Background

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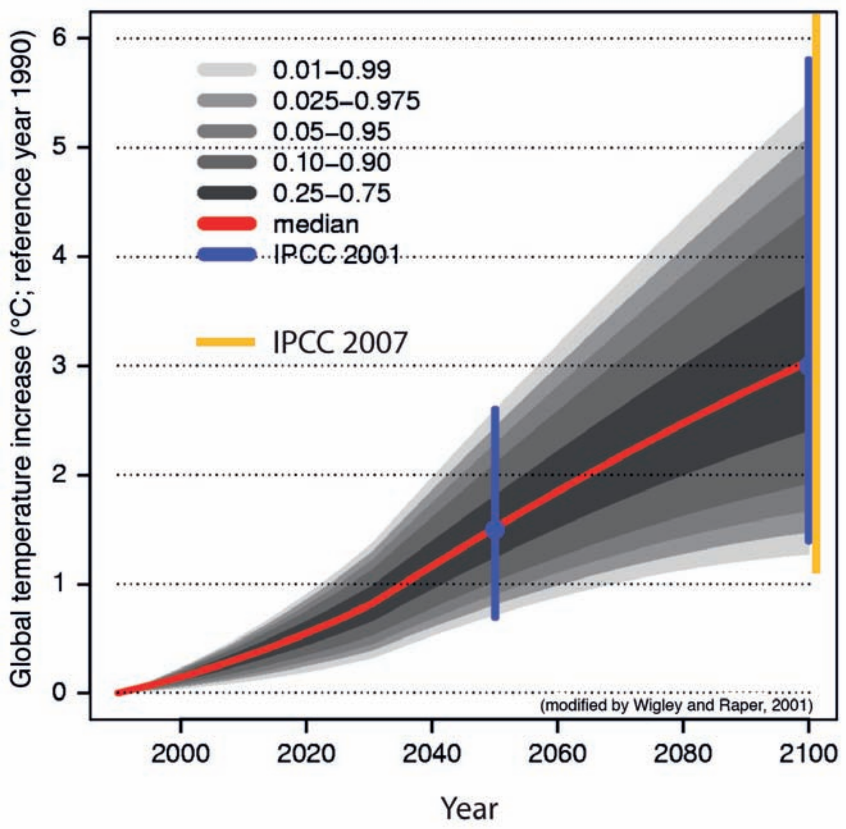

1. The future climate of Switzerland

Observed changes during the 20th century

During the 20th century, the mean global temperature increased by about 0.6 °C.[1] In Switzerland – like in other continental regions – the warming was stronger than the global average. In the 20th century, the temperature increase was about 1.6 °C in western Switzerland, about 1.3 °C in the German-speaking part of Switzerland and about 1 °C south of the Alps. North of the Alps, the frequency of abnormally warm months, that is, months with an average temperature more than 2 °C above the long-term mean, had already increased by about 70%.[2] The precipitation regime had changed as well. Annual rainfall increased by about 120 mm (8%) during the 20th century. In the northern and western part of the alpine area, mean winter precipitation increased by about 20 to 30%.[3] Heavy daily precipitation and heavy precipitation lasting between 2 to 5 days increased in autumn and winter in large parts of the midlands and the northern edge of the Alps.[4] Since evaporation rose in parallel to the warming by 105 mm (23%), the mean annual runoff remained virtually the same. At the same time, water reserves linked to glaciers decreased by about 50 cubic kilometres over 100 years. This decrease in the glacier volume contributed on average about 12 mm/a (1.2%) to the runoff.

Temperature and precipitation scenarios

In the future, climate change will accelerate. Depending on how greenhouse gas emissions develop, an increase of 0.8 to 2.4 °C in the global temperature by 2050 and 1.4 to 5.8 °C by the end of the 21st century compared to 1990 must be expected, unless drastic emission reduction measures are taken.[1,5] The water cycle will change as well (see fig. 4). However, climate change will not affect all regions in the same manner. How will the climate in Switzerland change in the future? Regional changes are distinctly more difficult to estimate because the respective surroundings (relief, distance from the sea, local wind patterns and their oscillations, etc.) have a significant impact. This report is based on a regional temperature and precipitation scenario for Switzerland.[6] The calculations of various combinations of global and regional climate models from the EU-project PRUDENCE[7] provided the basis for the calculations that enabled the uncertainties in the physical understanding of the climate system to be estimated.

In a second step, the dependency of the results on the future trend of emissions was taken into consideration. However, possible political measures to reduce greenhouse gas emissions (e.g.,

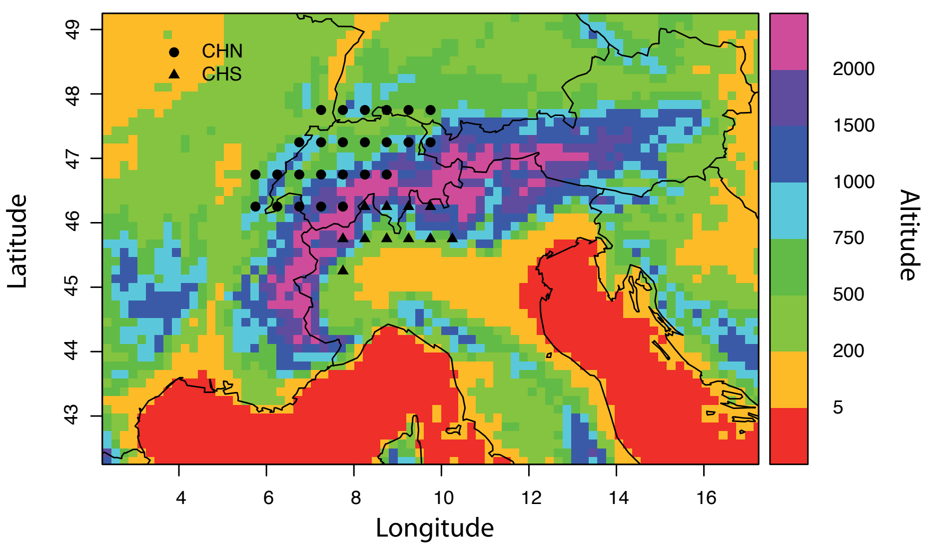

Figure 1: Representation of the grid points used for the analysis for northern (CHN) and southern (CHS) Switzerland, respectively. The topography (m a.s.l.) is shown in colour (resolution: 15 km).

the Kyoto Protocol and subsequent actions) were not included. Drastic actions to reduce emissions will not have a major impact before 2050 but will have an important influence on the development in the second half of the 21st century. The underlying data and statistical analyses are described in detail in Frei (2004)[6]. For this study, the mean values were calculated for the northern and the southern sides of the Alps (fig. 1) for the years 2030, 2050 and 2070.

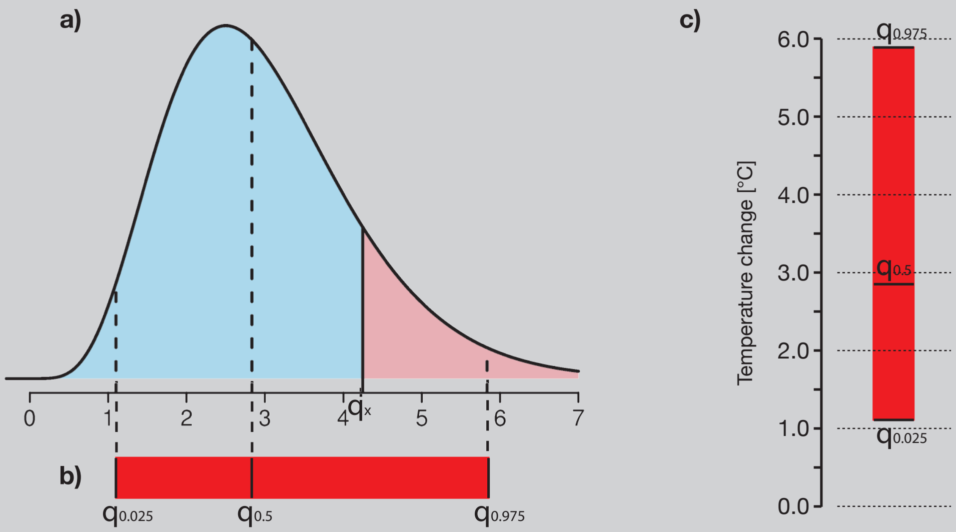

Figure 2: Schematic probability distribution using temperature change as an example (a). The distribution is characterised by the median ($q_{0.5}$) and the 95% confidence interval ($q_{0.025}$ to $q_{0.975}$) (b). In this report, the probabilistic scenarios are represented by these statistics (c).

Basis of calculation and presentation of results

The calculations from the EU project PRUDENCE served as the basis.[6] The uncertainties regarding the physical understanding (model uncertainties) were derived from the variance of the results of the 16 different model combinations for Europe. These combinations resulted from joining two medium IPCC emissions scenarios (SRES A2 and B2[7]), four different global climate models and eight different regional climate models in varying ways. The temperature values for the period 2071–2100 were scaled by means of a statistical method for the years 2030, 2050 and 2070.[6] Regarding the impact of the emission trend, the results on the regional scale were assumed to show a similar variance as the results on the global scale, based on the most important IPCC emission scenarios. The resulting uncertainties of the change may be represented as a probability distribution (fig. 2a). The value qx is the x% quantile and denotes the value of the change that will not be exceeded with a probability of x%. The median (i.e. the 50% quantile, $q_{0.5}$) divides the distribution into two areas of the same size and denotes the mean estimate of the change. The 95% confidence interval between the 2.5% and 97.5% quantile ($q_{0.025}$ to $q_{0.975}$) denotes the co-domain within which future change will occur with a probability of 95%, according to the calculations above.

The calculated distribution may therefore be represented in a simplified way by means of the quantiles 2.5%, 50% and 97.5% (fig. 2b). This report shows the distributions for the different seasons side by side as vertical bars (fig. 2c).

The availability of further model results from a current EU research project (ENSEMBLES) is likely to further improve the calculations in the near future. New findings may either reduce or enlarge the area of uncertainty. The latter may happen if, for instance, new sources of uncertainties emerge due to the detection of processes that have been so far neglected.

CH2050 Scenarios

The calculated temperature and precipitation changes for the northern and southern sides of the Alps for the years 2030, 2050 and 2070 are represented in figures 3 and 4. They show the expected future trend and make it clear that Switzerland will increasingly be exposed to faster and stronger climatic changes. Particularly in the second half of the 21st century, the process may be influenced considerably by major emission reductions. Such measures are not taken into consideration in the development depicted. Due to the inertia of the climate system, the course is already set for the coming years and decades.

The results for the year 2050 are compiled in table 1. They form the basis of this report. Until 2050, the warming will be practically the same on the northern and southern sides of the Alps. According to a middle estimate (median, see box), the temperature will increase in northern Switzerland by 1.8 °C in winter and 2.7 °C in summer, and in southern Switzerland by 1.8 °C in winter and 2.8 °C in summer. For the transitional seasons, the warming will be comparable to the warming in winter (spring: 1.8 °C on the northern and southern sides of the Alps; autumn: 2.1 °C on the northern side, 2.2 °C on the southern side).

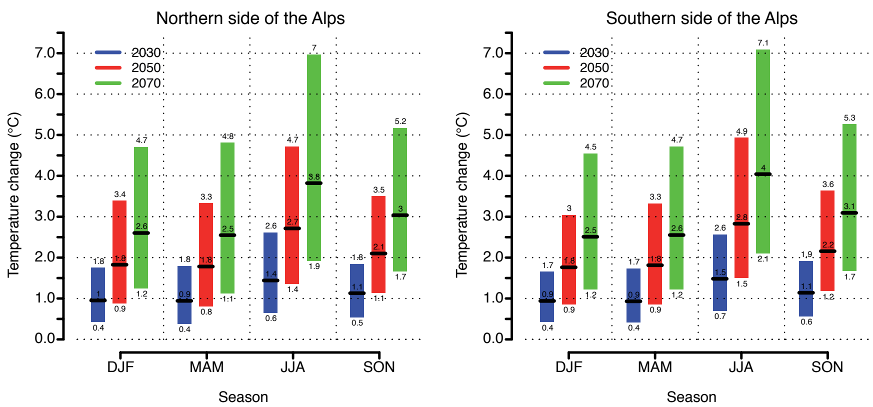

Figure 3: Change in the mean temperature in winter (DJF: December to February), spring (MAM: March to May), summer (JJA: June to August) and autumn (SON: September to November) on the northern and southern sides of the Alps in the year 2050 compared to 1990. The horizontal lines show the middle estimates (medians). There is a 95% probability that the warming will be within the coloured bars (95% confidence interval, see box).

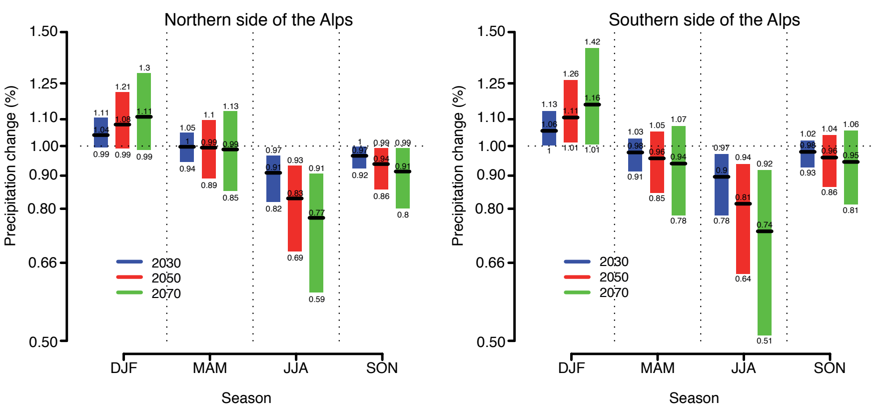

Figure 4: Relative change in the mean seasonal rainfall on the northern and southern sides of the Alps in the year 2050 compared to 1990 (logarithmic scale; for definition of seasons see fig. 3). A value of 0.50 indicates a decrease by 50%, a value of 1.25 an increase by 25% compared to today's conditions. The horizontal lines show the median. There is a 95% probability that the change in rainfall will be within the coloured bars (95% confidence interval, see box).

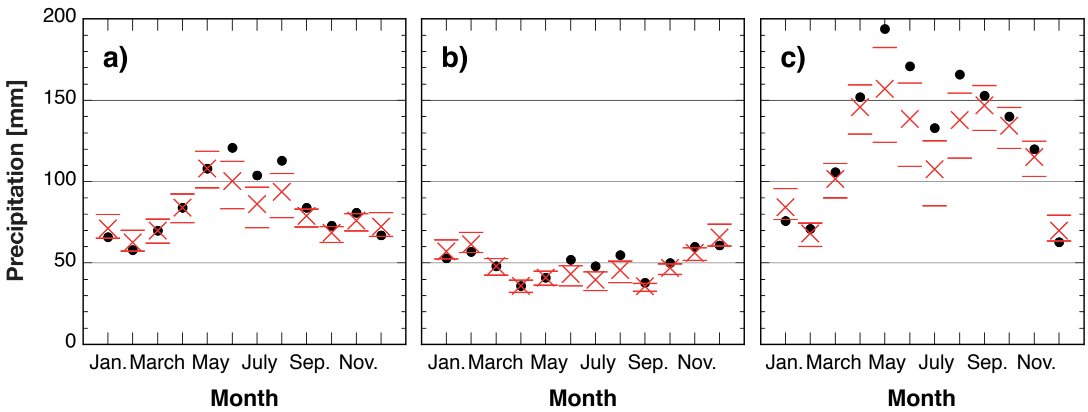

Figure 5: Monthly rainfall in a) Bern Liebefeld, b) Sion and c) Lugano today (black dots) and in 2050 (red; median and 95% confidence interval)

Table 1: Change in temperature (above) and in rainfall (below) in 2050 compared to 1990 (blue numbers: median; red numbers: 95% confidence interval). The 2050 scenario forms the basis of this report.

Region	Season	Probabilities		
		0.025	**0.5**	**0.975**
Northern Switzerland	Dec/Jan/Feb	0.9	1.8	3.4
	March/Apr/May	0.8	1.8	3.3
	June/July/Aug	1.4	2.7	4.7
	Sept/Oct/Nov	1.1	2.1	3.5
Southern Switzerland	Dec/Jan/Feb	0.9	1.8	3.1
	March/Apr/May	0.9	1.8	3.3
	June/July/Aug	1.5	2.8	4.9
	Sept/Oct/Nov	1.2	2.2	3.7

Region	Season	Probabilities		
		0.025	**0.5**	**0.975**
Northern Switzerland	Dec/Jan/Feb	-1%	+8%	+21%
	March/Apr/May	-11%	0%	+10%
	June/July/Aug	-31%	-17%	-7%
	Sept/Oct/Nov	-14%	-6%	-1%
Southern Switzerland	Dec/Jan/Feb	+1%	+11%	+26%
	March/Apr/May	-15%	-4%	+5%
	June/July/Aug	-36%	-19%	-6%
	Sept/Oct/Nov	-14%	-4%	+4%

The circumstances are also very similar for precipitation for the northern and southern sides of the Alps. The changes in the various regions differ in all seasons by only a few percent (fig. 4). On the northern side of the Alps, an increase of 8% is expected in winter (11% on the southern side) and a decrease of 17% in summer (19% on the southern side) by the middle of the 21st century. In spring and autumn, precipitation increases or decreases are possible. In summer, the area of uncertainty is particularly large.
The calculated absolute precipitation changes in Bern Liebefeld, Sion and Lugano are shown in figure 5. Generally, annual precipitation will decrease slightly (-50 mm in Bern Liebefeld, -20 mm in Sion, -150 mm in Lugano).

Assessment of changes

How can climate change be assessed? Will the climate in Bern in 2050 be like in Rome today? In order to answer this question, climate scenarios for different measuring stations of MeteoSwiss were compared to today's conditions. The comparison is complicated by the fact that temperatures and precipitation depend to a large extent on the topography, the geographical position and other local factors. For precipitation, the comparison of the stations does not result in a consistent picture and therefore makes little sense.
On the other hand, there are stations in Switzerland and abroad where today's temperature conditions match those that specific locations will experience in 2050 as a result of the warming. In a weak warming scenario, the temperatures in Zurich will resemble those of today's conditions in Sion, with medium warming they will be similar to today's conditions in Magadino, and with strong warming they will be similar to today's conditions in Torino (fig. 6). In a weak warming scenario, the temperature profile of Basel correlates well with today's profile of Grono, with medium warming with today's profile of Lugano, and with strong warming with today's profile of Verona.
However, with regard to such comparisons, one has to bear in mind that the problems of climate change are not primarily caused by the new climate state but rather by the process of change and the resulting problems of adaptation.

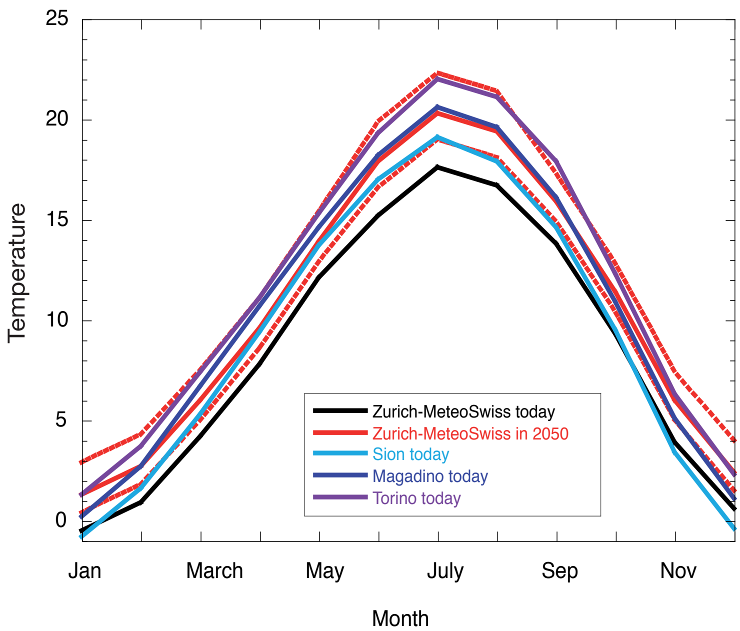

Figure 6: Comparison of MeteoSwiss temperature curves for Zurich today and in 2050, with today's temperatures in Sion, Magadino and Torino, according to weak, medium and strong warming scenarios.

2. Extreme events

Estimating the changes in extreme events is important with regard to many questions, for instance for the dimensioning of flood control structures. The climate scenario on which this study is based only makes statements about the seasonal means of temperature and precipitation and does not contain any information about the extremes. However, the changes in extreme events have been analysed in many studies. A compilation can be found in the OcCC report "Extreme Events and Climate Change".[8]
From our knowledge of the physics of meteorological processes and the climate system, it may be expected that certain extreme events will increase while others will decrease. The changes are likely to differ between regions. Today's climate models are only able to approximate the small-scale processes of extreme events. Scenarios of the trends of frequency and intensity of extreme events are therefore still very imprecise. Statistical statements about actual trends of extremes are also very difficult and only possible for a few categories of extreme events (see below).[9] The following compilation therefore discusses changes only if they are statistically significant with regard to past observations and/or if plausible evidence pointing to a trend in a certain direction exists.

Temperature extremes

Temperature extremes show the most distinct trend. With a rise in the mean summer temperature, hot spells with higher temperatures will occur (fig. 7).[2] According to climate models, the variability of mean summer temperatures will increase as well, which will also lead to more hot spells with higher temperatures.[2,10]
Climate models show a more significant increase in absolute maximum temperatures than in the mean daily maximum. According to this scenario, conditions like those of the 2003 summer heat wave will continue to occur very rarely in the case of weak warming, every few decades in the case of medium warming, and every few years in the case of strong warming (see section 3). The increase in extremely hot summers would occur even faster if, additionally, the variability of the summer climate increases, which most climate scenarios suggest as likely.
In contrast, the frequency of cold spells and the number of frost days will decline. In winter, the daily temperature variability will become smaller because minimum temperatures will rise more strongly than mean temperatures. This effect will be particularly pronounced in areas where the snow cover decreases as a result of the warming. The change in the risk of late frosts (frosts that occur after the beginning of the vegetation period) is uncertain since the vegetation period will shift with the warming as well.

Precipitation extremes

For Central Europe, new analyses show an increase in 1- to 5-day precipitation extremes in the winter half of the year.[11] The PRUDENCE models show that heavy precipitation events of a kind that occur only every 8 to 20 years nowadays, will on average occur every five years by the end of the century. The situation is less clear for the summer season. Although the models show a distinct decrease in the mean rainfall, the 5-yearly extreme value shows a slight increase.

Floods, landslides and debris flows

An increase in precipitation intensity and extremes harbours the potential for more frequent floods, landslides and mud slides. However, the actual effects on these natural hazards are also determined by other processes that are affected by climate change (soil moisture, snowmelt, runoff regime). Statements about the change of these natural hazards are therefore difficult (see Water management chapter).

Drought

In agreement with the decrease in mean rainfall and the number of rainy days, extremely dry periods will last longer and occur more frequently. The combination in decreasing rainfall and higher evaporation may result in a regional decrease of the soil water content. Furthermore, due to the decrease in snow reserves in the Alps, rivers that are fed by snowmelt in summer will more often dry up and the seasonal water sequestration in the Alps will diminish.

Storms

The frequency of storms in Central Europe will most likely decrease. At the same time, the frequency of very heavy storms (e.g., of the category of "Vivian or "Lothar") may increase. Generally, the paths of cyclones and storms will shift polewards.

3. Basic estimate of other climatic variables

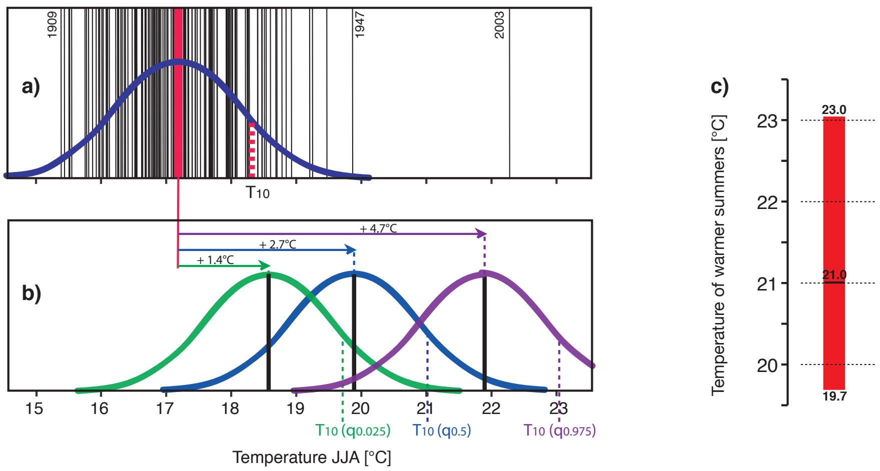

Figure 7:
a) Distribution of summer temperatures from 1864–2003, and b) in 2050.
c) The temperature of a 10-yearly hot summer also increases with climate change.

Based on the climate scenario here, basic estimates of changes in other climatic variables are possible. Following are some examples:

Hot summers

According to the climate scenario, warming will be particularly pronounced in summer. What does this mean for the temperature of hot summers?

Figure 7a shows the mean summer temperatures in the lowlands on the northern side of the Alps for the years 1964–2003. The corresponding probability distribution (blue curve) displays a mean value T_M = 17.2 °C (red line). A summer as hot as occurs on average only every ten years is warmer than T_{10} = 18.3 °C.

With climate change, the probability distribution of mean summer temperatures shifts by 2050 and the temperature of a 10-yearly hot summer increases. In 2050, every tenth summer will most probably be warmer than 21 °C. In the case of weak warming, every tenth summer will be warmer than 19.7 °C, and in the case of strong warming, warmer than 23 °C.

To simplify matters, this estimate is based on the assumption that climate change does not influence the shape of the distribution (year-to-year variability) of the summer temperatures. If the variability should increase as a result of climate change – as most climate models suggest[9,10] – the frequency of extremely hot summers would increase considerably faster and more strongly.

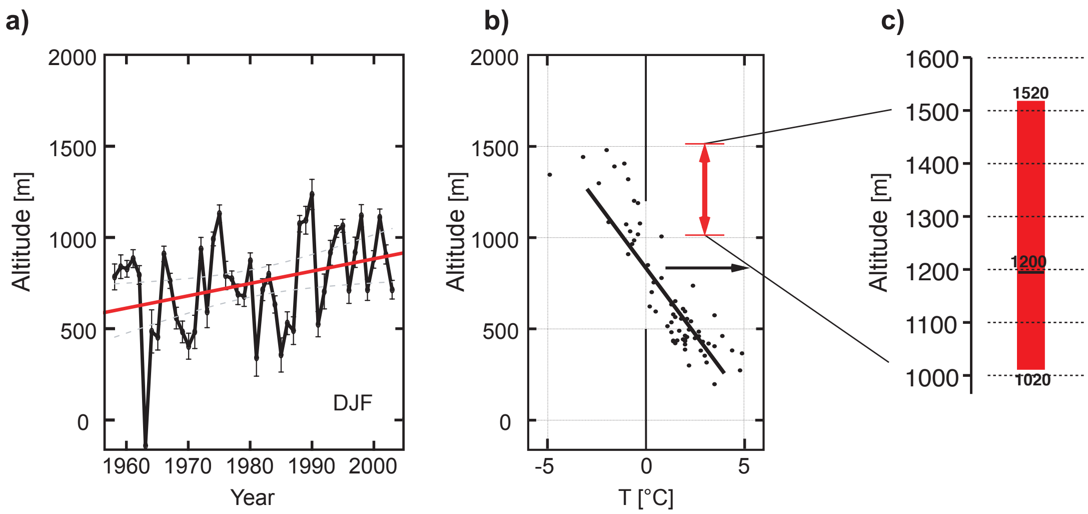

Figure 8: a) Change in the mean height of the zero degree line in the winter months (DJF) from 1958–2003. The calculation is based on 67 homogeneous ground temperature measurements. The red line shows the lineal trend, the dashed lines the corresponding uncertainty (95% confidence interval). b) Vertical distribution of average winter temperatures at MeteoSwiss measuring stations from 1959–1997. Today's zero degree line lies at ca. 840 m. a.s.l. c) By 2050, the zero degree line will have increased by ca. 360 m to 1300 m. a.s.l. (range 1020–1502 m. a.s.l.)

Zero degree line in winter

A temperature increase will result in a rise in the zero degree line in winter. This line roughly corresponds to the height of the snow line. Figure 8a shows the development of the snow line in winter for the period 1958 to 2003. In this period, the level rose from ca. 600 m in the 1960s to ca. 900 m in the 1990s (ca. 200 m per degree of warming).[12]

The vertical distribution of mean winter temperatures up to 1500 m a.s.l. is depicted in figure 8b (black dots). The regression line (black line) shows the average cooling with increasing height in winter. It cuts the 0 °C line at 840 m a.s.l., which corresponds to the mean height of the zero degree line during the observed period. If the observed rise (fig. 8a) continues in the future, the zero degree line will rise by about 360 m by 2050 in the case of medium warming (+1.8 °C in winter), by about 180 m in the case of moderate warming (+0.9 °C), and by 680 m in the case of strong warming (+3.4 °C) (fig. 8c).

Glacier retreat

The retreat of glaciers will be the most obvious change in the Alps as a result of climate change. Model calculations of the expected glacier retreat in relation to the reference period 1971–1990 are shown in figure 9.[13] They were calculated for a warming in summer between +1 and +5 °C and a change in annual rainfall between −20% and +30%.

According to the climate scenario here, by 2050, the area covered by alpine glaciers will have diminished by about three quarters in the case of medium warming (fig. 9b). In the case of a moderate warming, the loss in glacier area will be about 50% and in the case of strong warming about 90%. The relative losses will be smaller than the calculated average change for large glaciers and larger than the average for small glaciers. Many small glaciers may disappear.

Permafrost decline

The warming of permanently frozen ground in the high mountains is a slow process with long-term implications (see fig. 10). The warming described here will cause ice-rich rock faces in shady slopes between 2000 and 3000 m a.s.l. to melt, however, entire unfreezing will happen only here and there. The warming of the outer 50 meters of frozen rock faces, which has already occurred due to the temperature rise in the 20th century, will penetrate deeper and thereby cause thermal imbalance. In summit and ridge areas, such effects will be particu-

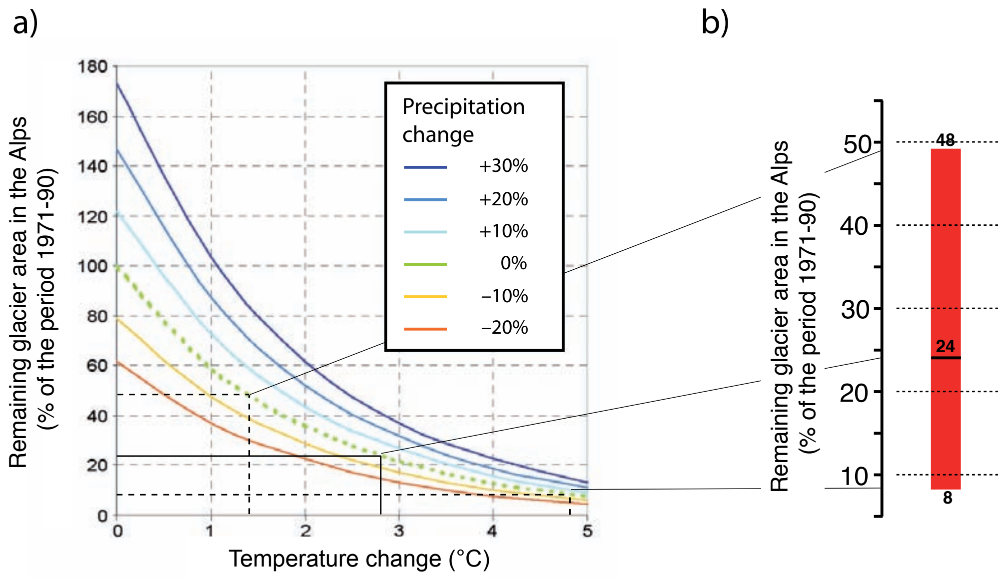

Figure 9: a) Change in alpine glaciation with an increase in summer temperature by 1 to 5 °C and a change in annual rainfall between –20% and +30%. b) According to this scenario, glaciation will decrease by about ¾ by 2050.

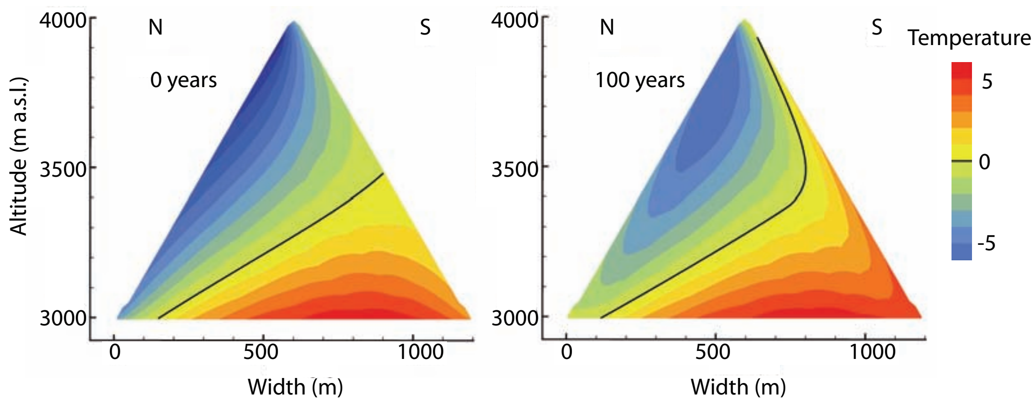

Figure 10: Warming of permafrost on an idealised summit (model calculation, thermal diffusion only).[14] Permafrost remains intact in the subsoil for a long time and can be present at places where the requisite climate conditions on the surface no longer exist. Heat penetrates from several sides into summits and ridges. As heat diffuses very slowly in the subsoil, this process takes place over centuries.

larly pronounced, since the heat can penetrate from several sides.

Rock slides

Since the mid-1980s there have been five major rock slides of more than 1 million m^3 in the Alps: Veltlin in 1987, Randa in 1991, Mont Blanc-Brenvaflanke in 1997, Thurwiserspitze/Ortler in 2004, and Eiger in 2006. The slide path sometimes reached far below the forest line (Veltlin, Randa, Mont Blanc) and all except Eiger affected tourism areas (roads, ski slopes, hiking trails). The relationship to glaciers and permafrost has been proven for three of these cases (Mont Blanc, Ortler, Eiger), in the other two it is probable (Veltlin) or likely, but uncertain (Randa).

The stability of steep rock faces in the high mountains (especially above the forest line) depends primarily on the geological characteristics, the surface slope, the previous history and the ice conditions (glacier support, ice-filled network of fissures in permafrost). Every rock slide event has a specific combination of factors. However, currently, ice conditions are changing the most quickly and are therefore considerable codetermining factors. Critical conditions result in particular from the disappearance of valley glaciers (loss of support) and from warm permafrost (ca. 0 to −1 °C: mix of rock, ice and water). With increasing glacier retreat, progressive warming of previously cold permafrost faces and more deeply penetrating thermal disruption in frozen rock faces, as well as the frequency of rock slides and the probability of large-scale incidents are likely to rise.

4. Impact of climate change on the hydrological cycle

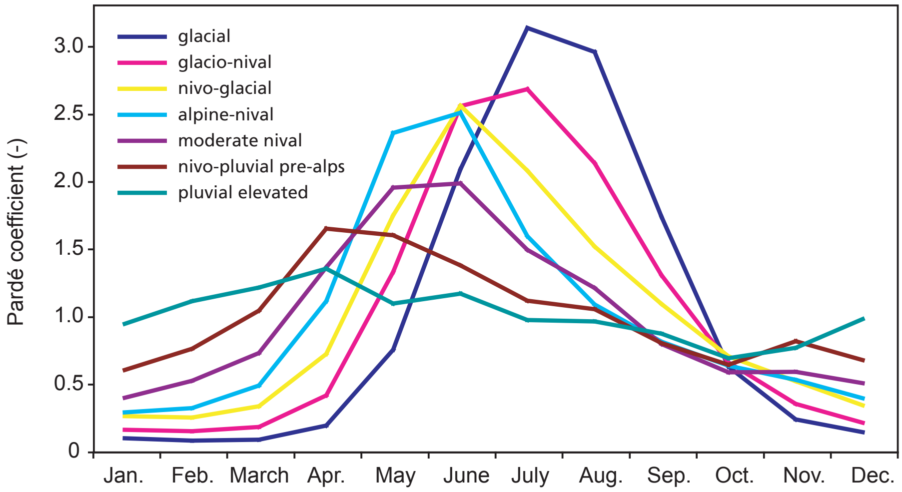

Figure 11: Mean runoff regimes of Swiss catchment areas at different altitudes. The spectrum runs from a regime mainly dependent on rainfall (pluvial, elevated, average height 800 m a.s.l.) to a regime mainly shaped by glaciers (glacial, 2700 m a.s.l.). The difference in height between the individual regimes averages 300 m. The Pardé coefficient describes the relationship between the mean monthly runoff and the mean annual runoff (glacial: shaped by glaciers; nival: shaped by snow; pluvial: shaped by rainfall).

Water resource systems – streams, rivers, small and large lakes, water in the subsoil, pores and crevices, groundwater and the large alpine water reservoirs like snow, firn and glaciers – are part of the hydrological cycle. It links atmosphere, soil, vegetation and bodies of water by evaporation and precipitation. The hydrological cycle is shaped by the climate and the actual weather, and conversely the hydrological cycle affects climate and weather – an extremely complex feedback loop. Humans interfere with this loop: Water is retained in storage lakes and reservoirs or redirected to other catchment areas, agricultural areas are extensively irrigated, wetland is drained and the groundwater level is raised or lowered.

Runoff is indirectly linked to precipitation. In the long term, with relatively steady evaporation, the runoff follows the changes in precipitation. However, only a small part of the rainfall runs off directly; the larger part is stored, for instance in snow cover and glaciers, in the ground, in the groundwater, and in natural and artificial lakes. In the short term, runoff is influenced by the release of water from the stores.

Different runoff types, showing different annual runoff patterns can be distinguished by the degree of glaciation and snow cover. A selection of runoff types is depicted in figure 11. Watercourses that are mainly fed by melting glaciers and snow (glacial type) show larger runoff variations. The mean monthly runoff can easily vary between winter and summer by a factor of 30. Watercourses that are mainly dependent on rainfall (elevated pluvial type) show the least runoff variations.

The following changes can be expected by 2050 on the basis of the climate scenario presented here:

- Less precipitation falls as snow at lower and medium elevations due to warming. The snow line, which separates snow-covered areas from lower lying areas, rises by about 360 m in the case of medium warming (see section 3).

- The frequency and intensity of flooding will increase in winter in small and medium catchment areas of the midlands. This is due to the increased prevalence of rain instead of snow at lower and medium elevations, and the rise in heavy precipitation (see section 2).

- In the case of medium warming, glacier area in the Alps will decrease by about three quarters by 2050 (see section 3, fig. 9). This simple estimate is consistent with earlier studies[15], which showed a rise in the equilibrium line of glaciers by 400 m in the case of a warming of 2.7 °C in summer.

- Evaporation will generally increase as a result of warming. Due to soil dehydration, evaporation may be locally and temporally restricted and therefore reduced.

- As a result of the decrease in precipitation volume and the increase in evaporation, annual runoff will decrease, particularly in the south, but also in the north. This will happen in spite of the temporary contribution of meltwater from the retreating glaciers. In summer, soil moisture may be reduced for extensive periods of time (particularly in late summer and autumn in the south, but also in the north). In small and medium watercourses of the midlands and the south of Ticino, dry spells will occur more frequently. In addition, dry spells may occur more often in late summer in areas where glaciers have disappeared.

- Groundwater replenishment will decrease in summer and autumn in all non-glaciated areas.

- As a consequence of the changed accumulation and degradation of the snow cover, the rise of the snow line and the retreat of the glaciers, the runoff regimes (fig. 11) at a particular altitude will shift downwards by about one regime level.

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