

Climate, Glaciers and Permafrost in the Swiss Alps 2050: Scenarios, Consequences and Recommendations

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Abstract

Climate scenarios for the time horizon of 2050 in the Swiss Alps as simulated by using high-resolution ensemble modeling indicate most likely changes in temperature/precipitation by + 2°C / + 10% in winter and + 3°C / - 20% in summer. Such a development would lead to the vanishing of about 75% of the existing glacier surface and deep warming of permafrost in mountain peaks. Corresponding impacts would mainly concern rather dramatic changes in landscape appearance, slope stability and the water cycle. The formation of lakes in the forefields of retreating or even collapsing glaciers together with the decreasing stability of rock walls leads to an increasing probability of major rock falls impacting onto water bodies and triggering dangerous flood waves. A special recommendation was therefore provided to systematically assess the safety of natural, artificial and newly forming lakes in the Alps.

Keywords: climate change; cold mountains; glaciers; permafrost; slope stability.

Introduction

Climate change in cold mountain areas is faster than on global average and most strongly affects one of their most characteristic aspects – surface and subsurface ice (UNEP 2007). Increasing concentrations of greenhouse gases are likely to cause accelerating rates of change, which would lead within decades to environmental conditions far beyond historical and Holocene precedence and to commitments for the future probably lasting for centuries if not millennia. A primary challenge to cope with such a rather clearly foreseeable development is the anticipation of impacts from the reaction of complex, highly interconnected and more and more disequibrated natural systems (Watson and Haerberli 2004).

In March 2007, the Advisory Body on Climate Change created in 1996 by the Swiss Academy of Sciences on behalf of the Swiss Federal Government published a report on climate change and Switzerland for the year 2050 (OcCC 2007). Based on corresponding assessments for various sectors of the environment, the economy and the society, recommendations were prepared to the Swiss Federal Government. The present contribution deals with glaciers and permafrost in the Swiss Alps as an example of corresponding analyses and assessments relating to cold high-mountain regions at lower latitudes. It briefly summarizes the now-available knowledge basis on climate projection, glacier and permafrost changes and possibly resulting impacts. An example (Stein glacier) is provided to emphasize the importance of combined glacier/permafrost

considerations within the framework of recommendations to governmental policy makers.

Projections

Climate

Excellent data document the climate and its recent change in Switzerland. Atmospheric temperature rise during the 20th century was > 1°C and, hence, about twice the global average of 0.6°C. During the same time period, annual precipitation increased by some 8%. Due to the fact that evaporation also increased, river runoff remained more or less constant. The topography of the Alpine mountain chain only introduces relatively minor spatial variability of these changes with time.

Regional and seasonal climate change scenarios for Switzerland and the years 2030, 2050 and 2070 (Figure 1) were calculated by Frei (2004) on the basis of the results from the EU-funded PRUDENCE project (Christensen et al. 2002). Uncertainties were estimated based on the distribution of the results from 16 model chains representing different combinations of 2 emission scenarios, 4 global and 8 regional climate models. The estimates are based on the assumption that mitigation policies will only have a major influence in the second part of the 21st century and that the time horizon of 2050 could mark a transition to much more severe conditions at later stages. According to the applied scenario, temperatures will increase until 2050 with respect to 1990 by 1.8°C in winter (95% interval 0.9°C to 3.4°C)

and 2.8°C (1.4°C to 4.9°C) in summer, both, north and south of the Alps. As a result, the 0°C-isotherm will rise during winter by about 360 m (180 m to 680 m). Precipitation will increase by about 10% (-1% to +26%) in winter and decrease by about 20 % (-36% to -6%) in summer. A trend towards more frequent and intense heat waves, probably also of droughts, is expected in summertime. Cold waves in wintertime will probably decrease in number and intensity.

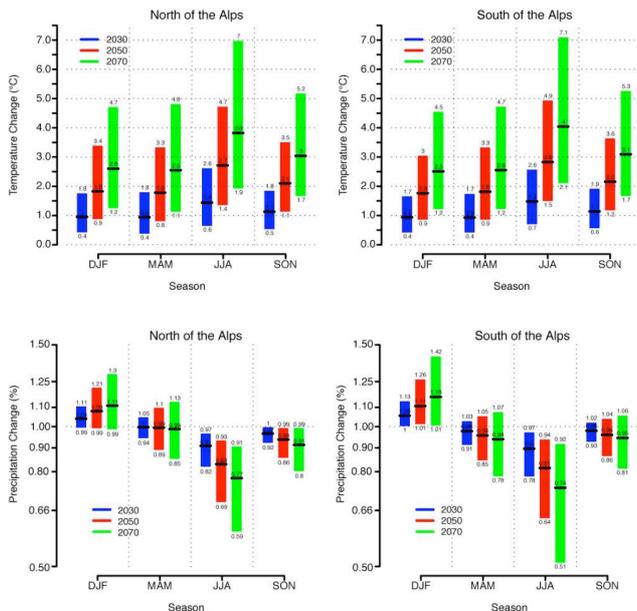


Figure 1: Seasonal climate scenarios (top: temperature, bottom: precipitation) for Switzerland and the years 2030, 2050 and 2070 for the parts north and south of the Alps (from OcCC 2007).

Glaciers

In the European Alps, a comprehensive database on glaciers and their long-term fluctuations has been built up over more than a century. This now enables the integration of in-situ measurements (length change, mass balance), remote sensing (glacier inventories), digital terrain information and numerical modeling for the entire mountain chain (Haeberli et al. 2007). The average loss in overall glacier volume was about 0.5% per year between 1850 – the end of the Little Ice Age – and 1975, then increased to about 1% per year of the remaining volume between 1975 and 2000, and since the turn of the millennium accelerated to about 2 – 3% per year. The extremely hot and dry summer of 2003 alone eliminated some 8% of the remaining ice volume. Many glaciers started to waste down or even collapse and disintegrate rather than to actively retreat (Paul et al. 2007).

Alpine-wide estimates of future glacier evolution had first been made by Haeberli and Hoelzle (1995; cf. also Maisch et al. 2000, Maisch 2001) and proved to be rather robust. The latest and most differentiated model uses statistically calibrated relations between equilibrium line altitude as

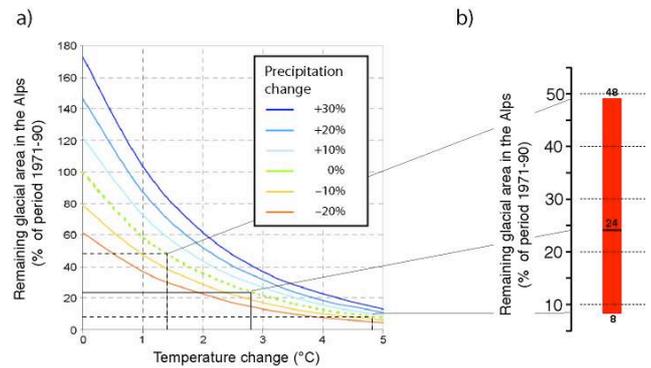


Figure 2: Glacier area in the Alps as a function of temperature and precipitation change (a) as combined with the assumed climate scenario for 2050 (b); after Zemp et al. 2006; from OcCC 2007.

measured in long-term mass balance observations, summer temperature and annual precipitation together with glacier inventory data and the SRTM3 digital elevation model (Zemp et al. 2006). Combination with the climate scenario applied for 2050 shows that the glacier surface area in the European Alps could be reduced with respect to conditions in 1971-1990 by further 75% (50% to 95%) as soon as by 2050 (Figure 2). Slightly smaller losses can be assumed for the Swiss Alps, where the largest glaciers exist. A remarkable part – roughly one third – of this anticipated development has already taken place by now (in 2007).

Permafrost

Systematic research on permafrost in the Alps only started well after World War II. First attempts to establish a long-term monitoring program began with the observation of borehole temperatures in the ice-rich debris of Murtèl rock glacier (Vonder Mühl and Haeberli 1991) and photogrammetric rock glacier monitoring (Haeberli et al. 1993). A decisive step forward was the installation of 100 m deep bedrock boreholes in the permafrost of European mountains within the Permafrost and Climate in Europe (PACE) project (Harris et al. 2003). Numerical models for estimating spatial permafrost distribution patterns in the Swiss Alps were first applied by Keller et al. (1998). Most recently, a model simulation was done at a 1:50,000 scale for the entire Swiss Alps on behalf of the Federal Office for the Environment (FOEN). Permafrost in the Swiss Alps is now known to occupy a surface area, which is roughly twice as large as the glacierized area. Its development is observed within the framework of PERMOS (Permafrost Monitoring Switzerland; Vonder Mühl et al., 2008) – one of the first networks of this kind.

Thermal conditions in commonly ice-rich permafrost in talus and moraines strongly depend on snow cover conditions and are thus difficult to predict. Because of latent heat effects, complete thawing of such frozen debris in any case takes many decades to centuries even with warming to 0°C. Permafrost evolution in bedrock of steep mountain peaks with highly complex topography is less snow-dependent. The PACE boreholes indicate surface warming during the 20th century by about 0.5 to 1°C and

corresponding thermal anomalies (heat flow reduction) down to 50 – 70 m below surface. Future scenarios can be simulated using 3-dimensional transient heat diffusion models.

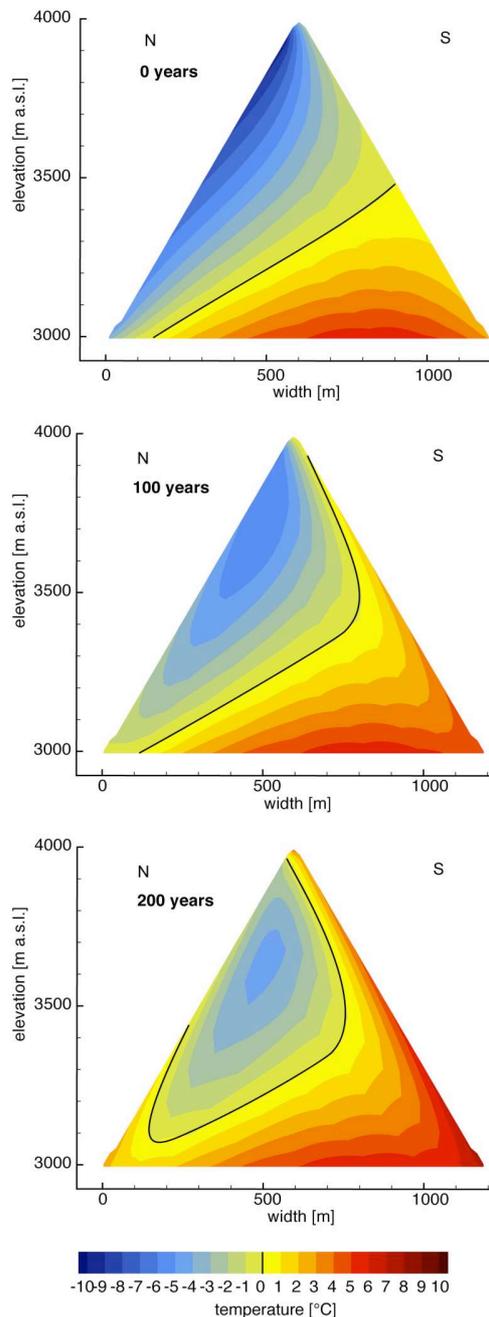


Figure 3: Model simulation (heat diffusion only) of the thermal field within a high Alpine mountain peak with realistic permafrost occurrence (from energy balance modeling), assumed centennial warming and idealized topography (after Noetzli et al. 2007; cf. OcCC 2007).

Corresponding calculations for idealized topographies (Noetzli et al. 2007) illustrate that the uppermost peaks are largely decoupled from the geothermal heat flow because of predominant lateral fluxes in strongly asymmetrical thermal

fields and that warming trends can penetrate from two or more sides (Figure 3). Due to the slow process of heat diffusion at depth, permafrost inside the mountains still persists after centuries but with warmer if not near 0°C temperatures over wide altitudinal ranges and at great depths.

Impacts

Landscape and surface processes

Rapid glacier shrinkage is among the most obvious and visible phenomena related to ongoing warming trends. Already today, the perception of high mountain landscapes is changing: the vanishing beauty of firm and ice as a symbol of an intact environment is more and more seen as a clear and easily understood indication of human-induced disturbance. In areas with a moderately humid to relatively dry climate, re-vegetation of newly exposed terrain is a slow process. For generations to come, therefore, de-glaciated high mountain chains will predominantly remain as areas of bare rock and debris without closed forests and mature soils (Egli et al. 2006). This will affect the attractiveness and touristic value of the respective landscape. Entire geo- and ecosystems as well as their individual parts have strongly different characteristics and time scales of response to fast climate change. This will undoubtedly lead to growing distances from conditions of dynamic equilibrium, which were able to form during the Holocene with its relatively stable climate.

One remarkable landscape element developing with continued atmospheric warming is the formation of new lakes with further glacier retreat and disintegration. Potential sites for future lake formation in over-deepened bed parts can be modeled by assuming constant basal shear stress along the central flow line, constant width-to-depth ratio of channel-type valley cross sections and compressive flow connected with negative bed slopes. New lakes will thus most likely form where present-day low-slope ice surfaces free of crevasses, have an enlarged width and grade into a narrower, steeper and more or less heavily crevassed part in the flow direction (Figure 4). Such lakes will be landforms of considerable attractiveness and, hence, to some degree compensate the loss in landscape attractiveness from glacier disappearance. In many instances, however, they will be situated within an over-steepened and destabilized surrounding topography with enhanced periglacial-geomorphological activity. Corresponding slope stability problems would cause hazardous situations not known from the past. One example out of the number of possibilities is outlined below.

Natural hazards

Most critical stability conditions in perennially frozen rock walls are expected to be found in areas with warm permafrost (Davis et al. 2001, Gruber and Haerberli 2007, Gruber et al. 2004, Noetzli et al. 2003). Deep long-term

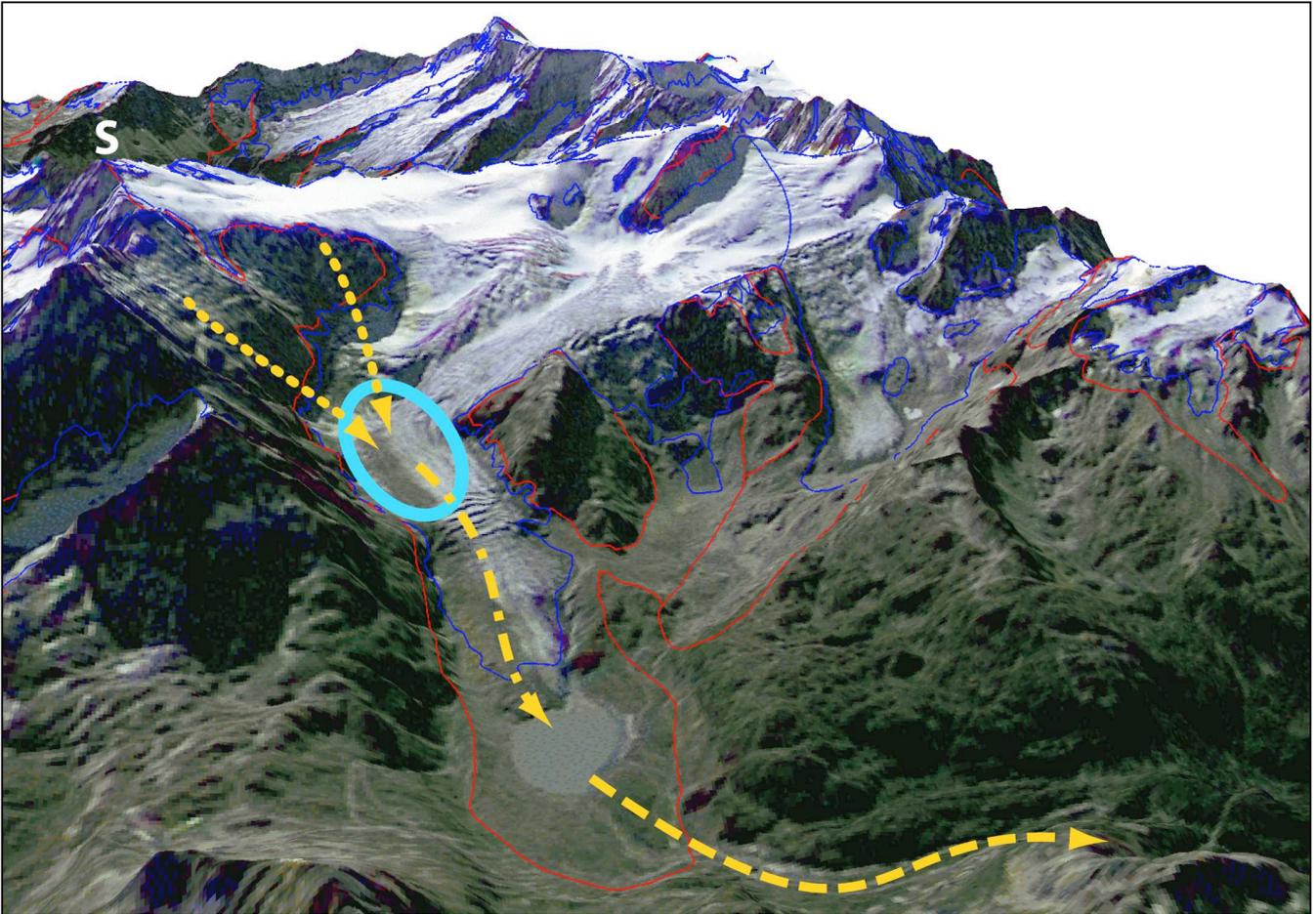


Figure 4: Modeled future development of a lake in an assumed overdeepened bed part of the Stein glacier near Sustenpass, Bernese Alps. Dotted lines indicate potential rock/ice avalanches from warming permafrost in the rock walls of Sustenhorn (S), dashed-dotted line related flood wave into the existing proglacial lake Steinsee, dashed line resulting flood wave from both lakes. Satellite image (combined SPOT/Landsat, September 1992) drawn over a DEM from swisstopo, image by F.Paul). Thin lines are former glacier margins (red 1850, blue 1973). Reproduced by permission of swisstopo (BA081042).

warming of perennially frozen mountain peaks has the potential to bring steeply inclined rock layers to critical temperatures, not only over more extended vertical ranges but also to greater depths. As a consequence, the probability of large rock falls is slowly increasing. Loss of support of steep slopes due to glacier disappearance leads to a reorientation of the stress field in adjacent slopes and further contributes to the destabilization of rock walls above newly forming lakes. The possibility of flood waves from impacts of large rock, ice, snow or mixed avalanches must, therefore, be seriously considered.

GIS-based models of trajectories from rock/ice avalanches can be applied for realistic assessments (Noetzi et al. 2006). The timing of the events, however, can involve long delays and is hardly predictable. The same is, in principle, true for debris flows, which can be triggered by intense convective summer precipitation events in so far glacier-covered starting zones with newly exposed moraine material. Examples of corresponding assessments for the Bernina group in the Upper Engadin were calculated by Rothenbühler (2006) within the framework of an integrative 4-dim-

ensional geo-information system, which was built up as a tool for environmental planning in high mountain areas. Another case of a future hazard potential from flood waves caused by rock/ice avalanches from high/steep rock walls with warming permafrost into a modeled future lake replacing the now existing glacier surface is illustrated for Steingletscher/Sustenhorn (Bernese Alps) in Figure 4.

Water cycle

As a result of climate change, the maximum in river discharge will occur earlier in the year and will be less pronounced. The combined effect of increased precipitation and 0°C -isotherms at higher elevations will lead to a growing risk of winter flooding in lowlands surrounding the Alps, because greater percentages of liquid precipitation must be expected to runoff directly instead of being temporarily stored as snow. Drier summers, on the other hand, will lead to more frequent and especially more severe droughts. With conditions like in summer 2003 (stable high pressure over central Europe during several months) becoming near average in the second part of the century, the

combination of missing precipitation, earlier snowmelt and strongly reduced melt water from disappearing glaciers could lower runoff to critical levels even in large Alpine rivers (Rhine, Rhone).

Despite the large water resources in the Alpine region, water stress could become a problem in some parts of Switzerland during the hot/dry season because of the decreasing availability of river water and its interconnection with soil humidity, water temperatures, lake/groundwater levels and aquatic ecosystems (fish, algae etc.) and the increasing demands for domestic freshwater supply, agriculture (irrigation), hydropower production, cooling of nuclear power plants or even firefighting in desiccated forests. Conflicts about water use are likely to grow and options for adaptation – for instance, redefinition of the use of reservoirs at high-altitude (irrigation and summer power production rather than winter power production) – should be investigated as early as possible.



Figure 5: Detail of the map 1:50,000 with numerically simulated permafrost distribution as compiled for the entire Swiss Alps on behalf of the Federal Office for the Environment (BAFU/FOEN). The area is the same as on Figure 4. Yellow colors indicate relatively warm/thin, violet colors relatively cold/thick permafrost.

Conclusions and recommendations

The “experiment with the global climate” has started. It cannot be stopped but only be influenced. Grave consequences for cold mountain areas are unavoidable and are already developing at accelerating rates. Corresponding

mitigation and adaptation measures must be planned. This primarily requires early and realistic anticipation of future developments and potential system reactions. The time scale to be considered involves several coming decades. As a consequence, rapid action is necessary. With modern digital terrain information, numerical and GIS-based models and satellite imagery, all necessary technical means are available.

As a follow up to the report on the climate in 2050 (OcCC 2007), a set of recommendations with respect to climate change impacts was provided to the Swiss Federal Government. Concerning Alpine glaciers and permafrost, the importance of adequate monitoring and the need for a systematic safety assessment of all existing natural and artificial lakes as well as of all newly forming lakes was emphasized. Perhaps the most important and most far reaching statement, however, relates to the rights for the use of water, an aspect which may well become a central focus of living conditions and economic development in a rather near future.

At a national level, first steps have already been undertaken. The numerically modeled 1:50,000 permafrost map of the Swiss Alps prepared on behalf of the Federal Office for the Environment (FOEN, Figure 5) greatly helps with providing transparent information to authorities and to rise public awareness. The Swiss Academy of Sciences, the Federal Office for the Environment and MeteoSuisse together now definitely established the highly developed network Permafrost Monitoring in Switzerland (PERMOS) and the glacier monitoring network is being reorganized in order to integrate modern technologies and strategies according to international climate-related observing systems (GCOS 2003, 2004).

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