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

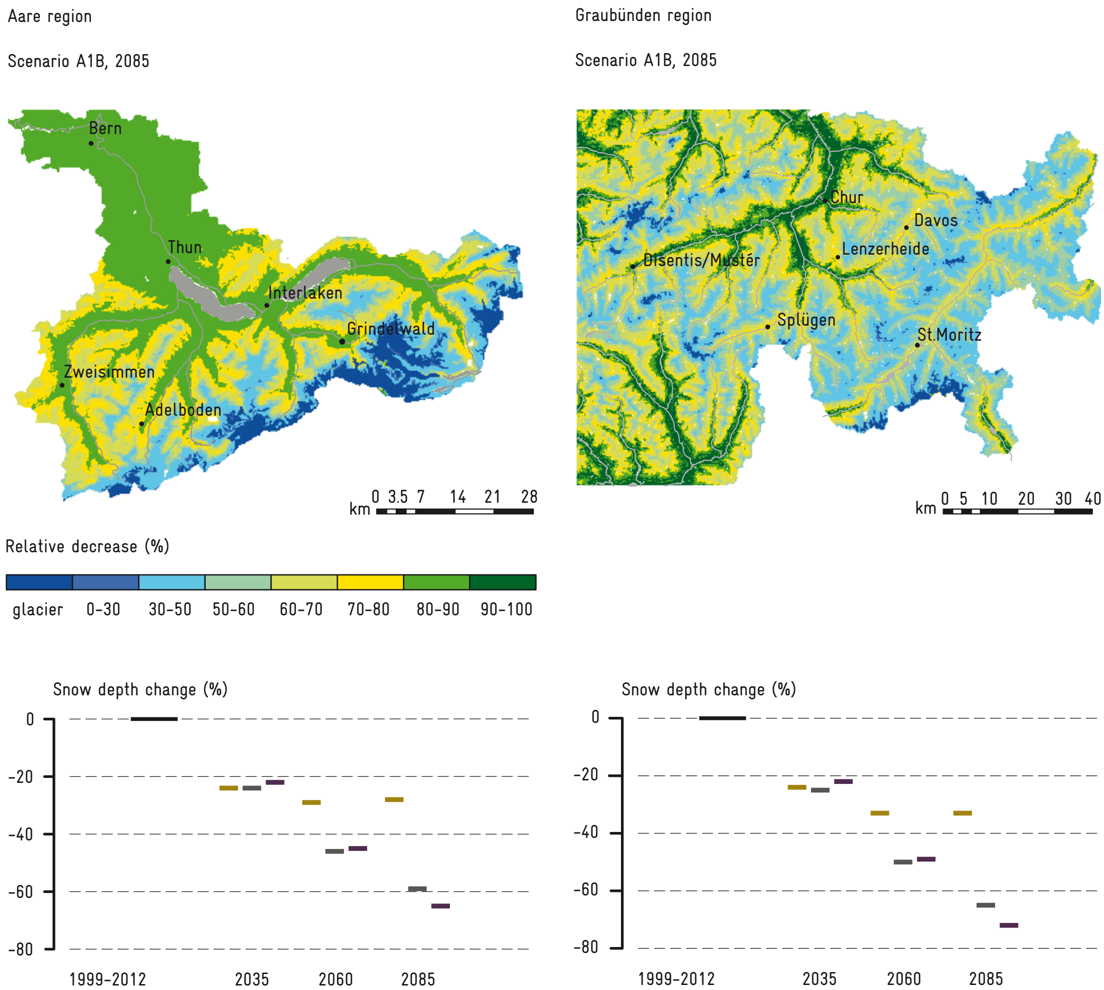

Figure 5.1: Relative decrease of annual mean snow depth compared with the reference period (1999–2012) for the Aare region (left) and the Graubünden region (right) for different scenarios (yellow: RCP3PD, grey: A1B, and purple: A2) and time periods (bottom) and for February 1 snow depth of the last time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

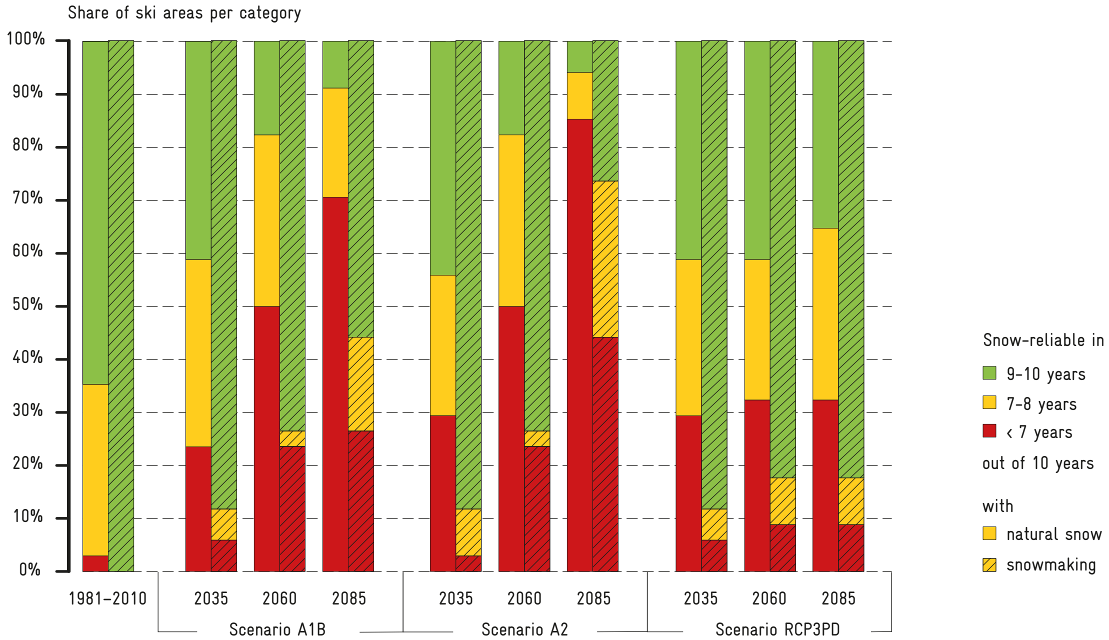

Figure 5.2: Natural and technical snow-reliability of ski areas in the Canton of Graubünden during the economically important Christmas holidays for all three scenario periods and greenhouse gas scenarios.

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 multi-day 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

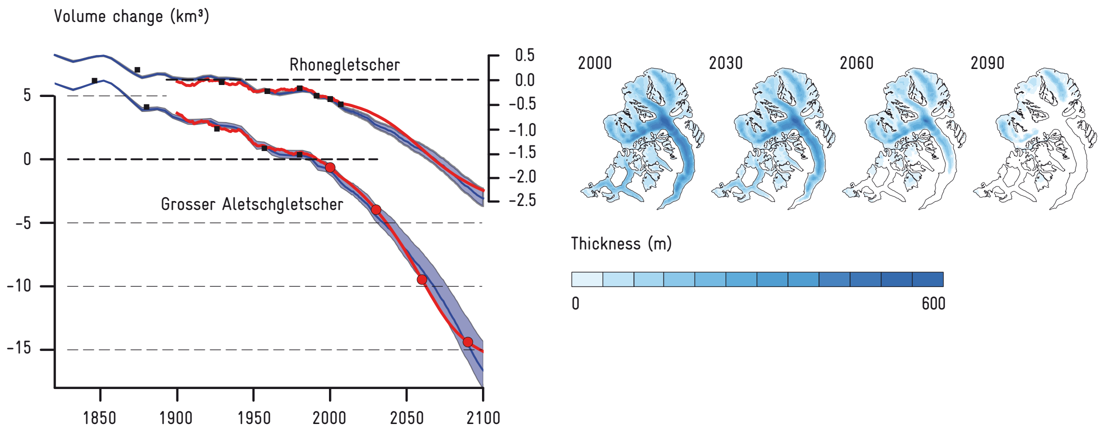

Figure 5.3: The future volume changes (A1B scenario) for the glaciers Grosser Aletsch and Rhone (left), as simulated with the LV-model (blue) and GERM (red). The blue shaded area is the envelope of the 100 model runs and the black squares indicate measured glacier volume changes. Red dots mark the times 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.

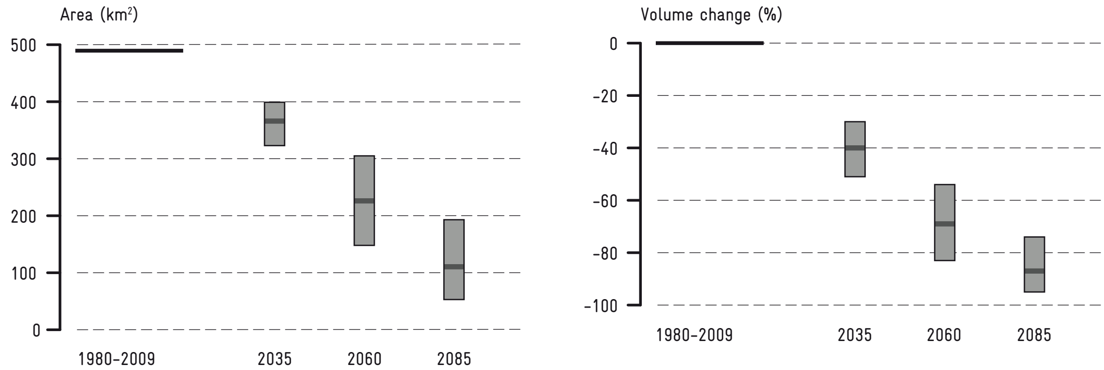

Figure 5.4: Glacier area (left) and ice volume change (right) with respect to the reference period (1980–2009) for 50 glaciers in the Swiss Alps as simulated with GERM for the greenhouse gas scenario A1B (average and range of all individual simulations).

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

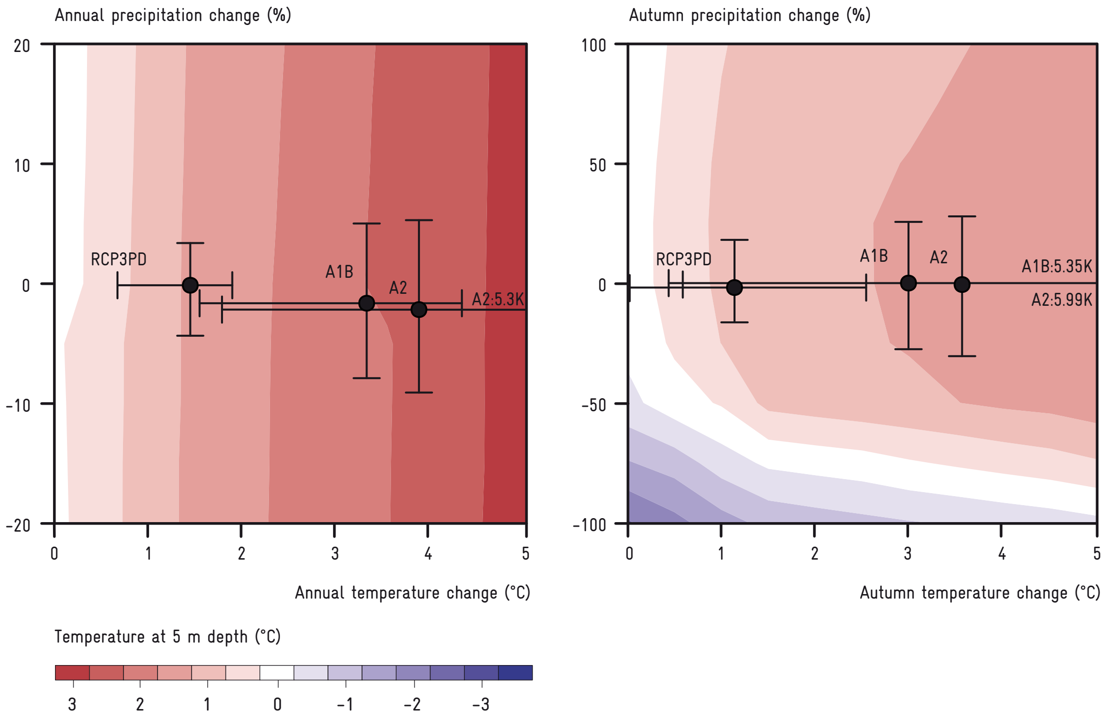

Figure 5.5: Sensitivity of simulated ground temperature at Schilthorn, Bernese Alps, to changes in surface temperature and precipitation applied over (left) the whole year and (right) the autumn months only (September–November). Panels show the difference in mean annual temperature at 5 m depth between 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).