. Overall, because of decreasing land area at higher elevations, many of these species will have less total area with suitable conditions, and will as a consequence experience decreases in population sizes. How ecosystems and their services will be affected by these changes in species composition remains largely unanswered.

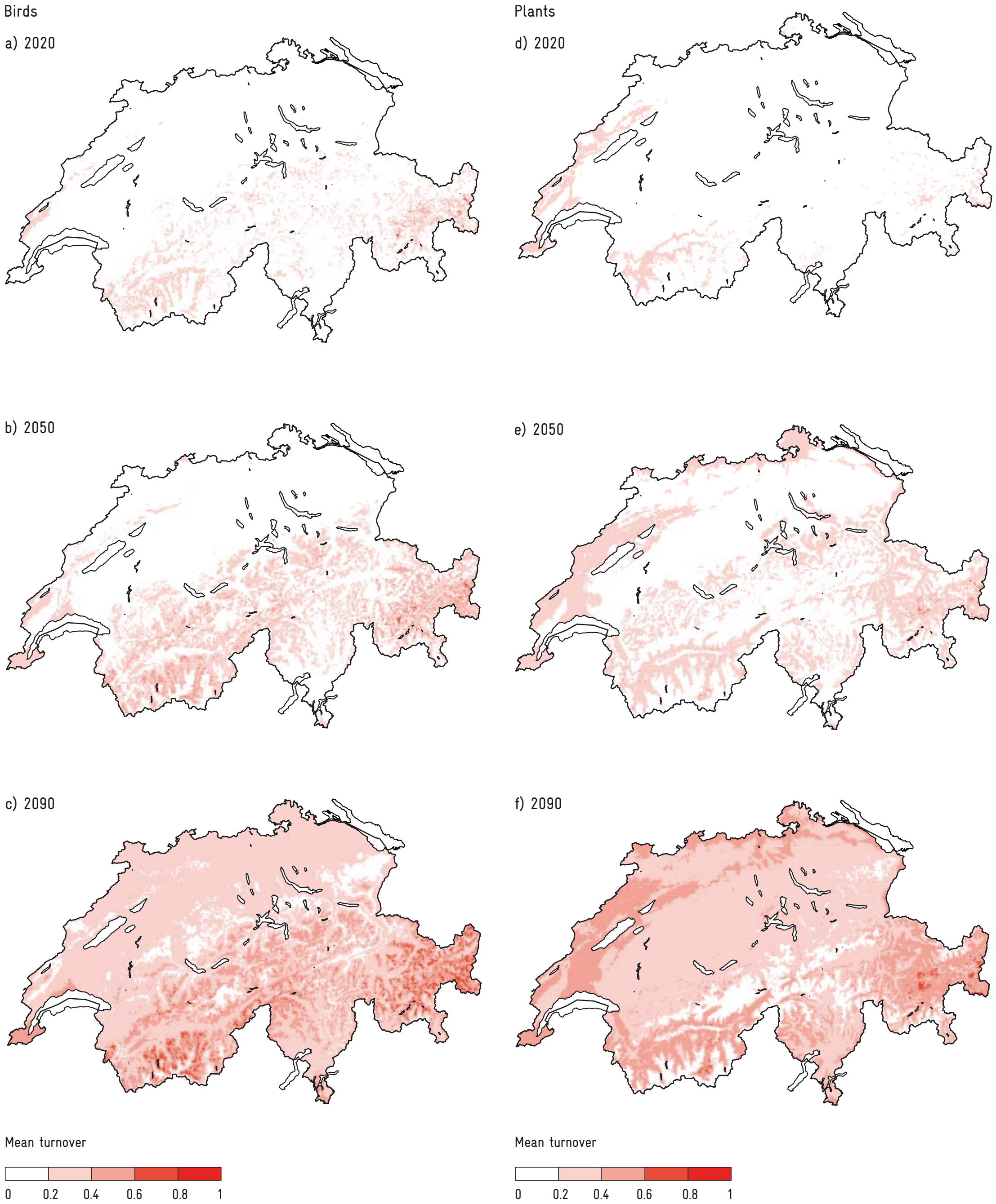
These initial results may be useful to canton agencies that are charged with natural resource conservation. Cantons at low elevations and/or having high projected rates of turnover need to evaluate the risk that new immigrating species (not studied here) may succeed in replacing the many species for which climate conditions will no longer be suitable. Cantons with low average levels of turnover in species composition likely have large elevation ranges, but vertical movement of species may need to be facilitated, e.g., through maintenance of sufficient habitat continuity to allow species with limited dispersal capacities to respond to changing distributions of suitable climates.

The substantial levels of turnover in species composition across many cantons, especially at low and moderately high elevations, signal the importance of identifying which species and biotic communities provide important ecosystem services, for instance for recreation, pest control, or valuable commodities. Studies with a more detailed focus on these particular species (Chapter 8 for some examples) can better identify risks of ecosystem service loss, as well as candidate species that are suited to new climate conditions and supply similar services.

A number of limitations must be taken into consideration in the interpretation of these results. Most importantly, for methodological reasons, the analysis is restricted to species that are broadly distributed in the data from both Europe (≥25 occurrences) and Switzerland (≥10 occurrences). Further, the study focuses on species represented by models with high validation performance on independent data. While broadly distributed species are largely responsible for the overall geographic pattern of species richness in Switzerland (Pearman and Weber, 2007), the species studied here constitute a small fraction of the entire Swiss flora and fauna. Other species, in the same or other groups, will respond to climate change differently, e.g., some may be more affected due to narrower climate tolerances, but the overall patterns are likely to remain similar. The focus on widely distributed species, for which models also transfer successfully between European (50 km) and Swiss (1 km) scales, means that the estimates of turnover are a lower bound. Immigration of additional species not yet resident in Switzerland will likely increase turnover, with these effects concentrated in lower elevations.

The approach also assumes that climatic requirements of species remain stable over time and do not change in response to changing species composition. This is certainly only partially true. Similarly, technical limitations here prevent the study of effects of changing landscape composition, although some species may be locally more limited by land cover, conversion of habitat to agriculture, infrastructure development, and habitat degradation than they currently are by climate.

Further, to interpret the results as reflecting the distribution of species, one must assume that species are distributed in equilibrium with the distribution of modeled suitable climate, both initially and in the future. This is certainly not true for long-lived trees, for which inevitable extinction may follow only after a long period (extinction debt; Dullinger et al., 2012). The assumption may be more reasonable for fugitive plant species having ample dispersal capabilities and short life cycles, and for many bird species.



Birds

a) 2020

b) 2050

c) 2090

Plants

d) 2020

e) 2050

f) 2090

Figure 7.2: Mean turnover in species composition for climate conditions under the A1B scenario at 2020 (a, d), 2050 (b, e), and 2090 (c, f) as compared to current simulated distributions of suitable climate conditions. Turnover is defined as 1–S, where S is the Sorensen Index of similarity. Results for birds (a, b, c) and plants (d, e, f) are shown. The resolution is 1 km × 1 km. Mean turnover for each pixel was calculated by averaging across the results of model application to six different regional climate simulations. A value of zero (0) for a pixel indicates there has been no change in which species are simulated to have suitable climate, while a value of one (1) indicates that the species that are modeled to find suitable climate currently or in the future form two distinct groups with no shared members. Turnover is independent of the absolute number of species, which may vary widely.

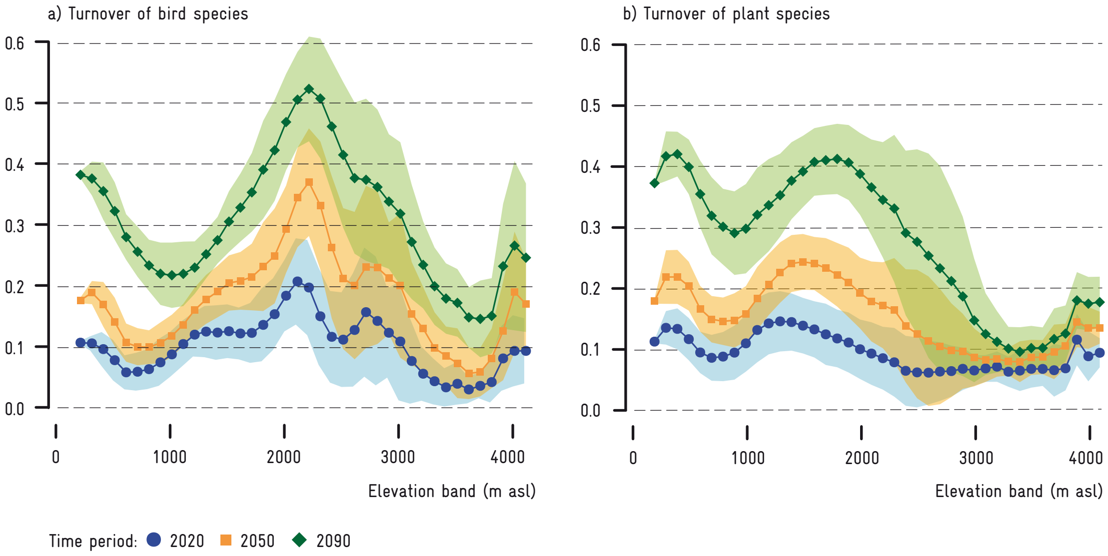


Figure 7.3: Values of mean turnover, averaged over all 1 km^2 cells in 100 m elevation bands in Switzerland for (a) 79 widespread bird species and (b) 135 widespread species of vascular plants. Turnover is defined as 1–S, where S is the Sorensen Index of similarity. Error bars show plus/minus one standard deviation for turnover values within elevation bands. The mean turnover for an individual cell is obtained by calculating six estimates of 1–S that come from extension of species distribution models to six estimates of potential future climate under the A1B scenario. All species distribution models are calibrated with European scale data and are validated to perform well at a resolution of 1 km × 1 km of the downscaled climate data for Switzerland.

Table 7.1a: Turnover for bird assemblages and associate statistics by canton as of 2090 under the A1B scenario. The table presents mean turnover across all 1 km^2 cells (pixels) in each canton, the standard deviation (sd) across all cells in each canton, the number of cells in each canton (n), and the absolute elevation range within each canton. The turnover value for each cell in a canton is itself a mean over the distribution models for each species and six different regional climate simulations. Lower turnover scores signify more similarity between modeled current and future species composition. Cantons marked with * have distinctly bi-modal frequency distributions of turnover values.

Canton	Mean Turnover	sd	n	Elevation Range (m)
Genf*	0.481	0.045	282	137
Graubünden	0.389	0.137	7110	3220
Wallis	0.387	0.131	5222	3939
Uri	0.368	0.113	1073	2827
Basel-Stadt	0.361	0.028	36	211
Tessin	0.353	0.106	2809	2766
Obwalden	0.328	0.114	491	2305
Glarus*	0.318	0.108	687	2731
Schaffhausen	0.314	0.021	296	530
Waadt	0.304	0.075	3214	2407
Thurgau	0.303	0.031	988	520
Bern	0.295	0.099	5959	3377
Nidwalden	0.294	0.100	277	1967
Aargau	0.293	0.038	1402	545
Zürich	0.281	0.042	1727	765
Schwyz	0.278	0.097	909	2066
Neuenburg	0.278	0.061	805	1000
Basel-Land	0.273	0.044	519	816
Jura	0.272	0.036	836	749
Solothurn	0.270	0.044	779	961
St. Gallen	0.265	0.084	2026	2435
Freiburg	0.261	0.052	1671	1633
Luzern	0.245	0.055	1500	1635
Zug*	0.245	0.055	237	974
Appenzell I. Rh.	0.208	0.073	172	1550
Appenzell A. Rh.	0.182	0.028	245	1277

Table 7.1b: Turnover for assemblages of vascular plants and associate statistics by canton as of 2090 under the A1B scenario. The table presents mean turnover across all 1 km^2 cells (pixels) in each canton, the standard deviation (sd) across all cells in each canton, the number of cells in each canton (n), and the absolute elevation range within each canton. The turnover value for each cell in a canton is itself a mean over the distribution models for each species and six different regional climate simulations. Lower turnover scores signify more similarity between modeled current and future species composition. Cantons marked with * have distinctly bimodal frequency distributions of turnover values.

Canton	Mean Turnover	sd	n	Elevation Range (m)
Genf*	0.491	0.042	282	137
Basel-Stadt	0.457	0.028	36	211
Neuenburg*	0.426	0.053	805	1000
Schaffhausen	0.399	0.034	296	530
Waadt	0.395	0.069	3214	2407
Jura	0.377	0.037	836	749
Aargau	0.377	0.043	1402	545
Solothurn	0.373	0.041	779	961
Thurgau	0.370	0.051	988	520
Basel-Land	0.362	0.046	519	816
Graubünden	0.360	0.127	7110	3220
Tessin*	0.338	0.094	2809	2766
Freiburg	0.330	0.047	1671	1633
Zürich*	0.327	0.068	1727	765
Wallis*	0.321	0.157	5222	3939
Bern	0.318	0.078	5959	3377
Nidwalden	0.315	0.060	277	1967
Luzern	0.307	0.046	1500	1635
Zug*	0.299	0.046	237	974
Obwalden	0.291	0.066	491	2305
St. Gallen	0.288	0.075	2026	2435
Schwyz*	0.288	0.063	909	2066
Glarus	0.276	0.080	687	2731
Uri*	0.260	0.102	1073	2827
Appenzell I. Rh.	0.244	0.059	172	1550
Appenzell A. Rh.	0.215	0.028	245	1277

8 — Climate change impacts on tree species, forest properties, and ecosystem services

- ○
- ● tree species
- ● forest properties
- ● ecosystem services
- ○

– Swiss forests experience strong impacts under the CH2011 scenarios, partly even for the low greenhouse gas scenario RCP3PD. Negative impacts prevail in low-elevation forests, whereas mostly positive impacts are expected in high-elevation forests.

– Major changes in the distribution of the two most important tree species, Norway spruce and European beech, are expected. Growth conditions for spruce improve in a broad range of scenarios at presently cool high-elevation sites with plentiful precipitation, but in the case of strong warming (A1B and A2) spruce and beech are at risk in large parts of the Swiss Plateau.

– High elevation forests that are temperature-limited will show little change in species composition but an increase in biomass. In contrast, forests at low elevations in warm-dry inner-Alpine valleys are sensitive to even moderate warming and may no longer sustain current biomass and species.

– Timber production potential, carbon storage, and protection from avalanches and rockfall react differently to climate change, with an overall tendency to deteriorate at low elevations, and improve at high elevations.

– Climate change will affect forests also indirectly, e.g., by increasing the risk of infestation by spruce bark beetles, which will profit from an extended flight period and will produce more generations per year.

8.1. INTRODUCTION

Climate is a key factor shaping the forest environment; thus changes in the climate are likely to strongly affect forest ecosystems by altering the physiology, growth, mortality and reproduction of trees, the interactions between trees and pathogens, and ultimately the disturbance regimes (winds, wildfires, insect attacks, etc.). The sensitivity to such changes depends on the level that is considered (landscapes vs. forest, stands vs. single trees) and on the specific site conditions (e.g., Elkin et al., 2013, Büntgen et al., 2008, Babst et al., 2013). These complex influences indicate that a changing climate may lead to non-linear responses, tipping points, etc., particularly since the longevity of trees implies that many individuals present today will experience substantial changes of the climate before they will be replaced by the next generation. Thus, the question arises to what degree current trees and forest ecosystems are able to cope with a changing climate.

Here, a selection of studies of economically relevant and regionally typical impacts is presented, based on the materials that were available at the time of writing this report.

An empirical study on the relation between climate conditions and growth of Norway spruce *(Picea abies)*, the most widespread and economically important tree species in Switzerland (Cioldi et al., 2010), is used to outline impacts at the level of individual trees. Then, a suite of modeling studies addresses issues that are not amenable to direct observation or experimentation. At the scale of the entire country, changes in the potential distribution of widespread tree species, focusing

‹ Growth conditions for widespread and economically important tree species in Switzerland may deteriorate with warming on the Swiss Plateau („plenter“ forest at Sumiswald, Emmental on October 23, 2012; photo: FOEN).

on Norway spruce and beech *(Fagus sylvatica)*, are investigated, combining results from static distribution models and a dynamic simulation model. At the landscape level, species-specific biomass changes are projected in two case studies for sites on the Swiss Plateau and in the canton of Ticino. Forest properties and three key ecosystem services (timber production, carbon storage, and protection from snow avalanches and rockfall) are assessed along elevational gradients in two Alpine catchments. Finally, the effect of future climate change on the spruce bark beetle *(Ips typographus)*, a major cause of mortality in spruce forests, is assessed, again at the national scale (Wermelinger, 2004; Meier et al., 2009).

8.2. METHODS

The SEASONAL-REGIONAL and DAILY-REGIONAL datasets from CH2011 (Chapter 3) are used in this study, including two non-intervention scenarios (A1B and A2) and one mitigation scenario assuming low emissions (RCP3PD). These data are augmented by raw ENSEMBLES simulation data for A1B (Chapter 3).

The potential impact of climate change on **growth of Norway spruce** is investigated using an empirically derived relationship between radial stem increment and mean temperature and precipitation sum over the growing season (April to September). The analysis is based on a sample of 156 trees from 11 sites in Switzerland and in the Aosta valley. Potential climate change impacts are discussed for two sites sampling the biogeographic diversity of Switzerland: Biel, representing the relatively wet-warm Swiss Plateau, and Goppenstein, located in a cool-dry inner-Alpine valley. Both sites are within the CHW domain of the CH2011 scenarios.

Climatic suitability maps for spruce and beech are generated using six statistical species distribution models (Guisan and Zimmermann, 2000) for each species, based on forest inventory data from >80'000 plots from the entire European Alps and nearby lowlands. Future projections are based directly on A1B climate simulations from six of the ENSEMBLES model chains that underlie the CH2011 scenarios (Chapter 3), which are downscaled to 1 km raster size. Climatic suitability for A1B is then projected for all 36 combinations of climate and statistical models, and ensemble maps are created showing to what degree the models agree on projected species presence/absence. These suitability maps represent the climatic potential of a tree species to establish and regenerate under the projected climate, but they do not indicate how fast changes will occur. This static approach is combined with simulation results from the TreeMig model to quantify the importance of migration lags. TreeMig is run with one A1B simulation from ENSEMBLES, downscaled to resolution of 200 m × 200 m. TreeMig incorporates forest dynamics and a mechanistic description of tree migration for 30 species (Lischke et al., 2006). Forests are restricted to the current forest area until 2007, and allowed to expand into alpine meadows at later times.

Forest dynamics at the site and catchment scale are simulated with the mechanistic models ForClim (Rasche et al., 2012) and LandClim (Elkin et al., 2012). ForClim is a detailed model of stand-scale forest succession whose main aim is to achieve appropriate sensitivity to climate and high local accuracy. LandClim incorporates a simplified version of ForClim and adds large-scale disturbances such as windthrow, wildfires, and bark beetle infestations.

LandClim is applied to two ~3000 ha landscapes surrounding two low-elevation lakes, Lobsigensee (514 m asl), Canton Bern, and Lago di Origlio (419 m asl), Canton Ticino. The model is initialized by simulating current forests based on recent local climate observations, and run through 2011–2300 using the CHW and CHS regional projections of CH2011 (2011). Climate scenario data are interpolated linearly between the CH2011 periods, and extended at constant values from 2100 through 2300. At Lobsigensee, a management regime to favor spruce is simulated throughout the simulation period. At Lago di Origlio, chestnut *(Castanea sativa)* cultivation is simulated until 1950, followed by abandonment to mimic past and current land use practices.

Using LandClim and ForClim, climate change impacts on forests and related **ecosystem services** are simulated in the two climatically distinct mountain valleys Saas (Canton Valais) and Dischma (Canton Graubünden; Elkin et al., 2013). This allows for a comparison of how the impacts on ecosystem services vary between and within regions. The simulated forest management incorporates the current region-specific practices that are aimed primarily at maintaining (1) the protective function of forests against avalanches and rockfall, and (2) structural diversity. The models are initialized with current climate and management regime, and run transiently for 2011–2300 for all three climate scenarios (RCP3PD, A1B, and A2) as described above. Changes in the central Alpine climate are approximated as the average of the CHW and CHE scenarios of CH2011 (2011).

To estimate the impact of climate change on the infestation potential of **bark beetles**, the number of annual generations is used as a key indicator variable. Since each generation attacks new trees and propagates further from there, this is a good measure of the overall infestation risk. A population dynamics model is used that covers the basic processes of bark beetle phenology, i.e., development from egg to adult, maturation feeding, swarming, oviposition, and sister breeding (Annila, 1969). Beetle generations are projected for each scenario period (2035, 2060, and 2085) using the DAILY-LOCAL dataset for the A1B greenhouse gas scenario, which represents ten model chains from ENSEMBLES (Chapter 3). The ten resulting projections of beetle generation numbers are then averaged. In the current model version, beetle population dynamics are driven by climate, but independent of the current distribution of spruce trees, their susceptibility, and resistance to bark beetle attack.

8.3. RESULTS

The statistical model shows that **Norway spruce growth** is strongly reduced if mean temperatures exceed 15°C and precipitation falls below 600 mm during the growing season (Figure 8.1). Temperatures below ca. 13°C also limit spruce growth, but sensitivity to

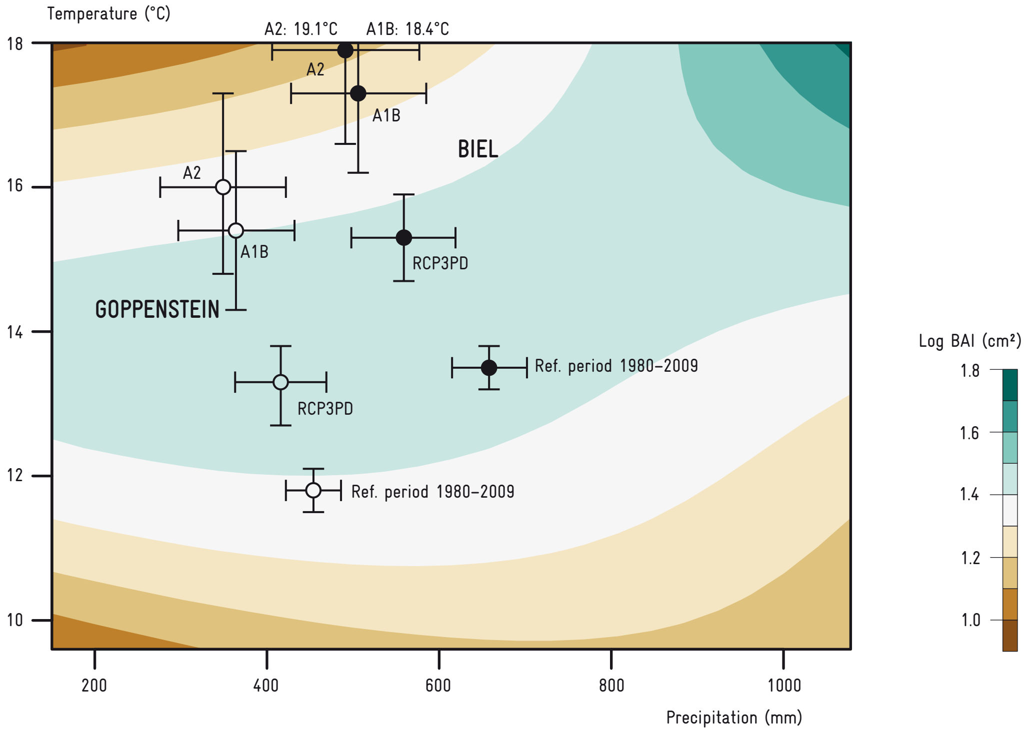


Figure 8.1: Natural logarithm of basal area increment (BAI; i.e., the annual change in the cross-sectional area of the stem) of spruce in the reference period and for the period 2085 as a function of average temperature and precipitation sum during the growing season (April–September) for the RCP3PD, A1B, and A2 climate scenarios for the sites Goppenstein (cool dry; open circles) and Biel (warm-wet; filled circles). The plot is based on the best linear mixed-effects model. Error bars show the 95% confidence interval for the reference period, and the uncertainty range between upper and lower estimates for the CH2011 climate scenarios.

precipitation is low under these conditions. The CH2011 scenarios depict summer warming (up to 6°C until 2085) and drying (up to 40% precipitation reduction) across Switzerland. Impact on spruce growth will vary depending on the present climate conditions at the respective sites. Moderate warming, such as in RCP3PD, stimulates growth at cooler sites (Goppenstein) or has little effect where precipitation is sufficient (Biel). However, as water demand increases with temperature, severe drought will reduce growth at already warm and precipitation-limited sites such as the central Valais. Drought will also occur widely when warming is very strong, as in the A1B or A2 scenarios at later scenario periods (2.7 to 4.8°C average warming during the growing season until 2085), except at presently cooler sites with ample precipitation, where growth is likely to be enhanced (Figure 8.1). As these considerations are based on average changes of climate variables, they do not take into account potential changes in climate variability (Chapters 2 and 3).

Climatic suitability projections are broadly in agreement with these results. Species distribution models (SDMs) project the Swiss Plateau to become unsuitable for spruce by the year 2100 in the A1B scenario (Figure 8.2). However, sizeable areas are classified as unsuitable already in the near future, in contrast to the empirical growth projections (e.g., for the Swiss Plateau where Biel is located; Figure 8.1). The dynamic model TreeMig projects spruce to persist on the Swiss Plateau throughout the century, though at declining levels. Some disagreement between the static SDM approach and the dynamic TreeMig simulations is expected, as the latter simulates transition between forest types, whereas the former yields equilibrium distributions only. However, the discrepancy between model results points to considerable uncertainty about spruce viability on the Swiss Plateau. High elevations exhibit both improving suitability and increasing prevalence of spruce in both the SDM and the TreeMig simulations, indicating that spruce distribution will not be limited by migration.

For beech, a similar shift of suitable climate away from the Swiss Plateau and toward higher elevations is projected (Figure 8.2). Again, the results disagree for the Swiss Plateau, with TreeMig simulating beech as present throughout the A1B scenario. However, the TreeMig simulations suggest that beech, in contrast to spruce, does not invade the high elevations by 2100 due to slow migration.

In general, migration speed is limiting colonization by trees at the rising treeline, thus leading to a deferred build-up of forest biomass in these areas. However, migration does not noticeably affect country-wide forest biomass. Downy oak *(Quercus pubescens)*, a species currently rare in Switzerland, is simulated to migrate only slowly. This suggests migration limitations where large distances have to be overcome. Mediterranean, drought–adapted species could experience a similar limitation and may have difficulties to reach by natural migration the dry regions of the Swiss Plateau and Alpine valleys, which expand rapidly under the A1B and A2 scenarios.

Regarding **forest dynamics** in small landscapes at Lobsigensee and Lago di Origlio, the RCP3PD scenario leads to rather small and gradual changes of forest biomass and species composition, whereas major changes are evident after the year 2050 under the scenarios A1B and A2 (Figure 8.3). These changes are driven by a scenario-specific increase in drought that causes a decline of spruce in all scenarios at Lobsigensee. Despite being favored by forest management, spruce largely disappears by 2100 in the A1B and A2 scenarios. At Lago di Origlio, chestnut declines due to drought under all scenarios, especially under A1B and A2. At both sites, after an initial increase of simulated landscape-scale tree biomass, strong declines are expected under all scenarios (in particular A1B and A2), with a minimum around 2100. The simulations suggest that silver fir *(Abies alba)* would increasingly prosper at both sites, as this evergreen species is favored over its deciduous competitors by the longer growing season, and over spruce by its greater drought tolerance. This is consistent with pollen records from Southern Switzerland showing long phases of fir dominance prior to agricultural land use and before anthropogenic fires became important (ca. 10 000–5 000 years ago; Tinner et al., 2005). However, fir is quite sensitive to wildfires, and its saplings are a preferred diet of roe and red deer. The latter currently occur in higher population densities than assumed in the simulations and could thus prohibit fir from reaching its simulated potential. Alternatively, the

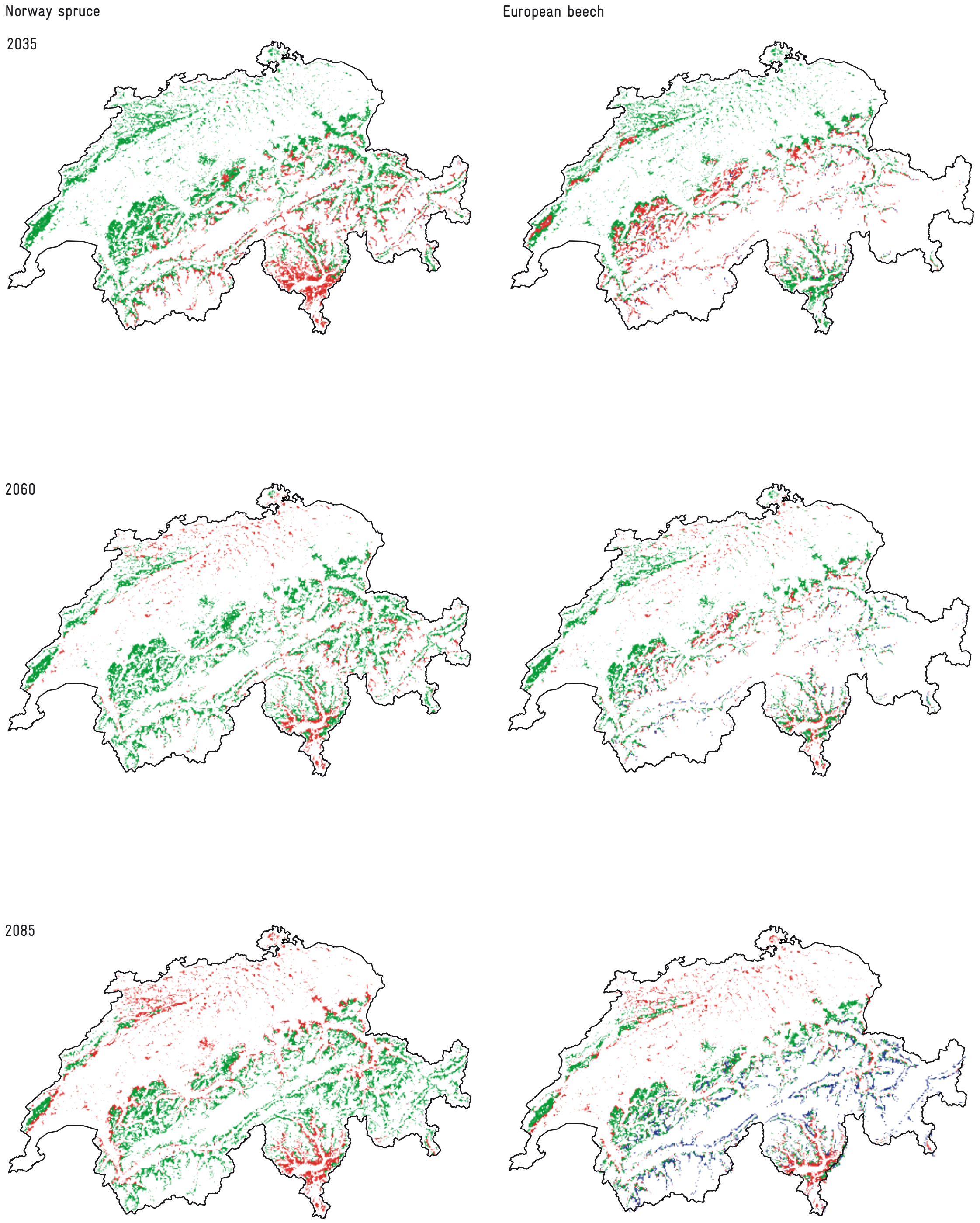


Figure 8.2: Comparison of the future suitability of tree species (left: Norway spruce; right: European beech) as simulated by empirical species distribution models (SDMs) and a model with mechanistic migration and dynamics (TreeMig). Red areas are projected to be unsuitable for the species by the SDMs, whereas in TreeMig simulations they still persist; blue areas are suitable according to SDMs, but not invaded by the respective species in the TreeMig simulations. Green areas indicate agreement between the two model approaches.

results suggest the continuing relevance of drought tolerant deciduous species (e.g., deciduous oaks) and an increased future potential for holm oak *(Quercus ilex)*, an evergreen Mediterranean species that is more fire-tolerant and grows well on dry sites even under the A2 scenario (Figure 8.3). However, this species is limited in its natural migration due to the large distances involved and migration barriers that would have to be overcome.

In terrain with large elevational gradients such as the Dischma and Saas valleys, simulation results indicate a fine-grained response to climate change both within and between regions. In the Saas valley (Figure 8.4), the lowest and driest elevations are most prone to increasing drought. Even the limited climate changes of the RCP3PD scenario lead to a strong decrease of biomass there. At mid-elevations, species composition is affected, but biomass decreases are small, and at the highest elevations an increase of biomass is simulated until 2050, followed by a slight decline back to the initial values. By contrast, the A1B scenario results in a strong biomass decrease in the long term at all elevations, also inducing a change of species composition. Drought gradients are very steep in the landscape, and it is quite difficult to precisely simulate species limits along such gradients. Thus, species such as lime *(Tilia cordata)* are incorrectly simulated to thrive at lower elevations in the Saas valley under the current climate. However, this does not affect the conclusion regarding the direction and magnitude of future changes in total forest biomass or tree species diversity. In contrast to the lowland sites (Figure 8.3) and the dry Saas valley (Figure 8.4), the cool-wet Dischma valley will not experience marked drought. Both the RCP3PD and the A1B scenario imply little change in the lower parts of the valley around 1600 m asl, and a biomass increase at high elevations near current treeline, i.e., around 2200 m asl (Figure 8.4).

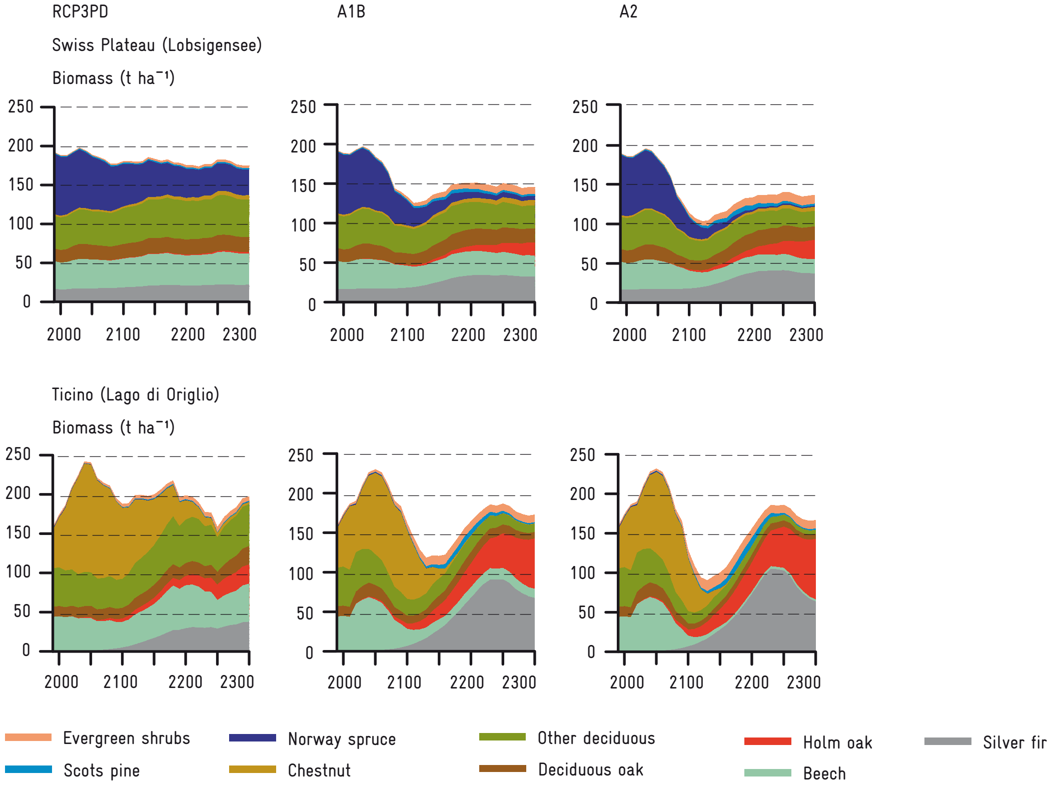


Figure 8.3: Vegetation simulated with the LandClim model within 3 km of Lobsigensee, Canton Bern (top row) and Lago di Origlio, Canton Ticino (bottom row) under the RCP3PD (left), A1B (middle), and A2 (right) climate scenarios. Average species-specific biomass for the entire simulated landscapes is shown.

Future trends in the portfolio of three **ecosystem services** (ES; Figure 8.5) are diverse and partly follow the trends in forest properties (Figure 8.4). Large negative impacts are projected for low and intermediate elevations in initially warm-dry climates (lower part of the Saas valley), where even the RCP3PD scenario results in negative drought-related impacts particularly regarding forest diversity and protection from avalanches and rockfall. In contrast, at higher elevations, and in regions that are initially cool-wet (Dischma valley), forest ES are simulated to be comparatively resistant to climate change. At mid-elevations, variability of ES across regions will be highest, and most ES will be affected negatively. These results indicate that the vulnerability of forest ES to climate change will vary

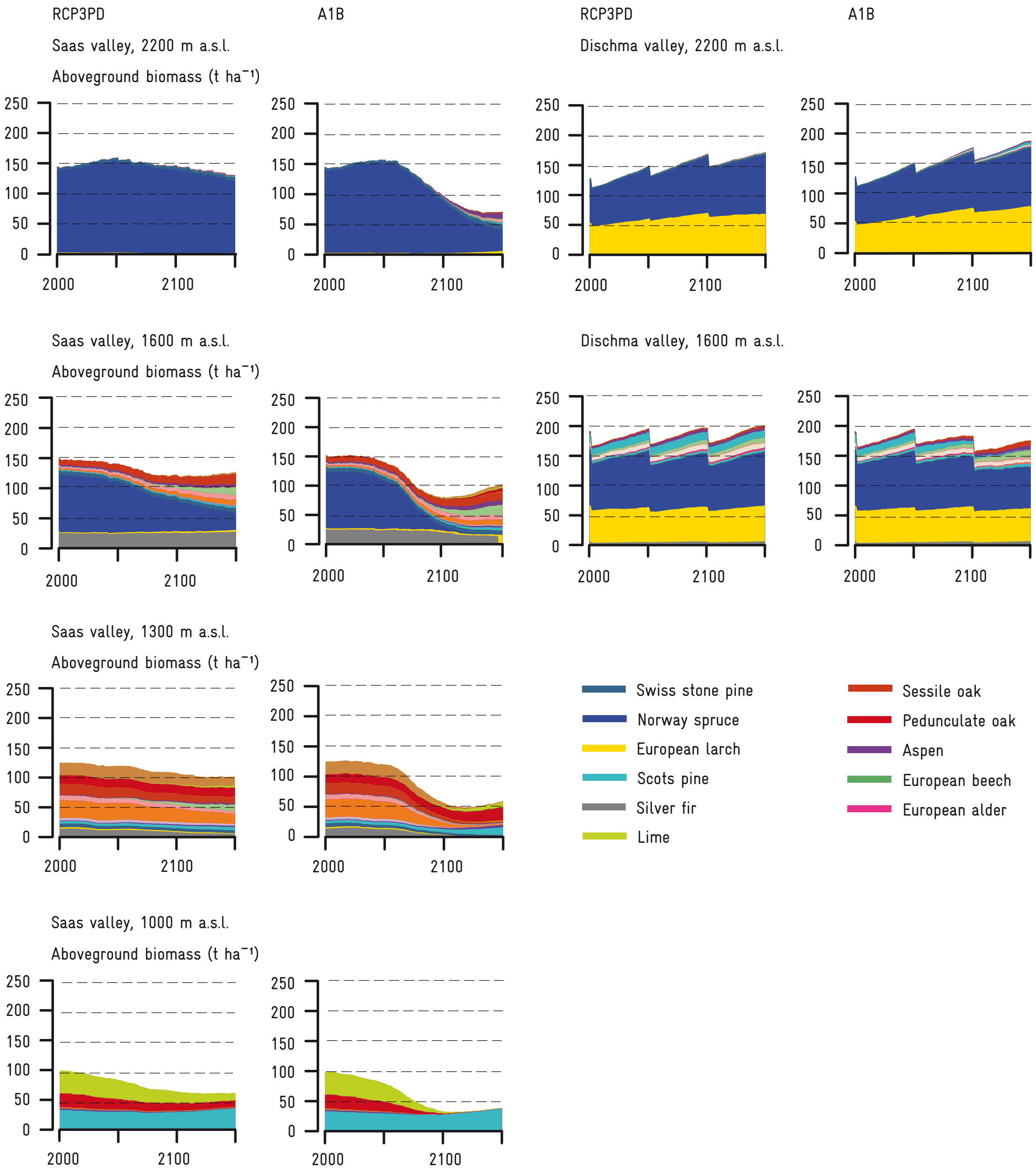


Figure 8.4: Forest biomass and species composition in the Saas (left) and Dischma (right) valleys under the RCP3PD and A1B climate scenarios as simulated by the ForClim model. Rows refer to different elevations. The stair-like pattern for the Dischma valley results from the fact that one specific stand is simulated, where the management interventions take place every 50 years.

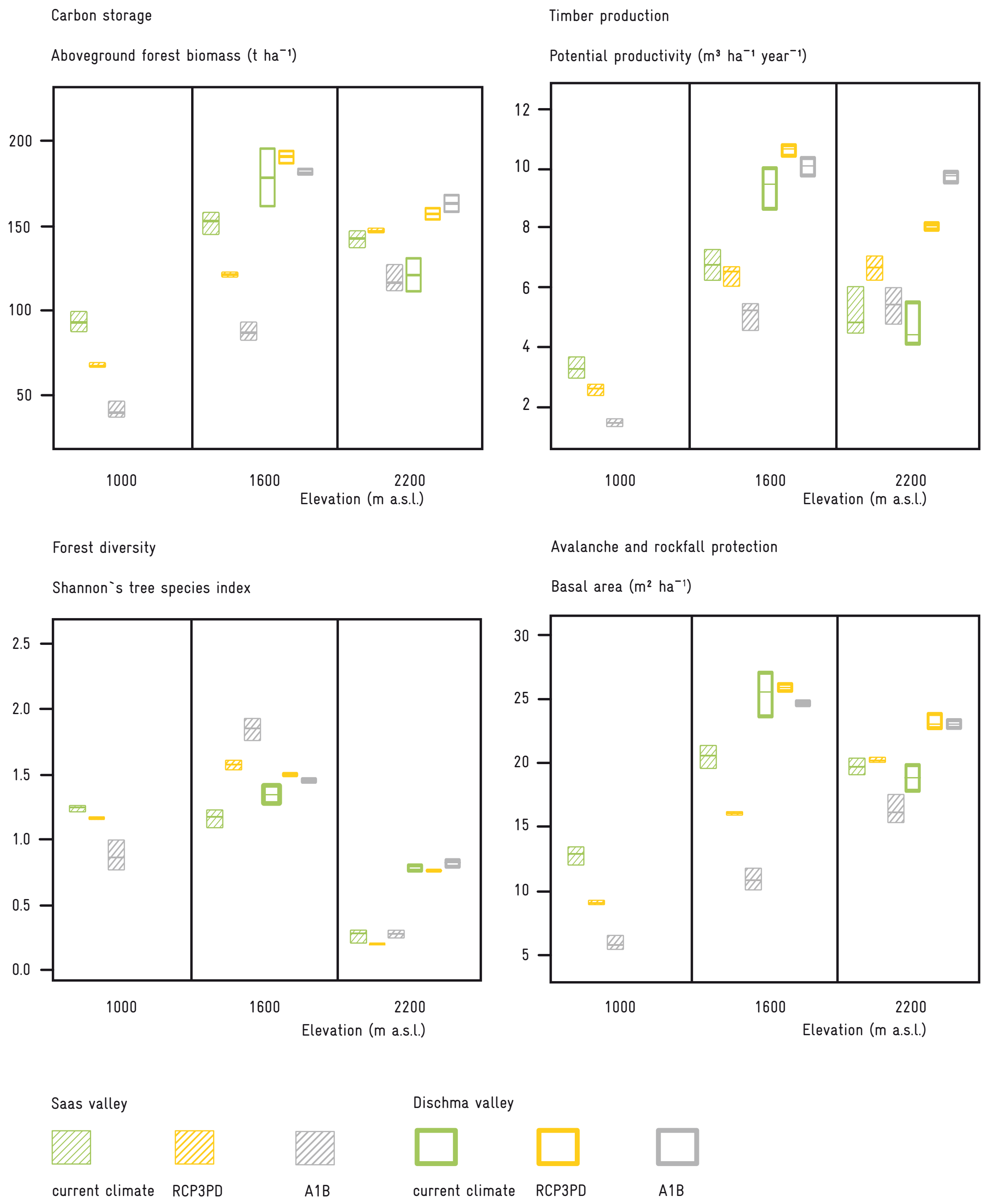


Figure 8.5: Projected impact of climate change on four forest ecosystem services (ES) at three elevations in the Saas and Dischma valleys based on the ForClim and LandClim models. The projected range and median of ES under current climate conditions, moderate climate change (RCP3PD) and more extreme change (A1B) are shown for the time period centered around the year 2085. The ranges shown in the figure refer to stochastic variability inherent in the ecological processes, not model uncertainty.

considerably, with some services such as protection against avalanches and rockfall being sensitive already to moderate climate change, but other services such as carbon storage being reasonably resistant. Thus, a heterogeneous response of mountain forest ES to climate change is to be expected both between and within regions. These results do not, however, consider the likely increased activity of bark beetles and other pests and pathogens, which may modify the ecosystem response rather strongly, as outlined below.

Bark beetles will most likely benefit from a warmer and potentially drier climate. Almost all over Switzerland, beetle populations will produce a higher average number of generations per year (Figure 8.6) and profit from a prolonged annual flight period. Spring swarming of overwintering generations and summer swarming will occur earlier (on average four and three weeks, respectively, under the A1B scenario in 2085). Particularly on the Swiss Plateau, and in some Alpine valleys with a current maximum of two beetle generations, a third generation will become frequent by 2085 (Figure 8.6). In the Alps and the Jura Mountains, generation numbers will increase from between one and two at present, to regularly two. Moreover, earlier spring swarming will generally be more pronounced at higher elevations in the Alps and the Jura Mountains than on the Swiss Plateau. The increased pressure of bark beetles (Figure 8.6) on spruce needs to be interpreted in the context of the limited drought tolerance of that species: drought periods may increasingly lead to growth reductions (Figure 8.1), increased susceptibility to bark beetle attacks and thus higher mortality.

8.4. IMPLICATIONS

Drought impacts on forests are already evident in the driest parts of Switzerland, e.g., at low elevations in the Valais (Rigling et al., 2012; 2013). These impacts are reinforced by biotic influences, but depend also on land use

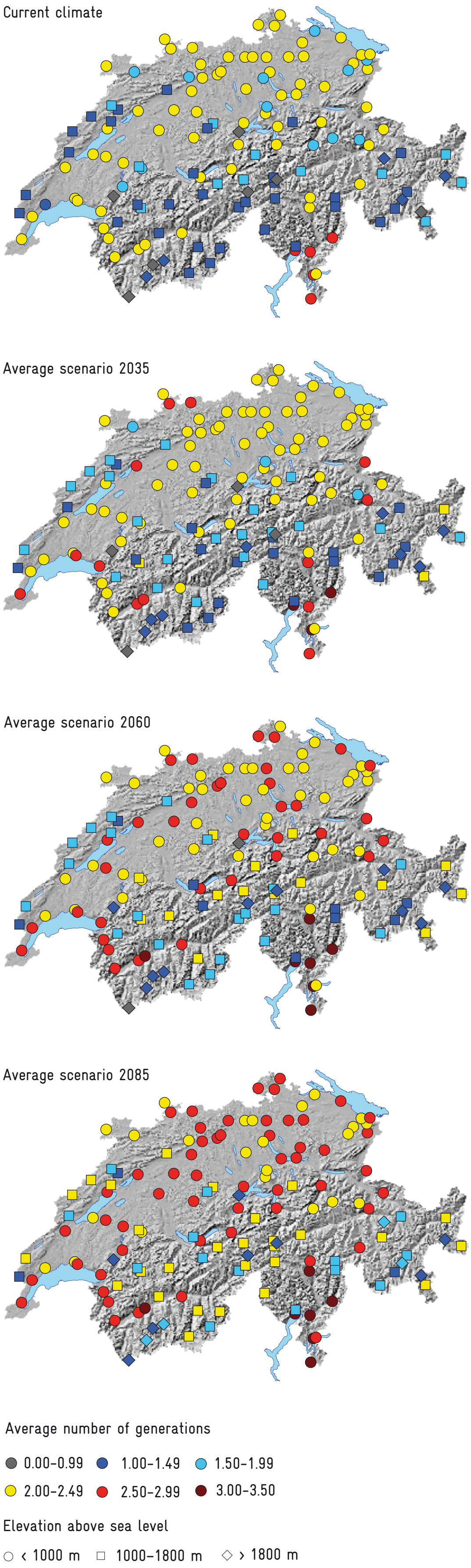


Figure 8.6: Average potential number of spruce bark beetle generations per year at 141 locations in Switzerland for the reference period 1980–2009 and under the A1B climate scenario for 2035, 2060, and 2085, respectively.

changes (Dobbertin et al., 2007). Another example of a complex climate change impact is the ongoing spruce decline on the Swiss Plateau, which is triggered by natural disturbances, i.e., storms and subsequent bark beetle infestations, and promoted by summer droughts (Engesser et al., 2008; Temperli et al., 2013). Many other indirect effects of climate change influence forest ecosystems, e.g., the spread of novel pathogens and pests introduced through global trade. Thus, climate impacts on forests will always be the result of multiple factors, whereas the scenario calculations of the present chapter tend to focus on few factors only. Accordingly, while the simulation results should be useful for guiding management decisions, they must not be taken literally as 'prognoses' of future forest states.

The results in this chapter are broadly in line with the large-scale impacts of climate change that were outlined in the Fourth Assessment Report of the IPCC (IPCC, 2007b), and provide a richer picture of the implications of climate change for forests at the national to local scale. They are also in agreement with the findings from the earlier report CH2050 (OcCC 2007), which provided a qualitative assessment of climate impacts. The results for the mitigation scenario RCP3PD represent an advancement with respect to the aforementioned reports. While for many forest ecosystem services the climate of this scenario would be "safe", for some it is clearly not. This finding shows the very high sensitivity to climate change of some Swiss forests.

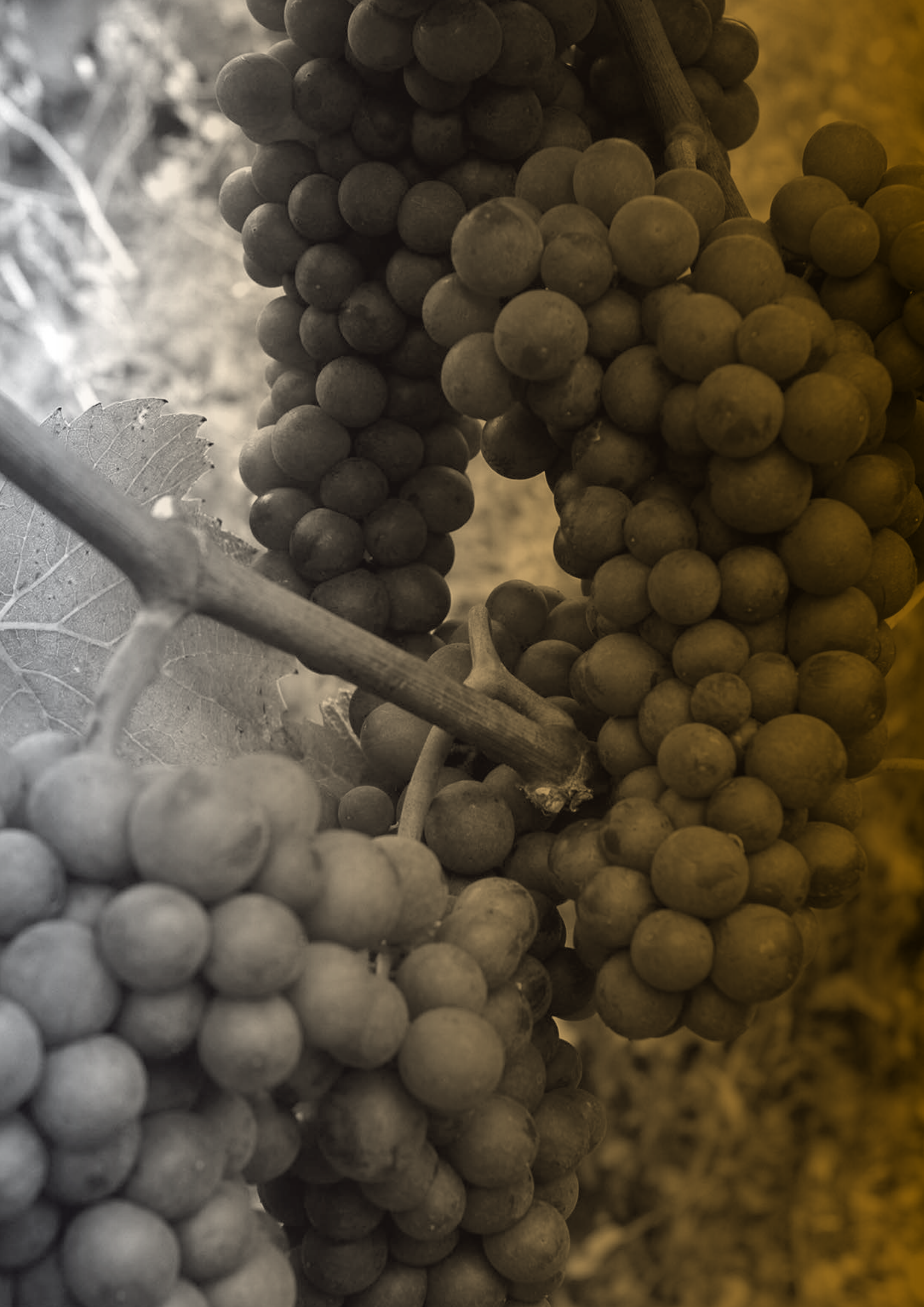
The impacts of future climate on forest properties will strongly differ between sites. While it is evident that climate scenarios with larger changes in temperature and precipitation will affect forests more strongly, forest vulnerability also depends on current site conditions and current stand properties. Empirical evidence (Figure 8.1) and simulation studies (Figures 8.2–6) suggest greatest changes for sites where forest growth is currently limited by water availability or low temperature, i.e., at the lowest and highest elevations of the current forest distribution in Switzerland.

At dry sites, e.g., low elevations of inner-Alpine valleys, already small changes of the climate (i.e., the RCP3PD scenario) can trigger major changes in biomass, forest composition, and the provision of ecosystem services. There, active management measures to alleviate drought (such as thinning) or even changes to novel tree species compositions may be sought.

In contrast, water availability is usually not limiting at cool sites in the Swiss Alps, which will therefore become increasingly suitable for forest growth and forest expansion. This will accelerate the trend of increasing forest area at high elevations, which may or may not be welcome, depending on the ecosystem service considered (e.g., landscape aesthetics vs. carbon storage).

At intermediate sites, the uncertainty about future biomass and forest composition is considerable, and current impact models often disagree. An example is the future presence of spruce on the Swiss Plateau. In such environments, different trajectories are possible, and may be largely determined by climate extremes, which are exceedingly difficult to project in timing, frequency and severity. A robust strategy under these conditions would be to diversify the portfolio of tree species where this is feasible with limited efforts, so as to allow for many different future trajectories of forest dynamics.

The case studies suggest a reduction in the provision of ecosystem services at low elevations in dry inner-Alpine regions and an increase at high elevations. The potential for conifer timber production and carbon sequestration will shift from the Swiss Plateau to the Alps and Jura Mountains. However, timber harvesting is more difficult and expensive in these regions, and the risk of bark beetle attacks on spruce also increases in a warmer climate. Protection forests will be particularly threatened at low elevations of inner-Alpine valleys, but may profit from climate change at higher elevations. Overall, this means that, from a forest sector perspective, negative changes in the dry Inner Alps will likely be contrasted by neutral to positive changes in the wetter parts of the Alps and in the Jura Mountains.



9 — Implications of changes in seasonal mean temperature for agricultural production systems: three case studies

○
● heat stress in cattle
● pest phenology
● wine production
○

– The performance of dairy cows will suffer from elevated temperatures, reflecting the extent and uncertainty of projected warming in different scenarios, with a marked increase in heat stress for non-intervention scenarios (A1B and A2) toward the end of the century. This calls for the adoption of protective measures in the management of indoor and outdoor animal environments.

– A substantial risk of a prolonged pest control season for the codling moth (an apple pest) is projected toward the end of the century for Northern Switzerland sites, and mid-century for the Ticino. Timely preventive programs are anticipated to represent a key ingredient of adaptation to changing risks from agricultural pests.

– Results suggest that in the near future viticulture could benefit from increasing temperatures as a wider range of grape varieties could be grown. Toward the end of the century negative impacts from extreme temperatures are nevertheless expected to become important.

‹ In the near future, moderately warmer summers could allow a wider range of grape varieties to be grown in northern Switzerland (photo: Peter Salzmann, Wein & Natur GmbH).

This chapter is dedicated to Dr. Jörg Samietz, head of the Zoology Research Group at Agroscope Changins-Wädenswil, who passed away unexpectedly on April 11, 2013, while this chapter was in preparation. We are grateful to Jörg for his initial contribution to this chapter, his continuous commitment to entomological research and his efforts to promote the modeling of orchard pest phenology.

9.1. INTRODUCTION

Agriculture is one of the economic sectors most directly exposed to climate and therefore most sensitive to climate change. Shifts in temperature and precipitation have the potential to alter the climate suitability for crop and animal production (Trnka et al., 2011), soil fertility and stability, and the distribution of agricultural pests and diseases. Climate change is already having an impact on agriculture at the global (e.g., Lobell et al., 2011), continental (e.g., Eitzinger et al., 2009; European Environmental Agency EEA, 2012), and national scale (e.g., Holzkämper et al., 2013a).

One of the main conclusions of the Working Group II IPCC Fourth Assessment Report (IPCC, 2007b) was that in Central and Northern Europe moderate warming (1 to 3°C), along with the increase in atmospheric CO_2 concentrations and associated improvement in the water use efficiency and productivity of crops (e.g., Torriani et al., 2007), would be beneficial for cereal crop and pasture yields. Yet further warming would entail negative impacts, in particular in relation to a projected shift in climate variability and an increasing incidence of extreme events.

Analogous arguments were also advanced with respect to Swiss agriculture in the CH2050 report (OcCC, 2007), with a qualitative discussion of climate change impacts on plant and animal production systems, water requirements and supply, the incidence of weeds, pests and pathogens, and the implications for farm management and national food security.

Going beyond the qualitative approach of the CH2050 assessment, this chapter examines in a quantitative way how specific aspects of agricultural production could respond to changes in long-term seasonal mean temperature as projected for the 21st century by the CH2011 scenarios (Chapter 3). Three case studies are presented, addressing animal performance (animal production), the potential shift in insect pest phenology and generation development (pest management), and the thermal conditions for viticulture (plant production). Crop suitability and crop productivity is dealt with elsewhere (Holzkämper et al., 2013b).

The case studies are chosen considering the economic importance of animal and fruit production (including viticulture) for Swiss agriculture. With 3.4 billion CHF, cattle meat and dairy production account for 35% of the total monetary output of the agricultural sector (SBV/USP, 2012). Fruit production and viticulture contribute with another 1.0 billion CHF, or 25% of the output generated through plant production and 10% of the total output (SBV/USP, 2012).

9.2. METHODS

Responses to long-term changes in seasonal mean temperature (△T), respectively, are evaluated by:

- defining response functions on the basis of either empirical equations or results of analyses carried out with process-based modeling tools;
- applying the response functions along with observed weather data for 1980–2009 to obtain a reference;
- simulating future responses by adjusting observed weather data according to the projected △T.

Dairy cows' performance as a function of temperature and air humidity is quantified using the temperature-humidity index (THI; Thom, 1958). A threshold of THI = 72 is assumed as a critical level (Johnson, 1994), and the number of days with THI > 72 is taken as a measure for the risk of heat stress. Relative humidity is evaluated as a function of daily mean and minimum temperature following Allen et al. (1998).

Pest management in fruit production is investigated relative to the shift in the seasonal phenology and generational development of the codling moth *(Cydia pomonella L.)*, a major insect pest of apple orchards worldwide. The long-term average risk of a third generation (start of larval emergence) is assessed by specifying a sigmoidal response function to changes in temperature. This function approximates the response obtained using the seasonal pest phenology model SOPRA (Samietz et al., 2008; Stoeckli et al., 2012) along with a statistical downscaling approach (Hirschi et al., 2012).

Climate suitability for viticulture is assessed on the basis of the heliothermal index (HI) introduced by Huglin (1978). The Huglin index is often adopted for impact assessments (e.g., Trnka et al., 2011) as it provides a better measure of the sugar potential of different vine varieties than the classic temperature sums (Jones et al., 2012).

Three stations (Changins, Wädenswil, and Magadino) are considered, representing the three core regions (CHW, CHNE, and CHS) defined in CH2011 (2011). Seasonal temperature anomalies needed to quantify the climate change signal are obtained for each of the three greenhouse gas scenarios (RCP3PD, A1B, and A2) and time periods (2035, 2060, and 2085) from the CH2011 SEASONAL-REGIONAL scenarios (Chapter 3).

9.3. RESULTS

The **performance of dairy cows** suffers under heat stress. THI values in excess of 72 induce a progressive decline in milk production (Johnson, 1994). Currently, this occurs on average during only five (Northern Switzerland) to 15 days (Southern Switzerland) per year. As seen in Figure 9.1, however, the average number of days with THI > 72 is projected to significantly increase in the future, more markedly starting around 2060 under the A1B and A2 greenhouse gas scenarios. The increase is most pronounced for Southern Switzerland, where the current situation already reflects higher thermal pressure. As a result, toward the end of the century critical conditions are expected on up to 70 days in Northern Switzerland and up to 90 days in Southern Switzerland.

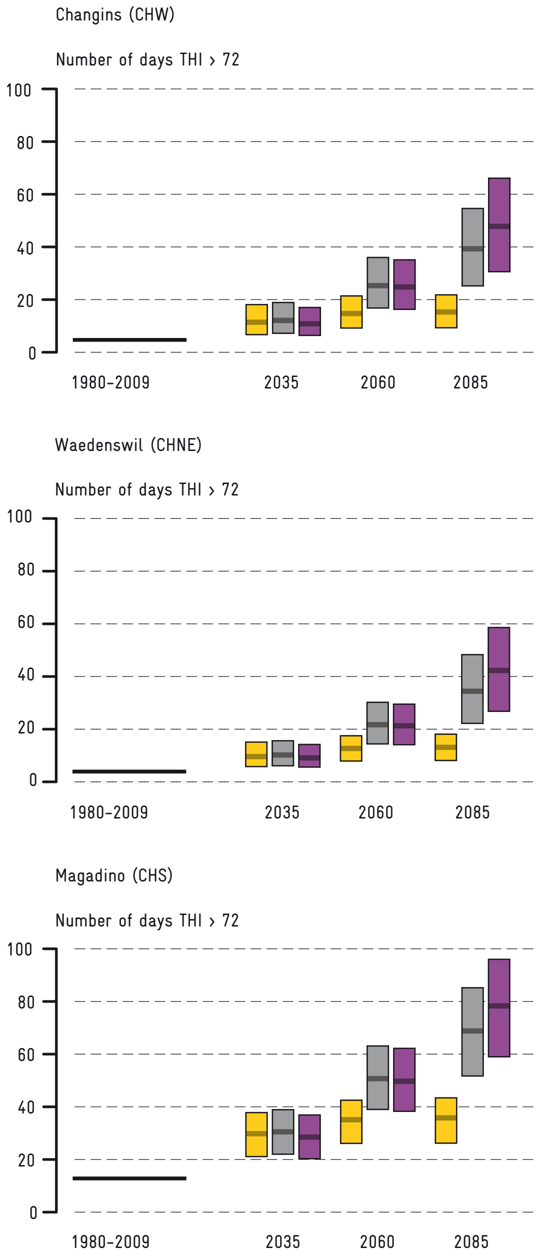


Figure 9.1: Average number of days per year with temperature-humidity index THI › 72 at Changins (top), Wädenswil (middle), and Magadino (bottom) under reference (1980–2009) and future climate conditions (2035, 2060, and 2085) as projected for the three greenhouse gas scenarios RCP3PD (yellow), A1B (grey), and A2 (purple). The corresponding CH2011 regions are indicated in parentheses.

Pest management in apple production in Switzerland is currently designed to cope with a high risk of a second generation of larval emergence start of the codling moth but a negligible risk of a third generation (Stoeckli et al., 2012). The risk of a third generation is likely to remain small for all time periods under the RCP3PD scenario in Northern and Western Switzerland (Changins and Waedenswil) but not in Southern Switzerland (Magadino, Figure 9.2), where a considerable risk is simulated for 2060 and 2085 even in this stabilization scenario as a consequence of the projected increase in temperature. For A1B and A2, a third generation risk in excess of 50% is simulated for Magadino around 2060, whereas at Changins and Wädenswil a significant increase is simulated only for 2085.

Climate suitability for viticulture as expressed by the Huglin index is essentially a linear mapping of the mean temperature during April–September. Hence, baseline values and scenarios presented in Figure 9.3 closely reflect the present and future temperature conditions at the three study sites. Current average values suggest a suitability limited to varieties with relatively low thermal requirements in Northern Switzerland (e.g., Müller-Thurgau, Pinot blanc, and Gamay), but extended to a wider range of varieties for the production areas south of the Alps. Based on the range of climate change projections considered, conditions suitable for growing varieties with higher thermal requirements are expected also for Northern Switzerland. This suggests the possibility to improve wine production in many areas in spite of the fact that negative impacts from extreme temperature could become relevant during the second half of the century (Eitzinger et al., 2009; Jones et al., 2012).

9.4. IMPLICATIONS

Appreciable impacts of changes in seasonal mean temperature on animal performance, orchard pest development, and the thermal suitability for grapevine production can be expected already by 2035 and in all cases and more markedly by 2060 and 2085. Impacts are usually more pronounced with A1B or A2 than with RCP3PD.

Given the linear or nearly linear response of the Huglin and temperature-humidity indices to changes in temperature, uncertainties relative to the projected changes in heat stress in livestock and in the thermal suitability for grapevine production closely mirror uncertainties in temperature change as exhibited in the CH2011 scenarios (Chapter 3). The codling moth responds to increasing temperatures in a more complex way and uncertainties in the impacts are conditional on the choice of greenhouse gas scenario and time frame. In any case, uncertainty ranges revealed in Figures 9.1–9.3 can only provide a partial estimate of the total uncertainty, since they do not account for simplifying assumptions and methodological limitations.

On the basis of the present results and earlier, independent assessments, there appears to be scope for adapting agriculture to climate change in Switzerland. Autonomous adaptation, as already practiced by farmers, is possibly sufficient to cope with altered climate conditions in the near future, but more specific measures could be needed later on to mitigate the adverse impacts of increasing temperatures. This holds true both in the context of plant production as well as in relation to animal husbandry. In the latter case, adaptation measures could include the identification of appropriate breeds, adjustments of the nutrition and feeding plans, as well as improvements of indoor and outdoor environments (Hugh-Jones, 1994).

The example of the codling moth underscores the importance of pest management for adaptation of agriculture to climate change. The spectrum of pests, pathogens, emerging infectious diseases and weeds that could challenge plant and animal production during the coming decades is wide (Anderson et al., 2004; Gregory et al., 2009, Bregaglio et al., 2013), and requires a full palette of preventive measures. Given the multitude of challenges, it is far from obvious how to design and implement effective approaches to pest management. In the case of the codling moth, the projected shifts in phenology and generation development will extend the pest control season for apple crops by at least one month. Regulating measures currently implemented include pheromone mating disruption, singularly or in combination with species specific biological control agents *(granulosis viruses)* in case of high population densities (Stoeckli et al., 2012). It is, however, unclear whether these measures will remain

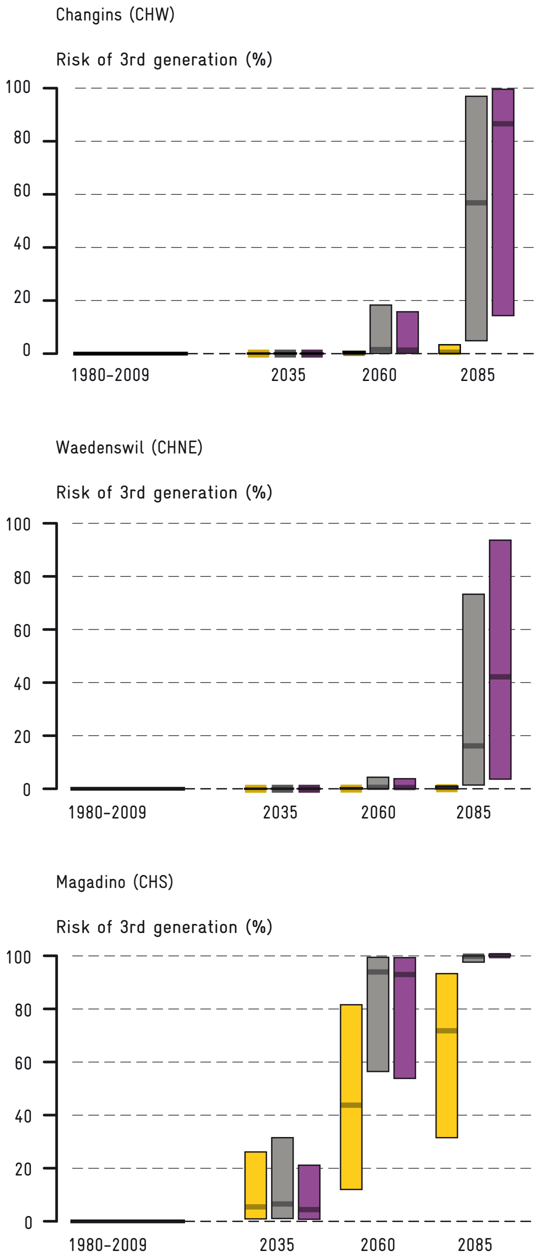


Figure 9.2: Risk of a 3rd codling moth generation at Changins (top), Wädenswil (middle), and Magadino (bottom) under reference (1980–2009) and future climate conditions (2035, 2060, and 2085) as projected for the three greenhouse gas scenarios RCP3PD (yellow), A1B (grey), and A2 (purple). The corresponding CH2011 regions are indicated in parentheses.

fully effective in the future. For instance, it is likely that with increasing temperatures and protracted pest development, current pheromone doses cannot offer protection over an entire season anymore. Similarly, the sole application of mating disruption or the combination with *granulosis viruses* may no longer be sufficient to control codling moth because during multiple generations higher population densities may build up. Additionally, resistances to chemical insecticides are expected if repeated treatments with the same group of ingredients are to be applied to cope with a longer pest control season.

Conclusions with regard to pest management are also sensitive to the assumptions on environmental factors other than temperature. As for other insect pests, the life cycle of the codling moth is regulated by day length. As days shorten toward the end of a season, winter dormancy is induced, which prevents the development of a further generation. An evolutionary shift in winter dormancy induction to a later season is likely to take place in a warmer climate (Stoeckli et al., 2012), and is assumed to be approx. 2 days/decade here. A more pronounced shift would imply a higher pest risk than projected in this study.

An implication of the present analysis is that not all effects of increasing temperatures on agricultural production systems need to be negative. In western and north-eastern Switzerland, for instance, viticulture could initially profit from warming because this would allow the cultivation of varieties with higher thermal requirements than those currently grown. For early-maturing varieties negative effects of accelerated growth on wine quality could further be avoided, e.g., through the adoption of measures for delaying maturity (Petgen, 2007). However, as warming proceeds there is an increasing risk that variety-specific, critical temperature thresholds are exceeded, with negative consequences for grape yields (Sadras and Moran, 2013).

With regard to pests and diseases affecting grapevine, increasing temperatures, along with drier summer conditions, could reduce the disease severity of fungal infections such as powdery mildew, but favor the appearance of insect pests like the European grapevine moth for similar reasons as discussed here in relation to the codling moth (Caffarra et al., 2012).

Although not explicitly examined here, shifts in the frequency and intensity of extreme weather events are likely to take place in Switzerland during the 21st century (CH2011, 2011; MeteoSchweiz, 2013). The consequence for agriculture is that production risks associated with heat waves, droughts, or extreme precipitation events are likely to be higher in the future (e.g., Calanca and Semenov, 2013).

In conclusion, risk management is going to play a crucial role in the context of adaptation (Sivakumar and Motha, 2007). In particular, precautionary measures will become necessary to cope with a more frequent occurrence of summer droughts (Calanca, 2007; CH2011, 2011). The adoption of irrigation, now limited to a few areas within the Valais and Western Switzerland, on a wider scale is one of the most obvious measures to face this situation. Along these lines, studies have already been conducted to evaluate demand and supply of water for agriculture (Fuhrer, 2012) and to analyze options for the management of water resources at the regional scale taking into account the multifunctional role of agriculture (Klein et al., 2013; 2014). Other possibilities to cope with increasing summer drought risks is through insurance instruments (Torriani et al., 2008), but in this case specific investigations are needed to develop products that can effectively cover the risks of a changing climate (Kapphan et al., 2012).

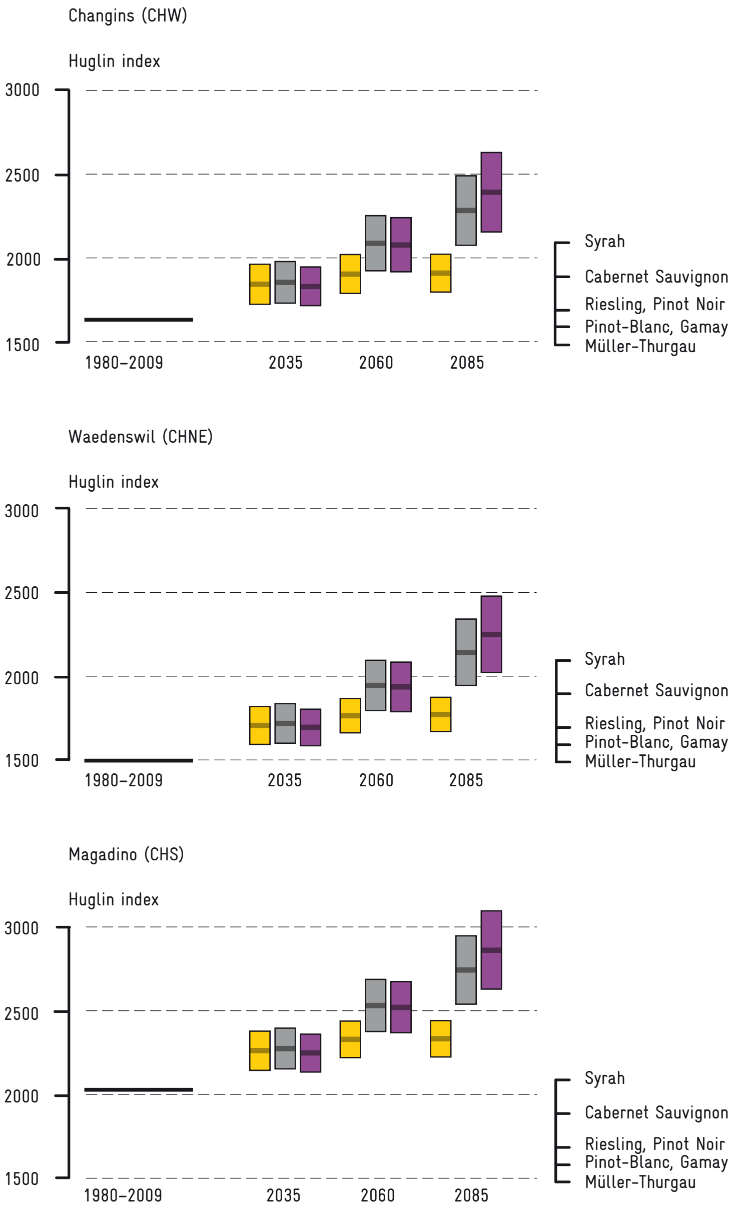
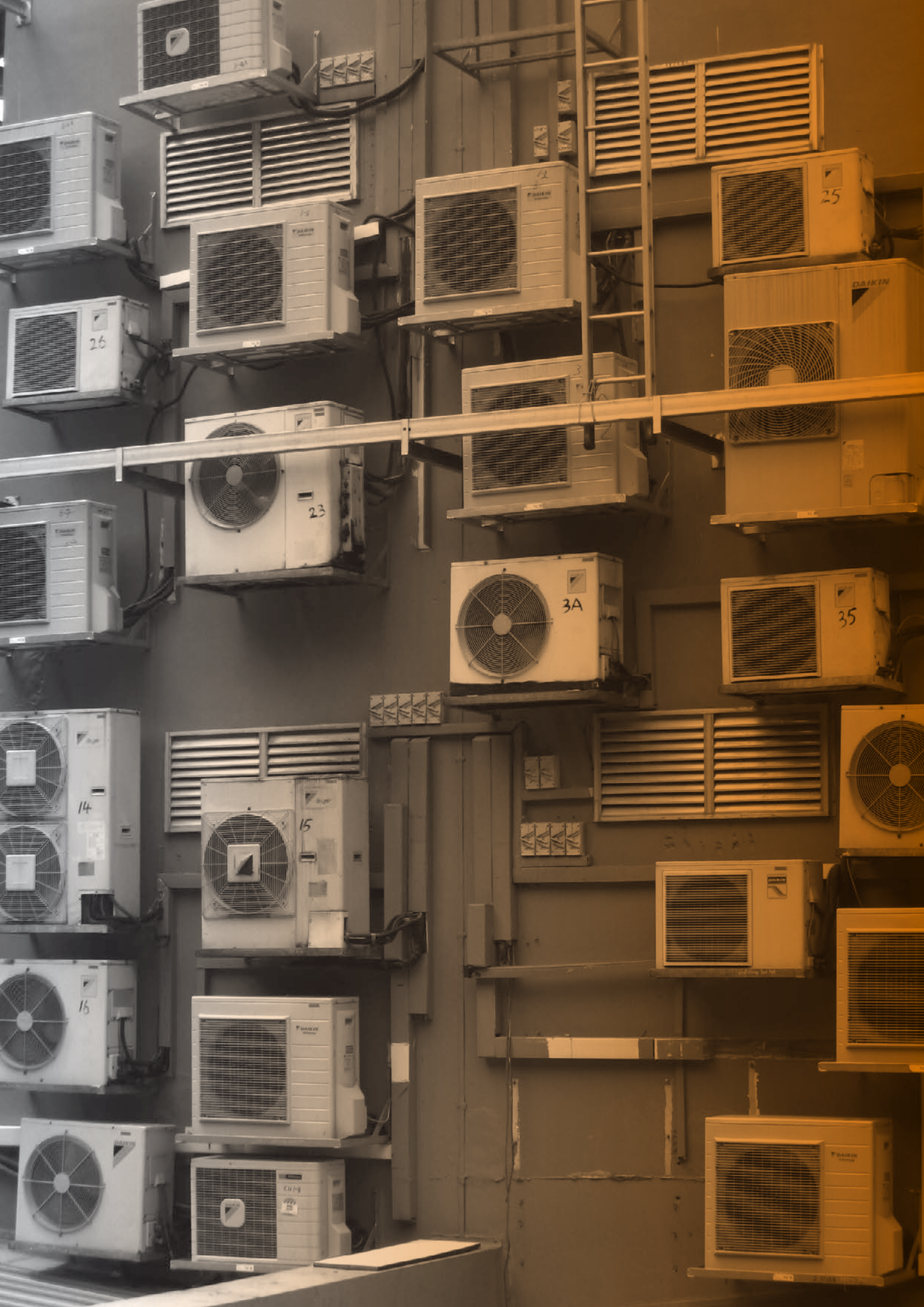


Figure 9.3: Long-term average Huglin index at Changins (top), Wädenswil (middle), and Magadino (bottom) under reference (1980–2009) and future climate conditions (2035, 2060, and 2085) as projected for the three greenhouse gas scenarios RCP3PD (yellow), A1B (grey), and A2 (purple). The corresponding CH2011 regions are indicated in parentheses, and the thermal requirements for different grape varieties are shown on the right of the graphs.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10 — Energy consumption of buildings – direct impacts of a warming climate and rebound effects

○
● energy for heating/cooling
● effect on total energy use and GDP
○
○
○

– Heating energy demand of Swiss households decreases by 0.5% for a 1% decrease in heating degree-days (HDD) based on the empirical relationship between household heating and outdoor temperature.

– The decrease in heating energy consumption due to warming is not offset by a concomitant increase in cooling energy consumption.

– Despite considerable reductions in HDD due to climate change (between 5 and 21% by 2050), the corresponding decrease in total energy consumption and CO_2 emissions is projected to be modest in all considered greenhouse gas scenarios.

– For all greenhouse gas scenarios the projected total welfare gains for 2050 are positive but small (0.04% to 0.23% of GDP).

‹ Swiss households use practically no space cooling today but this may change in a warmer climate (air conditioners in Singapore; photo: Allain Py).

10.1. INTRODUCTION

In 2011, 30.8% of final energy consumption in Switzerland was used for space heating and 2.8% for space cooling and ventilation (BFE, 2012). As average temperatures in Switzerland are likely to increase due to climate change, it is expected that energy demand for space heating will decrease while space cooling, which is currently almost non-existent in private households in Switzerland, is likely to increase. Given a constant building technology, one might expect that heating and cooling energy consumption should be proportional to changes in outside temperatures. However, this proportionality may be impeded by households' behavior. For example, if outside temperatures increase, the decrease in heating energy consumption could be less than proportional because households can now get the same room temperature at a lower price, which encourages them to enjoy more of it and shed their sweater in winter rather than to hold inside temperatures constant. Despite this increase in room temperatures, total expenditures for space heating will decrease, leaving more money for the purchase of other commodities. Depending on whether the additionally consumed goods are more or less energy intensive than space heating, the total energy demand of the household increases or decreases. In particular with respect to increasing energy efficiency, such direct and indirect rebound effects are well documented (Greening et al., 2000; Azevedo et al., 2013), yet their quantitative impact is mainly an empirical question that strongly varies with respect to geographic and economic circumstances.

In this chapter, both the direct and indirect impacts of climate change on the Swiss space heating and cooling energy demand are investigated. First, past weather data are correlated with heating energy consumption by Swiss households to elicit how temperature fluctuations translate into changes of heating energy consumption. The results are then used to project future heating energy consumption by the households in the sample in response to changes in outside temperatures as provided by the DAILY-GRIDDED dataset for the RCP3PD, A1B, and A2 greenhouse gas scenarios (Chapters 2 and 3). This first part only considers potential direct rebound effects in the heating demand of households.

The indirect rebound effects, the changes in cooling energy demand and non-household energy uses are investigated with a computable general equilibrium (CGE) model. This model takes into account the utilization by energy consumers of the revenue saved thanks to lower heating needs and the additional energy consumption that may entail. It allows simulating the entire Swiss economy with the complex interdependencies between different production sectors, households, and trade with foreign countries. The empirical relationship derived before is used to calibrate households' response to changes in outside temperature. The CGE simulations project the changes in total energy consumption and CO_2 emissions up to 2050 for the corresponding CH2011 scenario range.

10.2. METHODS

Two basic thermal indices called heating degree-days (HDD) and cooling degree-days (CDD) are used to relate energy consumption to outside air temperature. HDD are defined following the Swiss standard (SIA, 1982; Christenson et al., 2006): the difference between the target indoor temperature of 20°C and the external temperature, summed over all days with external temperatures lower than 12°C, the temperature below which heating is assumed to become necessary. CDD are calculated according to the U.S. standard (Christenson et al., 2006): the sum of the differences between the external temperature and the threshold indoor temperature of 18.3°C for all days during which mean external temperatures exceed 18.3°C, i.e., the temperature above which cooling is assumed to become necessary. Both HDD and CDD are designed to be approximately proportional to the energy demand for heating or cooling of a given building, respectively. Thus, relative changes in HDD (CDD) are expected to translate into equivalent relative changes in energy consumption.

The empirical analysis of past household data is performed on the spatial resolution of the ZIP codes; the HDD are interpolated by an inverse distance weighted regression (Pesquer et al., 2010) to each ZIP code area and each year between 2000 and 2010 from daily temperature data over the same period provided by MeteoSwiss (Frei, 2014). To project heating energy consumption, HDD are interpolated to ZIP code level based on the DAILY-GRIDDED climate scenarios. For the CGE analysis, which aggregates to the national level, HDD and CDD are calculated as population weighted (based on population density in 2000) national averages for the 2035 and 2060 time periods of the CH2011 scenarios. Values for 2050 are generated by linear interpolation between 2035 and 2060.

The empirical and the CGE analysis use slightly different HDD projections that are not directly comparable. First, the household sample of the empirical analysis is not representative for population weighted conditions as considered in the CGE analysis. Second, the time period is slightly different (2060 vs. 2050).

The **empirical analysis on the household level** of the direct effect of temperature change on heating energy consumption uses household-based data on heating energy and hot water consumption from 2000 to 2010 (NeoVac ATA AG). After discarding outliers, the data comprises 41'829 Swiss households with a total of 175'298 heating consumption observations over the years 2000–2010, collected almost exclusively from apartment buildings.

The effect of HDD on residential heating consumption is estimated by a multivariate regression model. The statistical analysis allows for the fact that households living in different climatic zones may have both a different average heating consumption per year and a different development of building technology over the years 2000–2010 by including indicator variables (fixed-effects) for zip-codes and a set of indicators for regions and climatic zones for each year.

The results from the statistical analysis are used to project future heating energy consumption for Swiss households. Future HDD on the ZIP code level are provided for all greenhouse gas scenarios (A1B, A2, and RCP3PD), and for all time periods (2035, 2060, and 2085). The lack of information on changes in households' characteristics necessitates the assumption that changes in HDD have the same effect on heating consumption in the distant future as during the observed period 2000–2010.

In the **CGE analysis** the GEMINI-E3 CGE model (Bernard and Vielle, 2008) simulates the adjustments of the entire Swiss economy to changing outside temperatures caused by climate change. GEMINI-E3 has been used extensively to derive total costs and benefits of various energy and climate policies for European countries including Switzerland. A recent improvement to the model allows for the integration and examination of the impacts of climate change on the Swiss economy (Faust et al., 2012). The time horizon of the GEMINI-E3 model is 2010–2050. The model's household consumption function is calibrated to replicate the elasticity of energy consumption with respect to HDD derived from the empirical analysis. As cooling energy consumption in Switzerland has been negligible so far, its relationship to temperature fluctuations cannot be deduced from past data, but must be based on plausible modeling assumptions.

Climate impacts are measured against a baseline model simulation assuming no climate policies and no climate change impacts. Based on official Swiss statistics, the economic growth rate is assumed to be 1.7% until 2020, and then to decline to about 0.8% until 2050 (data provided by M. Surchat, SECO; Surchat, 2011), while population is assumed to reach 8.4 million in 2050 ('middle' scenario, Swiss Statistical Office, 2010). In line with the recent decision of the Swiss federal council, nuclear power is assumed to be phased out by 2034, and replaced by natural gas and renewables. In contrast to the static empirical analysis, energy efficiency of household heating is assumed to increase by 1% per year.

Future changes in HDD (CDD) according to the projections described above are incorporated into the model via a decrease (increase) of energy consumption for heating (cooling). Changes in HDD and CDD are introduced separately to distinguish their economic effects. First, the decrease in heating energy consumption of the housing sector is simulated. Then the impact of HDD changes on the services sectors is implemented by simulating a corresponding reduction of heating energy consumption in offices. In the third and fourth simulations, the increase of space cooling demand is analyzed for households and the other economic sectors, respectively. In the final simulation, changes in heating and cooling demands by all sectors are modeled simultaneously.

10.3. RESULTS

The observations used for the **empirical analysis on the household level** show high variability in HDD over the data period 2000–2010 between different years and different geographical locations. Values range from 1735 to 7234 across ZIP code regions and yearly averages over all regions from 2902 to 3669 (Chapter 4, Figure 4.3). This high variability in HDD in our observed dataset assures that projections of HDD do not extrapolate beyond the empirical sample of the HDD-energy consumption relationship, which is important for the robustness of the projected future heating energy consumption.

The empirical analysis reveals that the elasticity of heating energy consumption with respect to the observed HDD variation is only about 50%, i.e., heating energy consumption decreases by approximately 0.5% if HDD decrease by 1%. This elasticity estimate is highly significant (0.1% level) and extremely robust (48.7% to 51.3%) for different model specifications. With the medium estimate of the climate scenarios (Chapter 3) for the mid-century period (2060), it yields a projected decrease

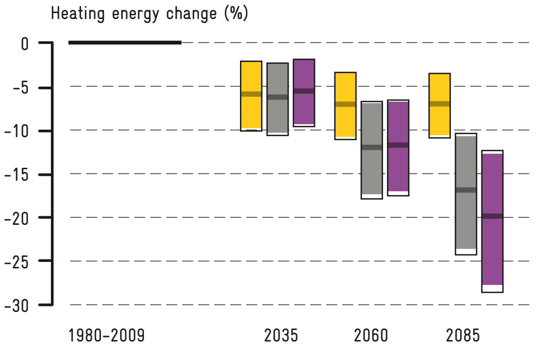

Figure 10.1: Projected reduction in heating energy consumption for the household sample in the empirical analysis for the RCP3PD (yellow), A1B (grey), and A2 (purple) greenhouse gas scenarios.

in heating energy demand averaged over all households in our sample ranging from 7% (RCP3PD) to 12% (A1B; Figure 10.1). For the end of the century (2085), projections range from 7% (RCP3PD) to 20% (A2). Combining the uncertainty estimates from the statistical model (95% confidence intervals) and from the climate change predictions (low, medium, or high; Chapter 3), projected decreases in energy demand range from 3% to 18% for the mid-century period and from 4% to 29% for the end of the century (2085).

The discussion of the **CGE analysis** focuses on the medium estimates for the 2050 period of the A2 scenario, according to the time horizon of the model, and the scenario exhibiting the most pronounced changes and impacts. In this scenario, HDD decrease by 14.5% (Figure 10.2). When only households are allowed to adjust, they lower the heating energy consumption by 7.25% with respect to the baseline, which corresponds to the 50% rebound effect of the empirical analysis. This implies reductions in the total consumption of oil and gas products by 1.8% and 0.3%, respectively (Table 10.1). In contrast, household consumption of other products grows by 0.07%, among which electricity consumption increases by 0.7%, a non-negligible indirect rebound effect. At the aggregate level, the simulation yields welfare gains of 858 million CHF, mainly from a smaller energy bill for heating consumption. As an environment friendly side effect, CO_2 emissions are reduced by 1.6%.

When adjustment is also allowed in all economic sectors other than housing, the 14.5% decrease in HDD leads to smaller fossil fuels savings: 1.3% for oil products, 0.8% for natural gas and 1.1% for CO_2 emissions. The associated welfare gain amounts to 465 million CHF, reflecting reduced production costs in the services sectors.

In contrast to heating, space cooling needs will increase with climate warming, as indicated by a CDD increase by 248.5% in 2050 (Figure 10.2). However, the impact on space cooling and associated energy use is much more uncertain, as currently the percentage of buildings equipped with air conditioners is very low in Switzerland, where air conditioning is tightly regulated. As a consequence it is difficult to project the impacts of a warmer climate on the penetration of air conditioning in buildings. The scenarios stipulate that in the services sectors 46% of spaces will be fully air-conditioned and 36% partially in 2050, in comparison to currently 19% and 20%, respectively. It is further assumed that in 2050, every tenth dwelling will be equipped with air conditioning, compared to a current share of close to zero. The projected increase in electricity consumption for cooling shows a detrimental, but relatively small effect on the Swiss economy. When only the housing sector adapts to more CDD, household electricity consumption is projected to increase by 2.5%, which raises overall electricity consumption by 0.9%. 42% of this increase is covered by renewables and 58% by thermal power plants using natural gas, which results in a 0.7% increase in

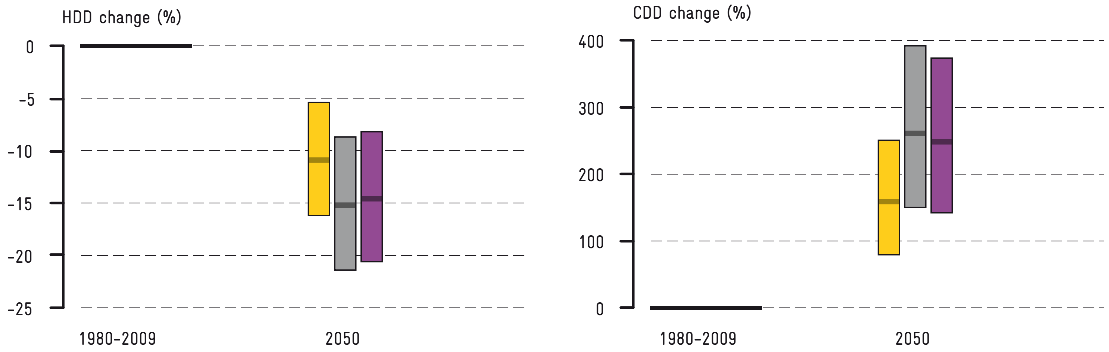

Figure 10.2: Projected changes of HDD (left) and CDD (right) from the CGE analysis for the lower, medium, and upper estimates of the RCP3PD (yellow), A1B (grey), and A2 (purple) greenhouse gas scenarios. The figure displays the percentage changes in 2050 compared to the reference period (1980–2009).

Table 10.1: Impact of heating energy savings due to climate change on total Swiss energy demand in 2050 for the A2 greenhouse gas scenario (medium estimate) as projected in the CGE analysis. Changes are given relative to the baseline scenario.

	Heating households	Heating other sectors	Cooling households	Cooling other sectors	Heating and cooling all sectors
Energy consumption change (%)					
Oil products	−1.8	−1.3	−0.2	0.0	−3.1
Natural gas	−0.3	−0.8	0.7	0.7	0.4
Electricity	0.7	−0.2	0.9	0.8	2.1
Total	−0.5	−0.8	0.4	0.4	−0.4
CO_2 emissions change (%)	−1.6	−1.1	0.0	0.2	−2.5
Welfare impact					
Million CHF (in 2010 prices)	858	465	−234	−130	955
% of consumption	0.13	0.07	−0.04	−0.02	0.15

Table 10.2: Impacts of climate change on the total Swiss energy demand in 2050 for the CH2011 range in greenhouse gas scenarios and climate uncertainty. Changes are given relative to the baseline scenario.

	RCP3PD			A1B			A2		
	lower	medium	upper	lower	medium	upper	lower	medium	upper
Energy consumption change (%)									
Oil products	−1.2	−2.4	−3.5	−1.9	−3.3	−4.7	−1.8	−3.1	−4.5
Natural gas	0.4	0.2	0.0	0.5	0.4	0.4	0.5	0.4	0.4
Electricity	1.1	1.5	1.9	1.5	2.2	2.9	1.5	2.1	2.8
Total	0.0	−0.4	−0.7	−0.1	−0.5	−0.8	−0.1	−0.4	−0.7
CO_2 emissions change (%)	−0.9	−1.9	−2.9	−1.5	−2.6	−3.8	−1.4	−2.5	−3.7
Welfare impact									
million CHF 2010	275	720	1157	487	999	1487	449	955	1429
% of consumption	0.04	0.11	0.18	0.08	0.16	0.23	0.07	0.15	0.22

overall natural gas consumption (Table 10.1). This is offset in terms of CO_2 emissions by lower consumption of oil products (–0.2%) by households who spend a greater share of their budgets on cooling. These changes entail a welfare loss of 234 million CHF. When only the services sectors adapt to more CDD, a 0.8% increase of electricity consumption and a welfare loss of 130 million CHF is found.

The corresponding simulation of all HDD and CDD changes with the coupled responses of both households and the services sectors suggests a beneficial overall impact, with welfare gains netting 955 million CHF by 2050 compared to the baseline.

Similar effects of varying magnitudes are projected for the other scenarios RCP3PD and A1B and across the climate uncertainty range (Figure 10.2 and Table 10.2). Even in the RCP3PD scenario, which supposes that greenhouse gas emissions are reduced globally by about 50% by 2050, Swiss energy demand still decreases by 0.4% relative to the baseline in 2050 due to a warmer climate, while A1B is similar to A2. Across all three greenhouse gas scenarios, a beneficial impact of climate change on the Swiss energy demand is identified, with welfare gains ranging from 275 to 1429 million CHF in 2050.

10.4. IMPLICATIONS

As the empirical analysis on household level shows, there is a pronounced direct rebound effect with respect to heating energy consumption: Households heat relatively more when the same room temperature can be obtained at lower cost. This direct rebound effect of 50% lies at the higher end of the estimates by Sorrell (2007), which range from 10% to 60% in 9 studies.

Applied to the 14.5% decrease of HDD in the medium A2 scenario by 2050, the 50% rebound effect yields a decrease in heating energy consumption of only 7.25%. This still leaves a decline of heating expenditures corresponding to 50% of the HDD effect. According to the general equilibrium analysis, this leads to a strong indirect rebound effect: the 7.25% decrease in heating energy consumption only translates into a 0.5% decrease in total energy consumption and a 1.6% decrease in CO_2 emissions. Despite a warming climate and a considerable reduction in HDD, the resulting decrease in heating energy consumption in particular and total energy consumption in general are rather modest. Thus, direct and indirect rebound effects may render partial energy savings inefficient in reducing overall energy use. It is important to keep this in mind when discussing energy efficiency standards and policies concerning heating and building technology.

Another important insight of the analysis is that the decrease in energy consumption due to a lower demand for heating is not offset by the increase in energy consumption due to an increased demand for cooling. As a result, welfare gains are projected for all greenhouse gas scenarios investigated. They are, however, projected to be modest, ranging between 0.04% and 0.23% of total household consumption. These results are in line with the findings of OcCC (2007) and other studies finding that climate change leads to decreasing energy demand in the colder and increasing energy demand in the warmer world regions (Isaac and van Vuuren, 2009).

The results rest on various strong assumptions and therefore should be considered with appropriate caution. First, the empirical projections of the direct effect of climate change on heating energy consumption by households are just that. They are not forecasts of energy consumption per se as they do not take into account changes in building energy efficiency, population size or space requirements per person, which are all expected to increase over the considered time frame. Second, for the CGE analysis a number of assumptions about the future development of the Swiss economy are made. A major source of uncertainty in our analysis is the projection of future heating and cooling needs. In particular, the projections for cooling energy demand rest on ad hoc assumptions about the future penetration of air conditioning systems in Switzerland, which is currently close to zero for private households due to restrictive regulation. Recent work suggests that the effects could be amplified in cities through the proximity of buildings (Allegrini, 2012). Nevertheless, the estimates are considered to be robust with respect to the pronounced total rebound effect. Although the reduction in

HDD days due to climate change is considerable, the effect on total energy consumption will be rather moderate.

The results indicate that promoting energy efficiency of buildings and heating systems remain important elements of an efficient climate change policy for Switzerland, even in a warmer climate.


ABEND
NOON

11 — The impact of climate change on selected indicators of human health: pharmaceutical sales, doctor visits, and hospitalizations

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○
● health indicators
○

– An adverse impact of climate change on hospitalizations is projected, with an increase of about +4%, showing little dependence on the scenario and time period considered.

– Doctor visits and pharmaceutical sales are projected to increase slightly, but statistical uncertainty limits the conclusiveness of results.

11.1. INTRODUCTION

Recent studies indicate that climate change may cause severe adverse health effects, including higher rates of mortality (Deschenes and Greenstone, 2011) and lower birth weights (Deschenes et al., 2009). A rich case study literature links the impact of extreme weather events like heat or cold waves to increases in mortality in Europe (Vandentorren et al., 2004; Conti et al., 2005) and the US (Zanobetti and Schwartz, 2008). Various channels exist through which weather can affect health, e.g., an increased risk of cardiovascular diseases and respiratory health problems (during heat waves), diarrhoeal diseases and malaria (related to natural disasters like floods mainly in developing countries), new patterns of influenza seasons (due to mild or very cold winters), and weather-related effects on mental health (e.g., WHO, 2009; 2012; Ballester et al., 2003; IPCC, 2007b).

This chapter derives empirical relationships between observed temperature and precipitation in Switzerland and selected indicators of human health, and applies these to the CH2011 scenarios to project the impact of climate change. Health indicators include over-the-counter pharmaceutical sales, doctor visits, and hospitalizations. The conjecture is that mild forms of weather-related health impacts may increase the consumption of over-the-counter drugs (which would display in pharmaceutical sales). More serious symptoms eventually require patients to see a doctor (for more effective prescription drugs or further medical treatment). Very severe forms of health impacts, including emergency cases, may lead to an increase in hospitalizations.

‹ Statistics suggests impacts on the health sector with more hospitalizations and sales of registered pharmaceutical products as a result of warming in Switzerland (photo: edia.con).

11.2. METHODS

The analysis is based on four data sets that contain information about human health and observed weather in Switzerland.

Data on over-the-counter **pharmaceutical sales** (in number of units sold) are provided on a monthly basis for the years 2002 to 2012 (129 months) by IMS Health Switzerland (IMS Health, 2012). The information is grouped into sales by pharmacies and sales by drug stores, as well as sales of registered products (authorized by Swissmedic) and non-registered products (health or sanitary products). Pharmacy sales are aggregated to 227 regions, drug store sales are aggregated to 82 regions.

Monthly data on the number of **doctor visits** from 2007 to 2011 (60 months) are obtained from NewIndex AG (NewIndex AG, 2012). The data are aggregated to 577 regions on the 3-digit zip-code classification level, and cover all physicians who are member of one of the Swiss Medical Associations (FHM, KKA, etc). Monthly numbers of **hospitalizations** from 1998 to 2010 (156 months in total) are provided by the Swiss Federal Statistical Office (SFSO, 2012). The data are aggregated to 785 medical regions on the basis of zip-codes.

Weather data include total daily precipitation and mean daily temperature for the period 1998 to 2012 and are available in gridded form at a resolution of about 2 km × 2 km from MeteoSwiss (Frei, 2014). To combine the information the weather data is aggregated on a monthly basis and at the respective spatial resolution of each health indicator. Table 11.1 summarizes the data and shows basic descriptive statistics.

The analysis builds on a statistical model similar to the one estimated by Deschenes et al. (2009) and Deschenes and Greenstone (2011). The model is based on the assumption that each health indicator (as listed in Table 11.1) can be expressed as a function of observed temperature and precipitation. To preserve as much of the daily weather information as possible and to allow for a flexible functional form of the relationship between weather and health, the original weather data is transformed as follows: The distribution of daily temperatures and precipitation is split into seven bins defined by intervals containing a certain fraction of all observations (quantiles):

- Temperature quantiles:
  0–15, 15–30, 30–45, 45–55, 55–70, 70–85, 85–100%

- Precipitation quantiles:
  0–10, 10–25, 25–40, 40–55, 55–70, 70–85, 85–100%

The number of days per month for which a certain region experienced weather conditions falling into any of these bins provides the weather variables included in the model. In other words, the transformed weather variables correspond to histograms of daily temperature and precipitation levels for each month and region. To match the level of aggregation of the health indicators, this transformation is done separately for each of the data sets.

Finally, a rich set of regional and time fixed-effects is included in the model to control for unobserved heterogeneity in space and time. More specifically, binary variables are included that indicate each of the regions, quarters, month of the year, and interactions with cantonal indicators to filter out as much of the seasonal and regional differences as possible. As a consequence, the estimates identify the effects of temperature and precipitation on health that are unrelated to regional and seasonal differences and common cantonal trends over time.

Future health impacts of climate change are projected based on the estimates of the relationship between observed weather and human health, using the DAILY-GRIDDED dataset (Chapter 3). The number of prospective days in each precipitation and temperature bin is calculated for the three periods (2035, 2060, and 2085) and the three greenhouse gas scenarios (A1B, A2, and RCP3PD) covered by CH2011 (Chapter 3). The statistical models for each of the six health indicators are applied to the climate change scenarios under a ceteris paribus assumption, i.e., assuming that all relevant background factors remain unchanged.

11.3. RESULTS

First, the observed relationship between **weather and the selected indicators of human health** is discussed, as this constitutes the basis for the projections of the impact of

Table 11.1: Summary statistics of the input data: Mean, standard deviation (Std. Dev.), minimum (Min), maximum (Max) and number of observations (Obs.). For human health indicators, monthly counts are listed. Sales are given for registered (R) and non-registered (NR) products.

	Mean	Std.Dev.	Min.	Max.	Obs.
Weather data (1998–2012, Source: MeteoSwiss)					
Precipitation	3.42	7.61	0	279.1	17'249'157
Temperature	8.46	7.88	–26.1	30.1	17'249'157
Pharmaceutical sales (2002–2012, Source: IMS Health Switzerland)					
Sales in pharmacies (R)	22'694	15'656	2'591	200'880	29'283
Sales in pharmacies (NR)	1'131	1'139	11	34'127	29'278
Sales in drug stores (R)	12'913	8'631	304	75'092	10'577
Sales in drug stores (NR)	1'450	1'213	25	69'469	10'576
Doctor visits (2007–2011, Source: Newindex AG)					
Number of patients	5'885	8'142	1	101'683	34'597
Hospitalizations (1998–2010, Source: Swiss Federal Statistical Office)					
Number of patients	170.5	152.9	1	4'970	100'236

climate change. In the following, the effects of weather are expressed in terms of percentage changes in the different health indicators induced by an additional day with temperature or precipitation in a certain quantile. All discussed effects are significant on the 5% level except where stated otherwise.

The results for over-the-counter pharmaceutical sales show modest empirical evidence for weather-related effects. While the effect of precipitation on pharmaceutical sales is small and insignificant throughout, high temperatures are found to have a positive effect on the sales of registered products in pharmacies, with an increase of about +0.5% in sales per additional warm day above the median temperature. This effect is not due to seasonal patterns, as seasonality is controlled for in the statistical analysis (section 11.2). The effect is also net of the possibly opposing effects of additional warm days in winter and in summer.

Given the observed average in registered sales in pharmacies of 22'694 units per month and region (Table 11.1), a +0.5% increase in sales corresponds to about 113 additional units sold per month and region for an additional day in the high temperature bins. For Switzerland this amounts to about 25'800 additional units, assuming homogeneous temperatures across the country.

Doctor visits increase both with additional cold days (+0.45%) and, somewhat less, with additional warm days (+0.3%). This corresponds to an increase of about +0.6 (+0.9) doctor visits on average per region and month and additional cold (warm) day, which adds up to about 346 (519) more doctor visits in Switzerland per month (577 regions times 0.6 or 0.9). The effect of precipitation on doctor visits is small and statistically insignificant.

Hospitalizations react to changes in both tails of the temperature distribution. For the very low temperatures, the effect is negative with about –0.5%. For high temperatures (above the 70% quantile) the effect is positive with about +0.5%. Thus, one additional day at high temperatures leads to an increase of about 0.85 admissions per medical region and month, or about 677 admissions for Switzerland (785 regions). The effect of precipitation on hospitalizations is weakly positive with about +0.2% for an additional day with precipitation levels in all but the highest bins.

Second, based on the above estimated relationships, projections of the **impact of climate change on the selected indicators of human health** are derived. For registered products in pharmacies, an increase in sales of about +2% is projected, with some variation depending on the scenario and time period (Figure 11.1a). The sales of registered products in drug stores are not affected by climate change according to the CH2011 scenarios (Figure 11.1c). The sales of non-registered products (Figures 11.1b and 11.1d) increase slightly, but with rather large confidence intervals which do not preclude the possibility of no impact at all.

The number of doctor visits is projected to slightly increase with about +0.5%, but the effect is only marginally significant or statistically insignificant at the 5% level (Figure 11.1e). Projections for the number of doctor visits are very similar across the different scenarios and follow similar patterns over time.

Among the selected health indicators analyzed in this chapter, the largest projected impact of climate change is that on hospital admissions (Figure 11.1f). As a result of the positive correlation between high temperatures and hospitalizations and the projected increase in temperatures for all greenhouse gas scenarios, hospitalizations increase by about +4%, with little dependence on the scenario and time period considered.

11.4. IMPLICATIONS

The results of the analysis indicate an adverse impact of climate change on human health as captured by the assessed indicators. A pronounced effect on the number of hospitalizations is found, which may be related to additional emergency cases due to extreme weather events. The projection does not, however, fully capture the impact of extreme weather due to the limited representation of extremes in the CH2011 climate scenarios (Chapters 2 and 3). A slight increase in the sales of registered pharmaceuticals and doctor visits is projected, possibly related to health problems that are non-emergency cases and treatable by a doctor or with specific medication (e.g., cases of general malaise).

The projections calculated above rest on the assumption that the relationship between weather and health remains stable, with the possibility of extrapolating to climate, and climate change. This assumption rules out adaptation in physiology, weather-related behavior, and other relevant socio-economic factors, which would likely reduce the long-term impact of climate change. As a consequence, the present estimates must be interpreted as an upper bound in this respect. On the other hand, changes in climate may introduce novel hazards not observed previously (e.g., new diseases), which in turn would reinforce the estimates of the adverse health impact of climate change.

From a data and modeling perspective, it should be noted that temperatures are relatively homogeneous across Switzerland (with small variations within and between cantons and climatic zones). Some within-variation in temperatures is needed such that common trends and seasonality patterns can be plausibly ruled out in the estimated relationships, and this condition is still fulfilled in our data. Precipitation, on the other hand, shows substantial regional heterogeneity. As a consequence, estimates for the latter likely reflect variations in local weather conditions and local responses in human health. For the extrapolation of the results from a regional to a country-wide impact this implies that estimates based on temperature tend to be more reliable (and have less statistical noise) than estimates based on precipitation. Future analyses should further disentangle these two sources to allow for more detailed projections of the impact of climate change.

Finally, since many climate change projections postulate an increase in extreme weather events, identifying the effects of weather on human health in the tails of the weather distribution is an important aspect. The model used here is flexible in this regard, with the inclusion of bins that stretch over all quantiles. A distinction between the different features of climate change scenarios (e.g., cold vs. heat waves) would be a valuable extension for future research to gain further insights into the impact of climate change on health.

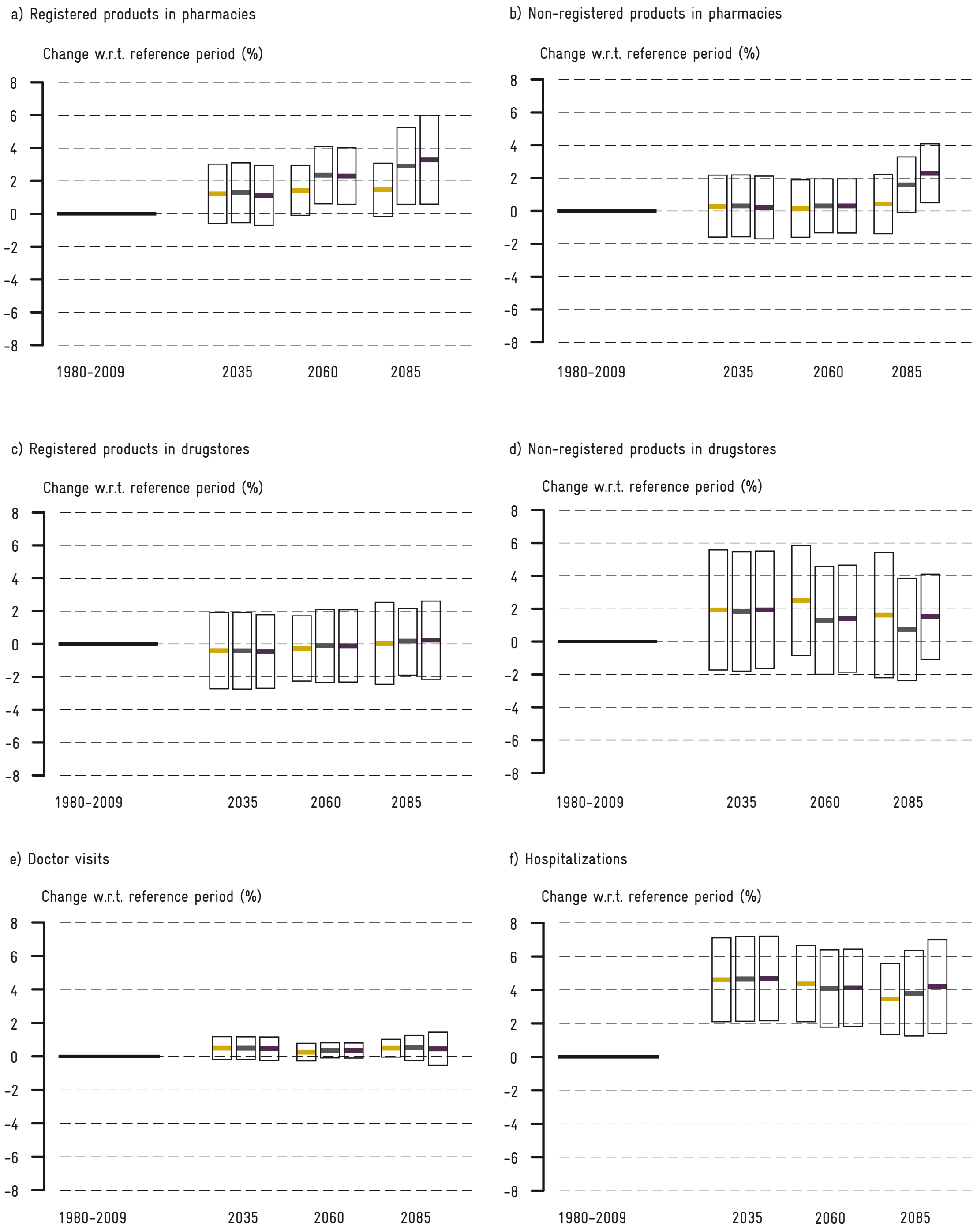


Figure 11.1: Human health indicators under reference (1980–2009) and future climate conditions (2035, 2060, and 2085) as projected for the three greenhouse gas scenarios RCP3PD (yellow), A1B (grey), and A2 (purple). Top: sales in (a) registered and (b) non-registered products in pharmacies. Middle: sales in (c) registered and (d) non-registered products in drug stores. Bottom: (e) number of doctor visits and (f) number of hospitalizations.

12 — Synthesis

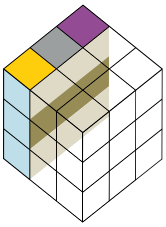
12.1. INTRODUCTION

CH2014-Impacts was initiated in the Swiss scientific community to leverage recent advances in the development of Swiss Climate Change Scenarios (CH2011, 2011) and impact models for a quantitative treatment of climate change impacts. The participating researchers offered their scientific contributions in response to an open invitation to all institutions in Switzerland engaged in research relevant to climate change impacts. The result is a "sample of opportunity" of impact assessments, which covers diverse issues, but has no claim to be comprehensive or representative for the entirety of potential climate change impacts in Switzerland.

This synthesis attempts to combine the report's results into a coherent picture (Figures 12.1–6). It starts with a survey of the evolution of impacts along the CH2011 time frame of **short-term** (2035), **mid-term** (2060), and **long-term** (2085) periods, according to the central importance of time in planning and decision making. Then, a selection of results is discussed with respect to cross-cutting issues, as well as beneficial and adverse impacts in the context of time periods and greenhouse gas scenarios. Finally, crucial limitations are addressed, including impacts missing from the present report and the restricted scope of the individual and independent assessments.

12.2. TIME PERSPECTIVE

The explicit treatment of **short-term** impacts (time period 2035) in this report is an important advancement as it corresponds to the time frame of many business and political decisions, and allows identifying areas where need for early adaptation exists (insets illustrate the possible combinations of greenhouse gas scenario and uncertainty level for each time period; Chapter 2). For the 2035 period it does not matter with regard to impacts which of the three greenhouse gas scenarios is considered, as they all evolve along a common climate path largely determined by the inertia in the global physical climate system and the economy, which delays the effect of vast differences in socio-economic developments and emissions among the scenarios. Most projected impacts in this period are relatively small compared to the complete range of projections, as might be expected due to the limited extent of short-term climate change. For example, the number of generations of the agricultural pest codling moth shows no short-term impact at all (Figure 12.2, Chapter 9). There are, however, important exceptions: The cryosphere exhibits profound impacts already for 2035, in continuation of recent trends; with respect to the reference period 1980–2009, the projected reduction of snow cover reaches about 1/3, and glacier melt 1/2 of the maximal impacts projected (A2, 2085, Figure 12.1, Chapter 5). In the health sector, the maximal impact on the number of hospitalizations is projected already for the period 2035.



‹ Some agricultural pests such as the codling moth will thrive under a warmer climate, putting pest management under pressure (photo: Ilona Ugro. Copyright © Province of British Columbia. All rights reserved. Reproduced with permission of the Province of British Columbia.)

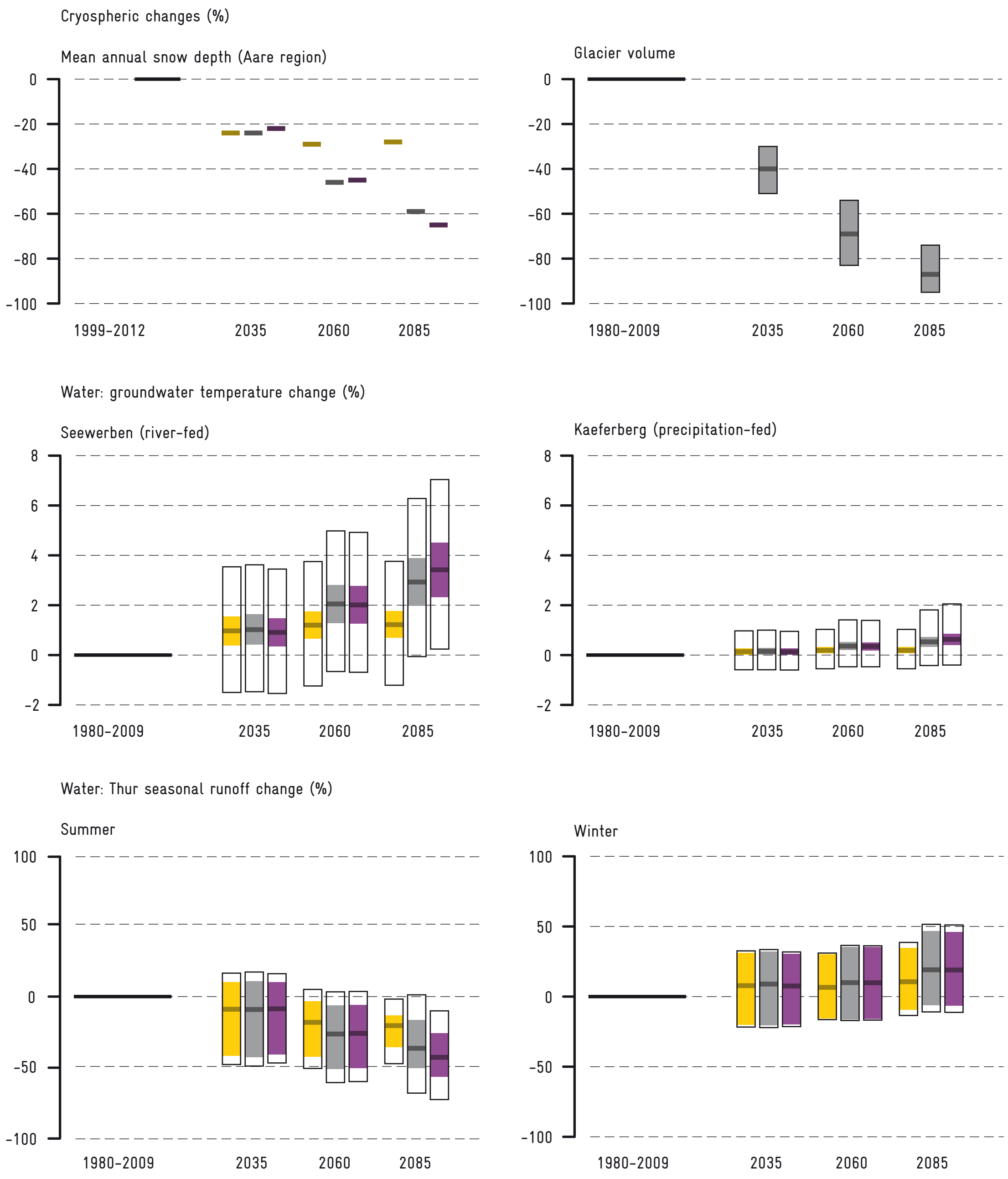
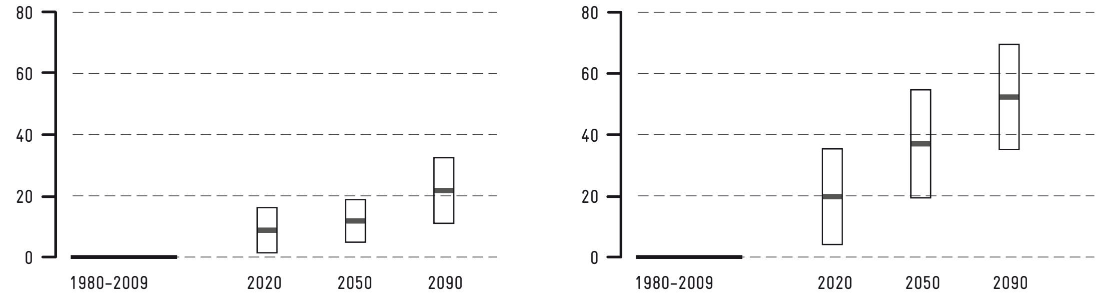


Figure 12.1: Selected climate change impacts (Chapters 5 and 6). Greenhouse gas scenarios are indicated by yellow (RCP3PD), grey (A1B), and purple (A2) color; bold colored lines correspond to the medium climate change estimate, and a colored bar shows the climate uncertainty range where available. Black outlines include impact modeling uncertainty to the extent that it is considered in each study (corresponding to two standard deviations in statistical estimates)

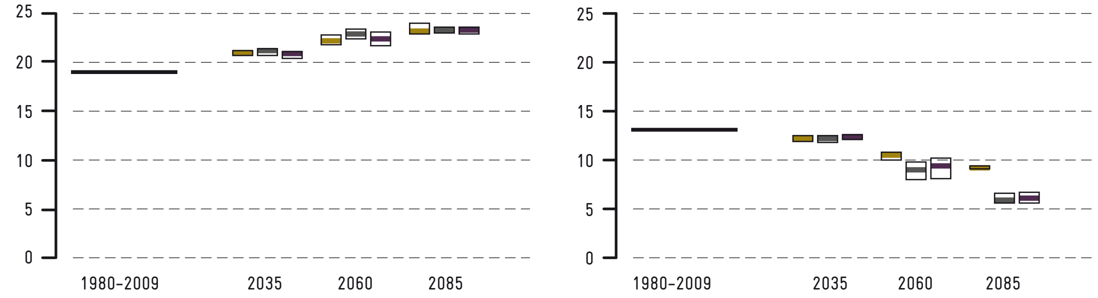
› **Figure 12.2**: Selected climate change impacts (Chapters 7-9) as in figure 12.1. Time ranges slightly deviating from the standard scenario periods were used for bird species turnover (20-year means).



Biodiversity: bird species turnover (%)

1000 m asl

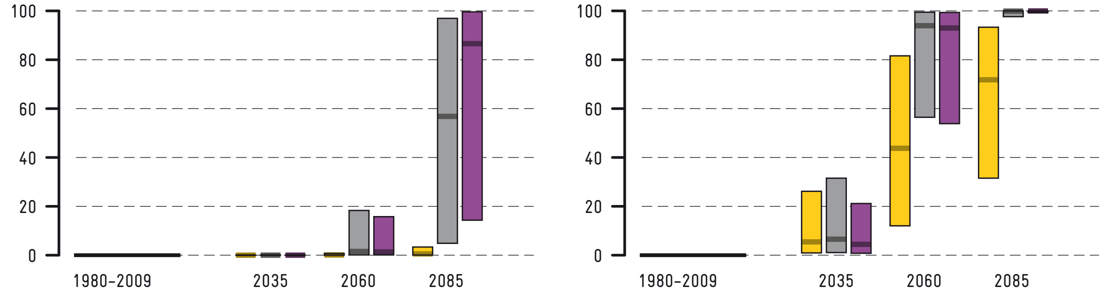
2200 m asl



Forests: avalanche and rockfall protection (basal area, m² ha⁻¹)

Dischma at 2200 m asl

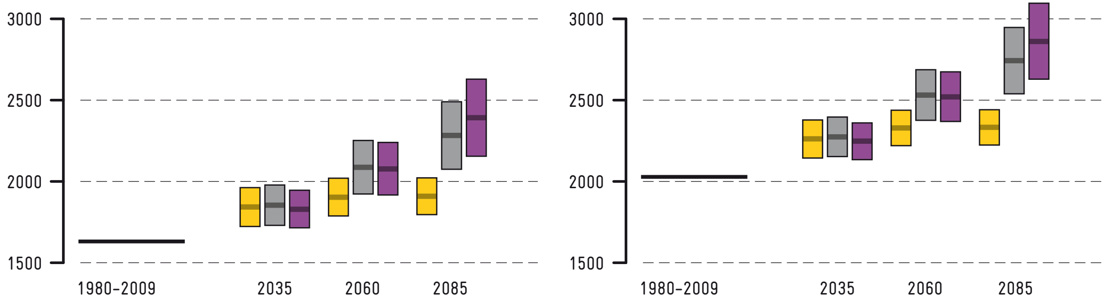
Saas at 1000 m asl



Agriculture: risk of codling moth 3rd generation (%)

Changins

Magadino



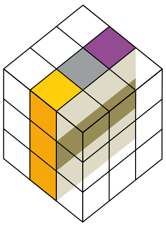
Agriculture: suitability for grape cultivation (Huglin index)

Changins

Magadino

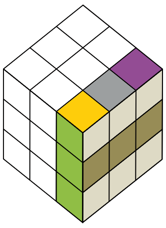
This report's limited set of studies already shows that short-term impacts must not be neglected – an aspect that the earlier impact assessment for Switzerland OcCC (2007) with its mid-century focus did not systematically explore. Though short-term impacts tend to be small in a century-long perspective, their relevance is heightened by the relatively shorter time for adaptation, and by the impact already experienced today (i.e., during the reference period 1980–2009). The assessment of short-term impacts remains challenging as the uncertainty of impacts is already large due to the natural decadal variability in the climate system.

In the **mid-term** period (2060), the effect of political intervention to reduce climate change (known as climate change mitigation) emerges, as seen by comparing the mitigation scenario RCP3PD to the non-intervention scenarios A1B and A2. The benefit of climate change mitigation is already felt widely as well, in that RCP3PD limits most impacts to the level of 2035 (Figures 12.1–3). In contrast, most non-intervention cases show progressively intensifying impacts, in tune with rising temperatures, and reach roughly half of their maximum projected extent. Deviations from this behavior are seen in complex responses such as those simulated for the health and energy sectors (Figure 12.3). An important special case is glacial ice whose volume has melted already by about 75% in the projection for scenario A1B (Figure 12.1), in line with earlier assessments (e.g., OcCC, 2007).

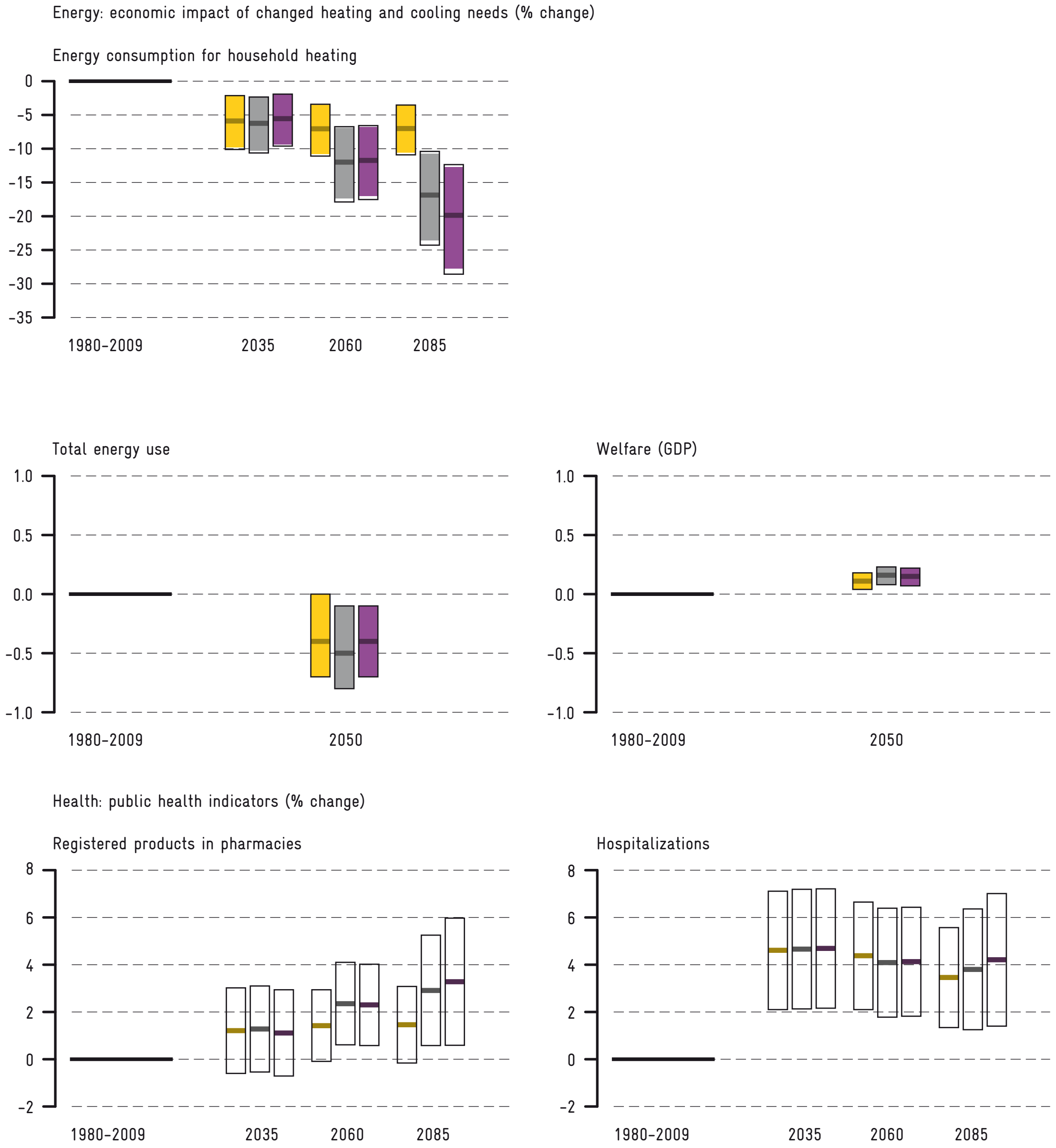


The 2060 time period roughly corresponds to the mid-century focus of OcCC (2007), and quantitatively projected impacts largely confirm the earlier, more qualitative findings of that assessment. This applies, e.g., to the changes in glacial ice and snow cover, and their consequences for runoff regimes and for winter tourism, respectively (Figure 12.1).

The 2085 scenario period affords a **long-term** perspective, which may at first glance seem less immediately policy-relevant than the more imminent future, but tends to reveal important long-reaching issues. For example, forest management must adapt early on to grow forests that will thrive under future climate. Similarly, long-lived buildings should be planned with the heating and cooling needs of a warmer climate in mind. Finally, mitigation of long-term climate change requires that greenhouse gas emissions be reduced as soon as possible.



The consistent use of this time horizon is a crucial step ahead with respect to OcCC (2007). The 2085 period is marked by a further unfolding of the differences between greenhouse gas scenarios. The importance of global climate policy becomes apparent as the gap between RCP3PD and the non-intervention scenarios A1B and A2 widens. RCP3PD reveals the full effect of mitigation in the period 2085, with projected impacts showing signs of saturation. A hint of inertia is suggested by the response of, e.g., the codling moth (Figure 12.2). Inertia is also expected to play a role in glacier melting and its far-reaching consequences, though it cannot be assessed on the basis of the available results, which do not cover the RCP3PD scenario. The projections for the two non-intervention scenarios begin to separate in the 2085 period, with A2 showing stronger impacts than A1B. However, this difference is small compared to the uncertainty. The scope of climate change impact in Switzerland over this century is thus sufficiently captured by those studies that consider A1B alone (e.g., Figure 12.1 for glaciers and Figure 12.2 for biodiversity). However, this judgment does not carry over into the 22nd century, where the differentiation at the high end of climate change scenarios will become very important, due to the long time scales involved in the response processes of the climate system.


Energy: economic impact of changed heating and cooling needs (% change)

Energy consumption for household heating

Total energy use

Welfare (GDP)

Health: public health indicators (% change)

Registered products in pharmacies

Hospitalizations

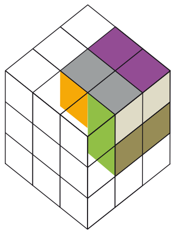
Figure 12.3: Selected climate change impacts (Chapters 10 and 11). Greenhouse gas scenarios are indicated by yellow (RCP3PD), grey (A1B), and purple (A2) color; bold colored lines correspond to the medium climate change estimate, and a colored bar shows the climate uncertainty range where available. Black outlines include impact modeling uncertainty to the extent that it is considered in each study (corresponding to two standard deviations in statistical estimates). A time period slightly deviating from the standard scenario periods was used for energy impacts (year 2050).

12.3. CROSS-CUTTING ISSUES

Of the illustrative selection of eleven independent impacts summarized in Figures 12.1–3, seven can be judged as adverse (snow, glaciers, groundwater, codling moth, species turnover, pharmacy sales, and hospitalizations), two as beneficial (grape cultivation and energy consumption), and another two are ambivalent (river regimes and protection against avalanches and rockfall). This is roughly representative for the mixture of impacts across the report. The beneficial and ambivalent examples point to opportunities in certain areas, such as wine production (Figure 12.2), and challenges in others, such as water supply in summer (Figure 12.1). The report provides several examples of potentially deleterious impacts that can probably be alleviated to a considerable extent with proper management: the adaptation to the increased reproduction of pests (codling moth in agriculture and bark beetle in forestry), the management of biodiversity shifts (species turnover), or the use of artificial snow to extend shortening skiing seasons (Chapter 5). Accordingly, the importance of foresight and management is highlighted in several chapters of this report (Chapters 6 and 7–9). This implies the need for an assessment of the cost of such adaptive measures, as well as potential undesired side effects. Adaptation costs are not assessed in this report but are expected to be potentially substantial.

The impact studies assess to a various degree the uncertainties arising from climate and impact modeling (Figures 12.1–3). Climate uncertainty (Chapter 2) affects the extent of the individual projected impacts, but hardly ever their assessment as beneficial or adverse. The relatively few studies in this report that assess impact modeling uncertainty already provide valuable information. They strongly suggest that the impact of a projected climate change is often just as uncertain as the climate projection itself.

The above survey of scenario time periods shows that unmitigated climate change and its impacts (scenarios A1B and A2) evolve over a very long time. Many impacts may give the appearance of a moderate development well into the mid-century. OcCC (2007) suggests overall beneficial agricultural impacts for moderate warming, tentatively defined as a rise of the mean annual temperature in Switzerland by up to 3°C with respect to the reference year 1990. When this limit is exceeded, the balance tends to tip to adverse impacts. Applied to the CH2011 scenarios (which use a similar reference period) this would mean that both non-intervention scenarios (A1B and A2) hold in store “immoderate” change with drastic impacts, though these crop up only toward the last time period (see inset showing the combinations of scenario, time period and uncertainty level where warming exceeds the “moderate” extent of 3°C). For the presented examples too, it is to be expected, albeit not explicitly assessed, that it will become increasingly harder to avoid damaging impacts and reap potential benefits when warming exceeds “moderate” levels (e.g., Chapter 9). The only truly “moderate” scenario in CH2011 (2011) according to the above tentative definition is the mitigation scenario RCP3PD. This underscores the importance of global climate change policy for Switzerland.



Most of the impacts assessed in this report are driven by temperature change. This is due to the pervasive influence of temperature on all climate-dependent processes as well as the relative weakness of the precipitation change signal as simulated by the climate models, and the incomplete treatment of potentially important extreme precipitation events, storms, or droughts. The one clear trend in precipitation is a reduction in the seasonal mean in summer. The lack of summer precipitation in combination with warming results in dryness with widespread and, depending on the site-specific conditions, potentially severe impacts, as demonstrated in the forest assessment (Chapter 8). Water scarcity may be an issue for agriculture and biodiversity as well although it is not explicitly assessed in the corresponding chapters of the present report (Chapters 7 and 9).

Further insights are gained by considering impacts not in terms of time period and greenhouse gas scenario but in relation to average annual temperature change (Figures 12.4–6). This perspective exploits the central role of temperature. Some cases, e.g., groundwater temperature and suitability for grape cultivation, suggest simple relationships between impacts and mean temperature change. Other responses are more complicated, showing signs of inertia and nonlinearity, as well as the influence of the change in precipitation and associated uncertainty (e.g., river runoff). In any case, the extent or even the sign of the impact can depend strongly on site-specific conditions. For example, the projected impact on forest ecosystem services (Chapter 8) and biodiversity (Chapter 7) depends strongly on elevation; likewise, the warming of groundwater depends on whether groundwater is recharged by river water or precipitation only (Chapter 6). Further, the variety of observed responses demonstrates that the results of the quantified impacts do not generalize easily to additional objects of study such as other species, agricultural products, ecosystems, etc.

12.4. LIMITATIONS AND CHALLENGES

The "sample of opportunity" of assessed impacts collected in this report inherently leaves out many important aspects. For example, the biodiversity assessment (Chapter 7) could be extended by a range of additional important species (amphibians, insects, etc.) and an ecosystem-oriented perspective (with regard to wetlands, meadows, etc.). Similarly, many agricultural issues (Chapter 9) remain to be quantified (e.g., crop- and irrigation-related issues). The narrow focus of the energy and health chapters (Chapters 10 and 11) should be widened to a more comprehensive treatment of these sectors under climate change (e.g., physiological underpinning of climate impacts, or renewable energy production). Finally, the topics geomorphology (e.g., slope stability), transport, insurance, and summer tourism are essentially absent from the report. In general, coverage decreases along the cause-effect chain of impacts from the physical environment to biological and ecosystem changes and further to socio-economic impacts.

Extreme weather events concern a cross-sectoral group of impacts that this report does not explore explicitly, owing to limitations of the CH2011 scenarios (Chapters 2 and 3). Extreme events are expected to contribute to impacts on forests, biodiversity, health, etc., as much as changes in average conditions (e.g., OcCC, 2003; 2007; IPCC, 2012). Prominent examples of impacts that are not treated here include the risk of heavy precipitation, hail storms, floods, heat waves, droughts, etc.

Between the individual impact studies there are several areas of overlap. Glacier melt is an important factor in the seasonality change of runoff regimes (Chapter 6). Changes in the distribution and prevalence of tree species are treated statistically under the aspect of "species turnover" in vascular plants (Chapter 7), as well as with process-oriented complex forest models (Chapter 8). Surface and groundwater changes (Chapter 6) are relevant for drinking water supply and quality and therefore have health implications (Chapter 11). The different assessments are broadly consistent with respect to these overlapping aspects. However, they do not use completely harmonized assumptions apart from the common climate scenarios, and neither do they integrate any relevant results from related chapters. Overlapping aspects provide links which could serve to tie these quantitative results together into a consistent cross-disciplinary assessment, uncovering and eliminating inconsistencies in the process. Therefore, a tighter integration of impact models is desirable for the future.

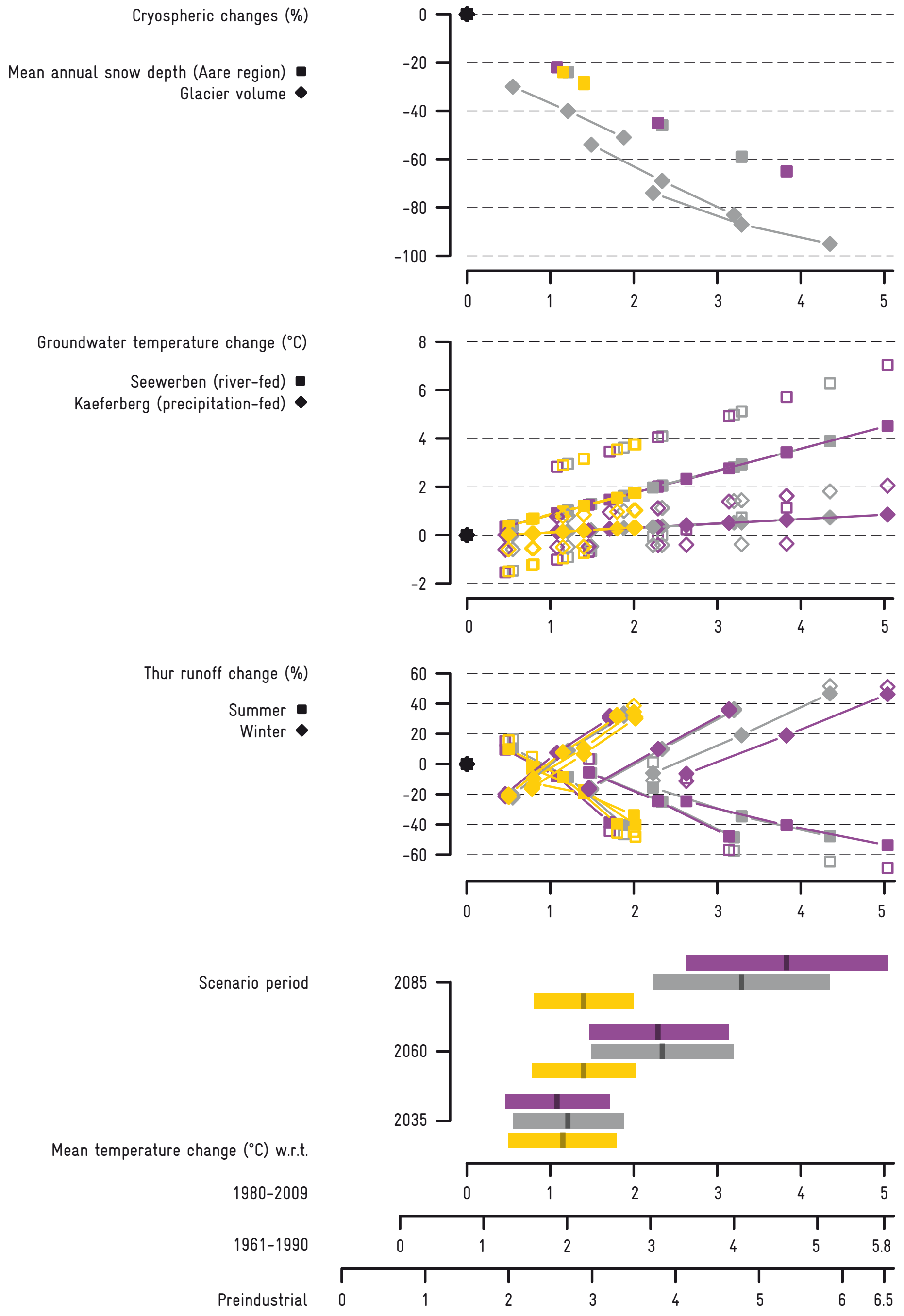
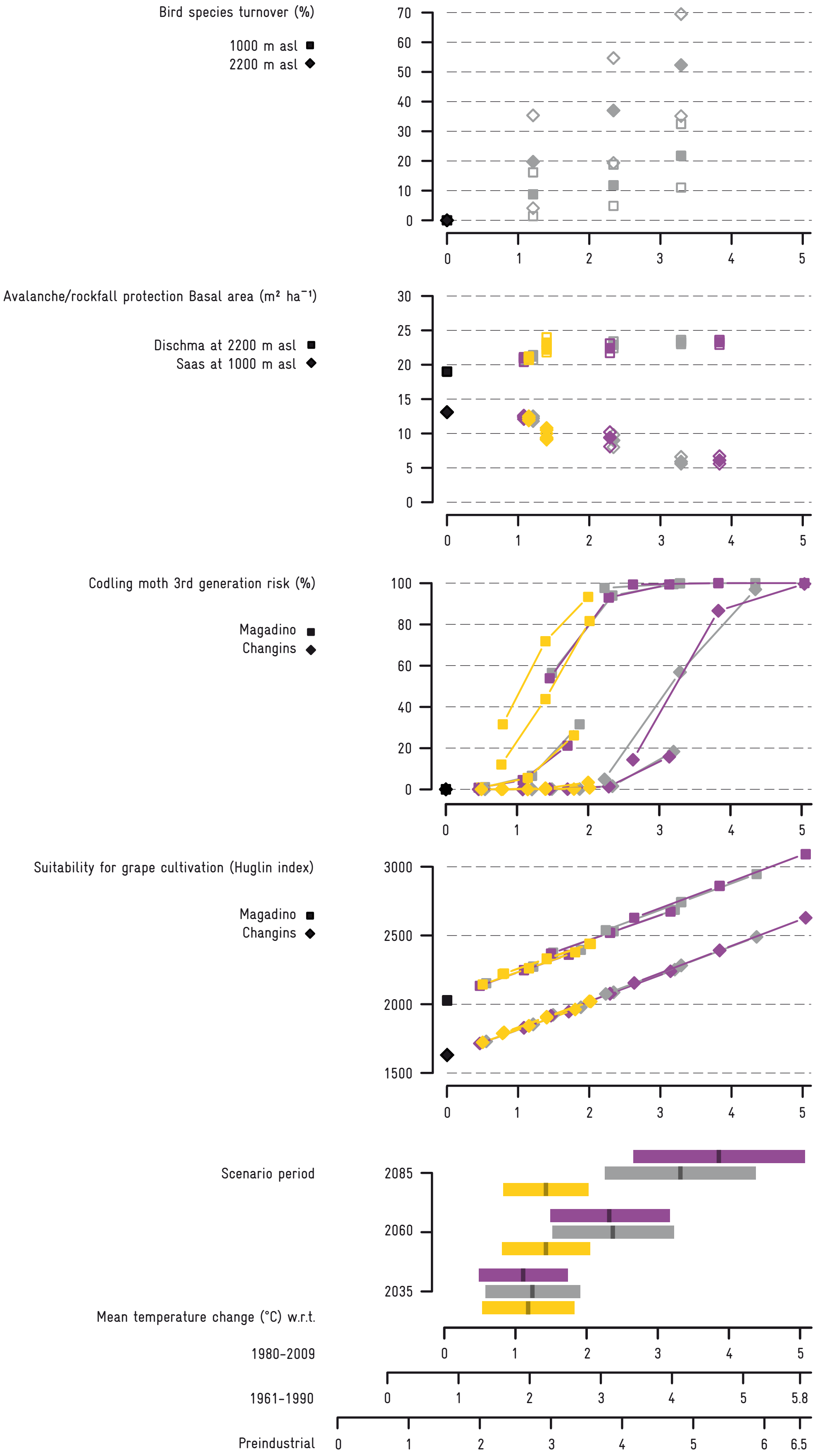


Figure 12.4: Climate change impacts from Chapters 5 and 6, plotted against mean annual temperature change in CH2011 scenarios (average of regions CHNE, CHW, and CHS). Greenhouse gas scenarios are indicated by yellow (RCP3PD), grey (A1B), and purple (A2) color. Estimates for different climate uncertainty levels (low, medium, and high) are shown with solid symbols connected with lines; open symbols correspond to additional impact model uncertainty where quantified (two standard deviations for statistical estimates). For glaciers and river runoff it is assumed that the greatest impact is associated with the upper end of the temperature range and vice versa.

› **Figure 12.5**: Climate change impacts from Chapters 7–9, as in Figure 12.4.


Bird species turnover (%)
1000 m asl ■
2200 m asl ◆
70
60
50
40
30
20
10
0
0
1
2
3
4
5
Avalanche/rockfall protection Basal area (m² ha⁻¹)
Dischma at 2200 m asl ■
Saas at 1000 m asl ◆
30
25
20
15
10
5
0
0
1
2
3
4
5
Codling moth 3rd generation risk (%)
Magadino ■
Changins ◆
100
80
60
40
20
0
0
1
2
3
4
5
Suitability for grape cultivation (Huglin index)
Magadino ■
Changins ◆
3000
2500
2000
1500
0
1
2
3
4
5
Scenario period
2085
2060
2035
Mean temperature change (°C) w.r.t.
1980–2009
0
1
2
3
4
5
1961–1990
0
1
2
3
4
5
5.8
Preindustrial
0
1
2
3
4
5
6
6.5

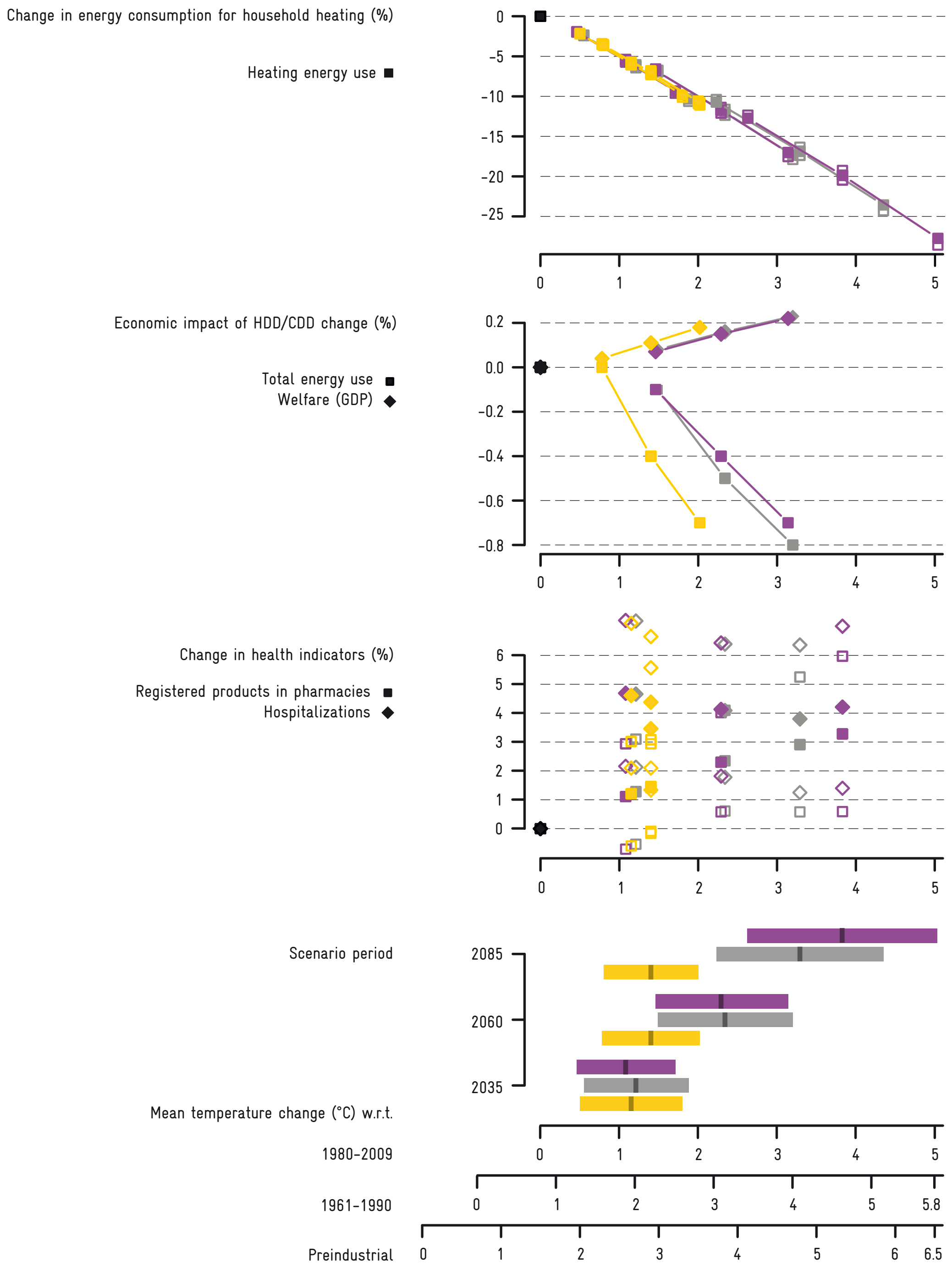


Figure 12.6: Climate change impacts from Chapters 10 and 11, plotted against mean annual temperature change in CH2011 scenarios (average of regions CHNE, CHW, and CHS). Greenhouse gas scenarios are indicated by yellow (RCP3PD), grey (A1B), and purple (A2) color. Estimates for different climate uncertainty levels (low, medium, and high) are shown with solid symbols connected with lines; open symbols correspond to additional impact model uncertainty where quantified (two standard deviations for statistical estimates).

13 — Future perspectives

The intention of the CH2014-Impacts initiative in producing the present pilot report is to stimulate an ongoing process toward the consolidation of quantitative scenarios of climate change impacts in Switzerland.

The contributions to the CH2014-Impacts report consistently apply the approach of linking quantitative impact models with the common data basis of the Swiss Climate Change Scenarios CH2011 (and the climate simulations from which the CH2011 data are derived). This common approach lends coherence to the set of results presented. However, limitations exist due to gaps in the treatment of climate and due to the incomplete coverage of potential impacts (Chapter 12). These gaps may be closed by applying the CH2014-Impacts approach systematically to a representative set of potential climate changes and associated impacts in Switzerland. This will yield "impact scenarios", which depict potential impacts of climate change in Switzerland quantitatively in a multidisciplinary and comprehensive way. Impact scenarios conceptually extend the scenario framework by the dimension of climate change impacts, in addition to the dimensions of greenhouse gases and climate change.

Further steps toward the goal of impact scenarios need to address more potential impacts and to consider the complete range of CH2011 climate change scenarios, i.e., the full "scenario cube" (Figure 2.2). The uncertainty analysis of impact modeling must be strengthened by using a richer set of models and by exhaustively testing the robustness of each model's results. This also requires further evaluation of models and acquisition of new observational and paleoclimatic proxy data needed for this purpose. Finally, the scientific understanding of impact processes and important facets of climate change in Switzerland needs to be improved, in particular with regard to extreme events.

A good understanding of potential impacts is necessary for cost-effective adaptation to climate change. Finding the existing knowledge of most potential climate change impacts insufficient to start with the planning and implementation of adaptation measures and to justify the potentially large investments involved, the first part of the Federal Council's adaptation strategy on adaptation to climate change in Switzerland refrains from proposing a catalogue of measures (FOEN, 2012a). The majority of efforts proposed in this stage of the adaption strategy aim to improve the knowledge base of how natural, social and economic systems will be affected and of what measures can be taken.

A chief impediment to progress in adaptation has been the scarcity of quantitative data, and the necessity to rely on qualitative information (e.g., from OcCC, 2007) for key elements of the federal adaptation strategy. Quantitative information facilitates many aspects of assessment. Analyzing the costs and benefits of impacts and adaptation measures, objectively comparing impact levels, setting priorities for action, are all tasks that call for quantitative information. Similarly, the quantification of uncertainty is an inherent feature of the CH2014-Impacts approach and supports risk analysis, which is essential to adaptation planning (Holthausen et al., 2011).

CH2014-Impacts advances the quantitative basis for the next steps in adaptation planning. The results, despite their patchiness, will support decision making in some policy fields and collectively enhance confidence in the adaptation process. In this way, the

‹ Thawing of permafrost can increase the risk of rockfall and affect infrastructure at high elevations (rockfall interrupts the Gotthard railway line in Gurtnellen on June 5, 2012; photo: SBB).

CH2014-Impacts report contributes to closing the knowledge gaps identified in FOEN (2012a). It provides input for the implementation and further development of the national adaptation strategy, and for other public and private adaptation efforts.

With the foreseen evolution of balanced and representative impact scenarios, much more comprehensive assessments will come within reach. The instrument of impact scenarios promises to enhance objectivity, balance, and detail of the adaptation discourse. In order to realize these benefits, a sustained commitment to the development of impact scenarios and the supporting basic research is needed. Future efforts in continuation of this pilot report will play an essential role in this process.

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