



The impact of climate change on snow cover and Alpine glaciers: consequences on water resources

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The Alpine Rhône illustrates how global warming could influence river flow, not only through changes in precipitation patterns but also through the effect on snow and glaciers, essential elements of the hydrological cycle in mountain regions such as the Alps. Projections of future climates, based on simulations by regional climate models, suggest an increase in winter precipitation, a sharp decrease in summer rainfall, a significantly reduced volume of snow, and a sharp decline in most alpine glaciers. As a result, by the end of the 21st century, flows are expected to be strongly influenced by these changes, with an increase in winter flows due to early snowmelt and increased precipitation, but a reduction in flows during the rest of the year. Seasonal changes imposed by a warmer climate will require a transformation of current water governance to allow for equitable sharing for the economic sectors concerned.

1. The Swiss Alps, Europe's water tower

Many of the rivers that supply Western and Central Europe originate in the Alps. The Alps in general and Switzerland in particular have often, and rightly, been called **Europe's water tower**. And for good reason, Switzerland receives an average of nearly 1500 mm of precipitation per year: one third is lost through evaporation when nearly two thirds feed streams and rivers on the surface. A small fraction is temporarily stored in lakes or groundwater.

According to the Swiss Climatological Atlas [1], the Central Swiss Alps region within a radius of 30 km around the Gotthard Pass alone irrigates four major basins. It supplies the North Sea through the Rhine basin (this basin accounts for about two thirds of all water exported by Switzerland). It supplies the Mediterranean through the Rhône basin (18% of Switzerland's water exports). It feeds the Adriatic through the Po basin (Ticino, a tributary of the Po in Italy, accounts for 10% of the flow from Switzerland). It finally feeds the Black Sea through the Inn which flows into the Danube in Germany, which represents 5% of the flows leaving Switzerland. More than 150 million people live in these different basins and depend on water originating in the central Alps.

2. The role of snow

Snow is an essential component of the mountain hydrological system. Any change in the quantity, duration and seasonality of snow cover can have lasting environmental and economic consequences [2]. The timing of snowmelt in the mountains strongly influences the **seasonal peak of flows in an alpine river**. The late melting that persists in the high mountains makes it possible to maintain a **minimum flow** even during the hot and dry periods of the year.



Figure 1. Summer break-up of a lake at Col du Grimsel, feeding the Rhône. [© M. Beniston]

Temperature and humidity regimes, strongly influenced by climate, control the behaviour of snow and ice. In the mountains, an average increase of 1°C is accompanied by an increase in the average snow limit altitude [3] of about 150 m. Beniston *et al.* have shown [4] that the **length of the snowmaking season** has tended to decrease since the 1970s in many alpine resorts, although with great year-to-year variability. This is particularly true for stations below an altitude of about 1500 m, where precipitation falls more often as rain than as snow. On the other hand, at altitudes above 2500 m, an increase in snow cover duration and depth was observed in some areas even in the 1990s, a decade in which snow became scarce at low altitudes for several seasons.

3. The effects of climate

According to climate predictions, warmer winter conditions combined with higher precipitation in the Alps will contribute to an increase in the amount of snow at high altitudes. As a corollary, they will result in a significant decrease in snow cover in low- and mid-altitude regions, where precipitation will tend to fall as rain. There could also be more rain-on-snow events, including in mid-winter. This could result in flash floods [5].

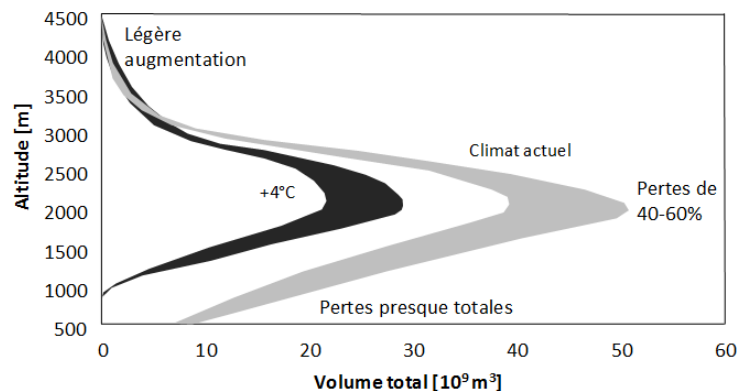


Figure 2. Altitudinal distribution of the maximum seasonal snow volume in the Swiss Alps for the current climate (grey) and a climate with winters 4°C warmer than the current climate (black). The width of the grey and black bands gives an indication of the variability of more or less dry or wet winters. [Source : Beniston et al.[4]]

The **volume of snow** is considered a key parameter of the amount of water flowing through alpine watersheds. This is defined as the product of the thickness of the snowpack and the surface area of the snow-covered terrain. Figure 2 shows how this volume, measured at its seasonal maximum, is distributed according to altitude. Below 2000 m, even if the area of the territory is larger, the amount of snow accumulated is significantly less and the volume of snow is therefore lower. On the other hand, above 2000 m, the thickness is significant, but the volume is lower because the areas concerned have smaller and smaller areas as you climb up the mountain.

According to many climate models, if winter minimum temperatures were to increase by 4°C, it is estimated that snow cover would decrease by more than 100 days in the altitude range between 1500 and 2500 m asl. The increase in winter precipitation would therefore only slightly offset the effect of temperature on snow cover. At low elevations, increased temperatures would result in almost no snow during most winters, while changes at very high elevations would be minimal.

4. What are the impacts on glaciers?

The volume of a glacier, which is reflected in its surface and thickness, is determined by the balance between snow accumulation and glacier melt. If the climate changes, this balance will change. This will disrupt the altitude of the glacier's equilibrium line, the altitude at which accumulation and ablation are in equilibrium. This will result in a change in thickness and the advance or retreat of the glacier. Most alpine glaciers except those at very high altitudes (above 3500-4000 m) have surface and internal temperatures very close to the freezing point. Therefore, any increase in temperature above this 0°C threshold can lead to a very pronounced glacier response.

Between 1850 and 2000, the glaciers of the European Alps lost between 30 and 40% of their surface area and about half of their volume [1]. A similar finding has been made on many mountain glaciers around the world, both in mid-latitudes and in the tropics.

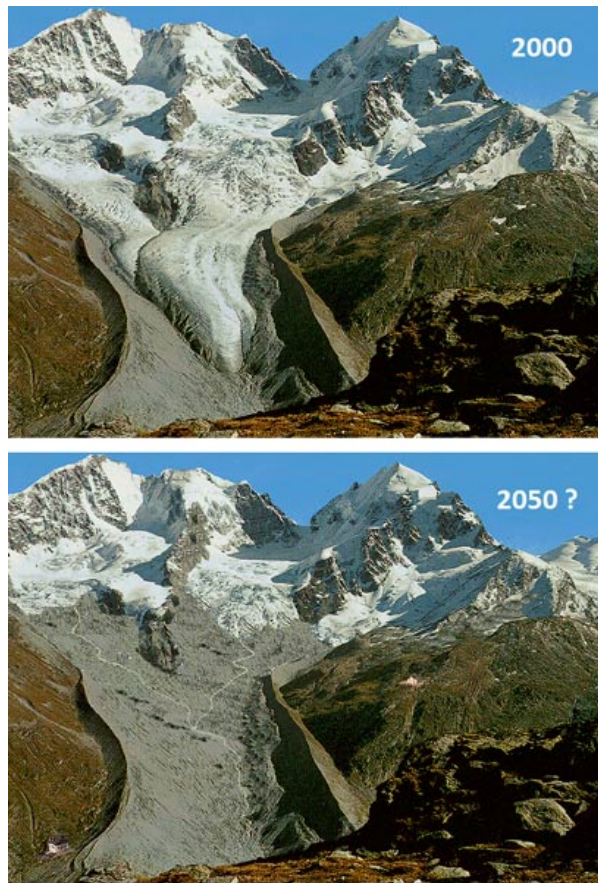


Figure 3. Views of the Tschierva glacier (Bernina Massif, south-eastern Switzerland) in 2000, and as it would appear in 2050 according to forecasts following a warming of +3°C. [Source : Computer graphics and GIS applications: Max Maisch, University of Zurich, Switzerland]

Numerous studies [6] [7] [8] [9] on the future behaviour of alpine glaciers have been published. Whether based on empirical models or more detailed energy balance models, their conclusions converge: they indicate that **50 to 90% of existing mountain glaciers could disappear** by 2100 depending on the extent of future global warming [1]. The smaller the glacier, the faster it will react to changes in climate. For most mountain glaciers in temperate regions of the globe, researchers establish that the altitude of the equilibrium boundary of the glacier increases strongly and linearly with temperature. Conversely, this altitude also decreases linearly as precipitation increases, better feeding the glacier at higher elevations.

Assuming a warming of +3°C by the second half of the 21st century, Maisch [10] calculated for several glaciers in the Swiss Alps the future altitude of the equilibrium line (i.e. the transition level between the ablation and accumulation zones of the ice). Using computer-generated images and Geographic Information Systems (GIS) techniques, he was able to highlight the future morphology of the glaciers, their volume, and the position of their frontal tongue, as in the case of the Tshierva glacier (Bernina massif) in south-eastern Switzerland (Figure 3).

5. What are the consequences on the flow rates of the Alpine Rhône?

For a river like the Rhone, flows and their interannual variability are influenced by evaporation, precipitation, storage of water in artificial reservoirs and melting snow and ice. Precipitation throughout the year, as well as snow and ice melting areas between May and October, contribute mainly to flows in the alpine part of the Rhône basin [11] [12] [13]. In addition, the use of hydropower modulates **flows in the Rhône** in certain seasons and sometimes significantly: water is retained, especially during summer and autumn during snowmelt and summer melting of glaciers, and released to produce electricity, especially during winter when energy demand is at its highest. However, this water retained by dams represents only a small fraction of the total quantities of water at stake in the Rhône basin

The snowpack in the mountains is a much larger water supply. It is retained between November and May, while evaporation reaches its maximum during the summer months. Since, in the current climate, precipitation is relatively well distributed throughout the year, it is the melting of the snowpack that has the greatest influence on flows during the year. This surface runoff in late spring and part of summer is a function of the amount of snow accumulated in the mountains during the previous winter.

Whatever the nature of the change in the hydrological characteristics of many rivers with their source in the Swiss Alps, changes in mountain climate patterns will have an impact on the regions with low altitude populations. These depend on water resources

from the Alps for their domestic, agricultural, energy and industrial uses. For example, according to various studies mentioned above, the Rhône, at its alpine outlet in Lake Geneva, could see its winter flows increase from 100 m³/s in the reference climate (1961-1990 period) to 200 m³/s by 2100, but decrease from 350 to 200 m³/s in the middle of summer (see Figure 4).

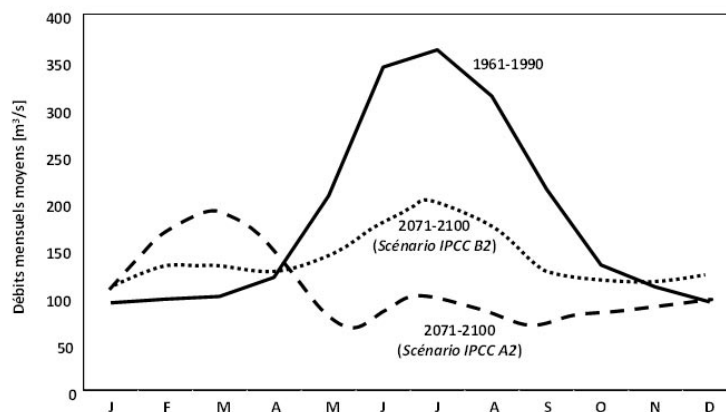


Figure 4. Possible changes in monthly Rhône flows at the entrance to Lake Geneva (Porte du Scex) between the 1961-1990 reference climate and for two IPCC emission scenarios: B2, moderate; A2, strong. [Source: according to Beniston[11]].

Figure 4 shows the average monthly flows of the Rhône for the years 1961 to 1990 and their evolution under two climate change scenarios from the work of the Intergovernmental Panel on Climate Change (IPCC): the "A2" scenario (high greenhouse gas emissions leading by 2100 to a global warming of 4 to 5°C compared to pre-industrial values), and the "B2" scenario corresponding to a warming of 2°C, considered as the limit not to be exceeded, recommended in the Paris COP-21 Agreement, 2015.

This figure shows that, for the 1961-1990 reference period, the flow of the Rhône is strongly influenced by the melting of the snowpack between spring and mid-summer, whereas after this melting and during the generally hottest and driest period of summer (between mid-July and early September), it is the flows linked to the summer melting of glaciers that continue to provide significant quantities of water in the Rhône.

What about flow forecasts according to climate change? By the end of the 21st century, **profound changes** are expected in the flows of the alpine part of the Rhône. Indeed, **climate model projections** [14] suggest that the central Alps will experience atmospheric warming in all seasons, but a seasonal shift in precipitation patterns, with a 10-20% increase in winter precipitation and a 10-40% decrease in summer rainfall [9].

Since glaciers are likely to have almost completely disappeared by the end of the century [1], there will no longer be this essential water supply which, in the current climate, serves to avoid **severe low water levels**. In a situation of high heat waves and significant water deficits, as in 2003, it is even possible that a river like the Rhône may dry up during part of the summer and autumn. For, unlike what happened in 2003 in Western and Central Europe, where an accelerated melting of glaciers has maintained a good flow in the Rhône despite the heat and drought, the glaciers would no longer be there to provide this relay. The future hydrological characteristics illustrated in Figure 4 are not unlike those already observed in the Mediterranean parts of the Alps, such as the Provençal Alps or the Italian slopes of the Alpine massifs.

Under the selected greenhouse gas emission scenario, maximum flows could occur two to three months earlier in the year due to earlier melting of the snowpack, while the maximum amount of water would be reduced because the total volume of the snowpack would be severely restricted by 2100. Despite the sharp decrease in flows during the summer (around 50 to 75% compared to the 1961-1990 reference curve), Figure 4 shows a slight peak in flow in mid-summer. This is due to convective rains that would appear from time to time despite the likely decrease in global summer precipitation. But we also note [15] [16] that even with some heavy rainfall in summer, the hydrological regimes of the Rhône will be much weaker than at present because of the virtual disappearance of alpine glaciers, as well as earlier snowmelt.

6. What are the environmental and economic impacts?



Figure 5. Irrigation is traditionally used in the central Valais, one of the driest regions in this part of Europe because of the effect of the barriers of the Valaisan Alps in the south and Bernese in the north. [Source : Photo by Kecko, via Flickr]

In the future, it will be important to recognize that a **new water management** will not be limited to a simple adjustment to changes in the natural environment. It will also have to take into account socio-economic changes where water use tends to increase and where economic and political changes are able to modify its allocation between the different economic actors in a given region. They will be tempted to compete for a scarce resource at certain critical times of the year [17] [18]. These hydrological changes could have an impact on some key sectors of the Alpine economy (*see the final report of the European project "ACQWA": www.acqwa.ch*), in particular tourism, agriculture and hydro-energy [19] [20] [21] :

The multiplication of winters with little snow will cause economic problems for low- and mid-altitude resorts (up to around 1,200-1,800 metres above sea level). A diversification of the tourist offer beyond the ski industry will be necessary for most alpine mountain resorts.

In areas where agricultural irrigation is practiced (e.g. in the Rhône Plain of the Canton of Valais in Switzerland, and in the South of France), the demand for water could exceed the resources during very hot and dry summers. In addition, mountain farming is increasingly under pressure due to agricultural production at more competitive prices in lowland regions. It is likely to cause serious damage if, in addition to these economic pressures, extreme events such as droughts or floods were to increase. New regulations on the allocation of water resources to different users, the installation of new reservoirs, and technical improvements will have to be put in place.

The large Alpine dams will be affected by the expected strong retreat of glaciers from the second half of the 21st century, as meltwater no longer fills the reservoirs as much as it does now. As a result, storage capacities could be reduced, resulting in a decrease in hydroelectric production. This will make it difficult to meet electricity demand, which will gradually shift from winter (peak energy demand) to summer due to air conditioning requirements. This will require optimal water management in the interconnected network of large dams, as well as economic mechanisms to influence supply and demand. This could challenge various strategies, both Swiss and European, to reduce dependence on fossil fuels in order to accelerate the implementation of the Paris Climate Agreement (COP21), signed in December 2015 and since then ratified by many countries. This would also affect the electricity grid not only in the Alps, where the problem originates, but also throughout Europe.



Figure 6. The Emosson dam, the second largest dam in Switzerland by capacity, 227 million m. [© M. Beniston]

Beyond these key sectors, changes in land use have generated changes in water supply and demand [22] over decades due to increasing urbanization and new land uses for agriculture. Thus, the crucial role of alpine forests, which protects against erosion and contributes to surface water quality, could also be threatened by a redistribution of alpine vegetation linked to changes in climate regimes [23] [24]. If the vegetation and forest cover were to become more scattered, surface runoff would accelerate, increasing the risk of erosion and sediment loading into the watercourses. This would create additional risks for infrastructure, such as downstream hydroelectric facilities.

Finally, in terms of **natural hazards** in the Alps, the cumulative effect of heavy rainfall in low- and mid-altitude regions would lead to high rates of slope erosion. The expected increase in extreme precipitation is expected to lead to an increase in flood frequency and severity [25]. When these events occur in late summer, when soils are dry and have difficulty absorbing large and sudden amounts of surface water, many watersheds respond by overflowing. At other times of the year, flooding potential may also increase when precipitation, combined with snowmelt during winter and early spring, releases unusual amounts of water. This kind of situation has prevailed in the recent past, for example in February 1995 when the early melting of the snowpack in the Alps, combined with heavy rains in Germany, led to flooding along the Rhine route.

References and notes

Cover image. The Rhone glacier [Source: Beniston]

Note: this text is based on extensive extracts from Chapter 8 of Martin Beniston's book ("Climate Change and Impacts: From Global to Local", 2012), reproduced with the kind permission of Presses Polytechniques et Universitaires Romandes in Lausanne, Switzerland

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