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# Impacts of climatic change on water and associated economic activities in the Swiss Alps

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## SUMMARY

The European Alps are one region of the world where climate-driven changes are already perceptible, as exemplified by the general retreat of mountain glaciers over past decades. Temperatures have risen by up to 2 °C since 1900 particularly at high elevations, a rate that is roughly three times the global-average 20th century warming. Regional climate models suggest that by 2100, winters in Switzerland may warm by 3–5 °C and summers by 6–7 °C according to greenhouse-gas emissions scenarios, while precipitation is projected to increase in winter and sharply decrease in summer. The impacts of these levels of climatic change will affect both the natural environment and a number of economic activities. Alpine glaciers may lose between 50% and 90% of their current volume and the average snowline will rise by 150 m for each degree of warming. Hydrological systems will respond in quantity and seasonality to changing precipitation patterns and to the timing of snow-melt in the Alps, with a greater risk of flooding during the spring and droughts in summer and fall. The direct and indirect impacts of a warming climate will affect key economic sectors such as tourism, hydropower, agriculture and the insurance industry that will be confronted to more frequent natural disasters. This paper will thus provide an overview of the current state of knowledge on climatic change and its impacts on the Alpine world.

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## 1. Introduction

This paper is a contribution to a special issue of the Journal of Hydrology based on the Hydrology Conference 2010 in San Diego (October 11–14, 2010). Its aim is to report on various physical and socio-economic aspects of climate impacts on water regimes in the Alpine part of the Rhône river in Switzerland on the basis of existing knowledge and emerging results from the European large integrating project “ACQWA” (see below) initiated and coordinated by the author. As such, this contribution should not be viewed as a research article *per se* but more as an attempt to highlight some of the issues that are emerging from increasingly-accurate projections of changes in the determinants of the hydrological cycle in a warming climate, the impacts that these changes will exert on a number of key economic sectors in the region, and the possible implications for improved water governance to avert possible rivalries between economic actors. By providing a succinct overview of these issues, the paper thus seeks to emphasize the complex interlinks between the natural sciences and the social and economic sciences.

As the evidence for human induced climate change becomes clearer, so too does the realization that its effects will have a range

of impacts on socio-economic systems and important elements of the environment such as water. Some regions are likely to be more vulnerable than others, both to expected physical changes and to the consequences they will have for ways of life. Mountains are recognized as particularly sensitive physical environments where climatic change would considerably influence the runoff regime of the rivers downstream and the related water availability. Increasing evidence of glacier retreat, permafrost reduction and snowfall decrease have been observed in many mountain regions, with consequent alterations of stream-flow regimes. If these trends accelerate in the future, they would in turn threaten the availability of water resources, increase downstream landslide and flood risk, and impact hydropower generation, agriculture, forestry, tourism and aquatic ecosystems. As a consequence, socio-economic structures of populations living downstream would also be impacted, calling for better preparedness and improved water governance.

Regional climate models have over the past decade provided the essential information on shifting precipitation and temperature patterns, while snow, ice, hydrological models and biosphere models are now beginning to allow coupled system approaches in order to assess the changes in basin hydrology and seasonality, amount, and incidence of extreme events in various catchment areas.

A major EU project (ACQWA: Assessing Climate change impacts on the quality and quantity of water, Framework Programme 7, contract 212250; [www.acqwa.ch](http://www.acqwa.ch)), coordinated by the Institute of

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Environmental Sciences at the University of Geneva, is currently underway (duration: from October 2008–September 2013) to investigate not only the physical response of mountain hydrological systems, but also the environmental and socio-economic responses to changes in water availability. This involves focusing on a range of impacts, such as natural hazards, aquatic ecosystems, hydropower, tourism, agriculture, and the health implications of changing water quality. Attention is also being devoted to the interactions between land-use/land cover changes, and changing or conflicting water resource demands. Integration of the information from all these sectors and the impacts on economies will ultimately provide the basis for EU-wide decision making in terms of water supply and demand.

While the ACQWA project focuses on several river basins in the Alps, the Andes in Chile, and Argentina, and the mountains of Central Asia, the present paper will look primarily at the Rhone river in its Alpine setting within Switzerland (see Fig. 1). Indeed, the Rhone represents an excellent and “test ground” for model investigations, where different methodological approaches converge to the basin scale through appropriate up- or down-scaling techniques. The Rhone catchment constitutes an ideal case-study region, because it includes all the elements of the natural environment to be modelled (snow, ice, vegetation, hydrology). At the same time, it is highly regulated, with water uptake for hydropower, irrigated agriculture, and tourism activities in the context of a climate that is at the borderline between Mediterranean and continental, thus, as shown *inter alia* by Beniston (2000), particularly vulnerable to climatic change.

## 2. Methodology, modelling sub-components of river basin response to climatic change

Within the European Union project PRUDENCE (Christensen *et al.*, 2002), a suite of regional climate models have been applied to the investigation of climatic change over Europe for both the baseline reference climate (1961–1990) and the last 30 years of the 21st century, enabling an insight into possible changes in the extremes of temperature by 2100.

One technique that was pioneered in the early 1990s and refined by Giorgi and Mearns (1999) and has since become commonplace in the climate modelling arena is that of “nested modelling”. This technique was initially used to address the problems related to insufficient grid resolution in Global Climate Models (GCMs), in order to enhance climate information over particular regions and to provide climate data at an appropriate resolution for impacts studies, for example. In the original procedure, results from a GCM are used as initial and boundary conditions for regional climate models (RCMs) that operate at much higher resolution and with generally more detailed physical parameterizations. A regional model can thus be considered to be an “intelligent interpolator” that can help fill whatever data gaps require attention, since it is based on the physical mechanisms governing climatic processes and serves to enhance the regional detail lacking in Global Climate Models.

When analyzing the results for temperature in Europe, the different RCM simulations broadly agree on the magnitude of change in mean, maximum, and minimum temperatures; Deque *et al.* (2005) have highlighted the clustering of model results that constitutes one measure of the uncertainty or reliability of the regional-scale simulations. Precipitation, on the other hand, is a more complex variable to compute, because it is generally related to processes that take place at scales smaller than the grid-mesh of even a fine-scale climate model. The precision of precipitation estimates is thus highly sensitive to the parametric scheme used and to the manner in which surface-atmosphere interactions are taken into account (e.g., the representation of land-use, soil moisture, topography, etc.).

Recent studies of changes in temperature and rainfall regimes (e.g., those reported by EU projects such as “PRUDENCE” – <http://prudence.dmi.dk>) have shown that quite a number of models exhibit genuine skill in reproducing observed precipitation and even the complex precipitation characteristic of complex topography as in the Alps. The HIRHAM regional climate model (RCM) of the Danish Meteorological Institute (Christensen *et al.*, 1998) is one such model whose results correspond well with those of the other RCMs used in PRUDENCE. Furthermore, simulations of the reference climate period 1961–1990 has shown that HIRHAM exhibits

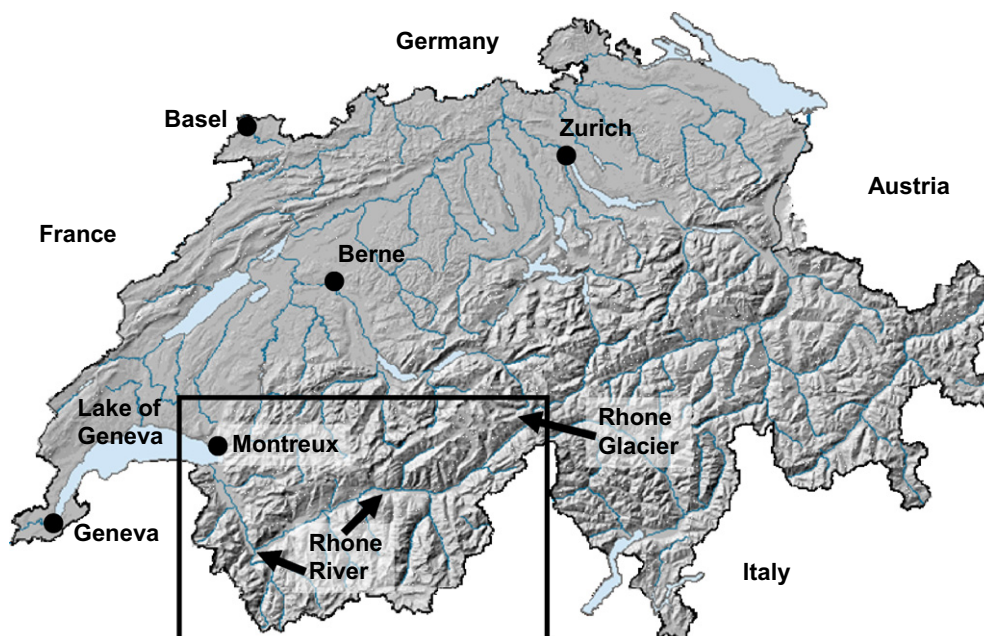


Fig. 1. Map of Switzerland showing the geographical location of the upper course of the Rhone river, from its source in the Rhone Glacier to the Lake of Geneva near Montreux.

skill in reproducing contemporary climate particularly in the Alps, thereby providing some confidence as to its capability for simulating the mean and extreme characteristics of Alpine climate into the future (see *inter alia* Beniston et al., 2007).

### 3. Climatic change

RCM simulations undertaken in the context of the aforementioned EU projects suggest that southern and central Europe will experience generally less precipitation than today, but northern Europe may gain in moisture. Christensen and Christensen (2003) have shown that in northern Europe, there is likely to be more precipitation on average, while in a large band stretching from France to the Black Sea and beyond, summer precipitation is projected to diminish by as much as 40%. Simultaneously, RCM results point to a strong increase of short-lived but very intense precipitation events in certain regions that are already prone to such hazards today, such as the river systems of central Europe.

Increased flood hazard is likely to affect many parts of Europe as a consequence, both because of higher overall precipitation in northern Europe or because river catchments may respond to short-lived but very high intensity events. When these occur towards the end of the summer, at a time where soils are dry and have difficulty in absorbing abrupt and large quantities of water at the surface, flood risk is significantly enhanced. At other times of the year, flood potential can also increase when precipitation, associated with snow-melt during the winter or early spring, discharges unusual amounts of water that cannot be absorbed by the river catchments. Such situations have prevailed in a recent past along the entire course of the Rhine river basin, as in the late winter of 1995 for example.

In the Swiss Alps, RCM results show fairly consistent trends in both temperature and precipitation by 2100. For example, Fig. 2 (Beniston, 2008) shows the future course of minimum and maximum temperatures in Montreux (located at the eastern end of the Lake of Geneva, close to the mouth of the Rhone as it enters into the Lake), compared to the observed climate record since 1931. The gray shading corresponds to the 95% range of variability for the reference time frame. Any part of the curve outside of the shaded zone can be considered to depart significantly, in statistical terms at the 95% confidence level, from the normal range of variability. In the past 75 years, winter minima have risen from about  $-0.5^{\circ}\text{C}$  in the 1930s to  $+1.8^{\circ}\text{C}$  in the 1990s, i.e., an increase of more than  $2^{\circ}\text{C}$  that is substantially more than the global-average warming of about  $0.7^{\circ}\text{C}$  in the same period (e.g., IPCC, 2007). The maximum summer temperatures (averaged for June–July–Au-

gust) shown in the lower left hand segment of Fig. 2 do not mimic the minimum winter temperature trends, but nevertheless have risen by about  $1.3^{\circ}\text{C}$  since the coldest part of the record in the 1960s. In the scenario climate, average 30-year temperatures (2071–2100) rise by close to  $4^{\circ}\text{C}$  in winter and by over  $6^{\circ}\text{C}$  in summer compared to the baseline climate (1961–1990). The stronger summertime warming can be largely attributed to reduced cloudiness in summer and greater soil-moisture deficits (e.g., Seneviratne et al., 2006) than under current climates because of the reductions in precipitation in all seasons other than winter, as discussed below. Fig. 3 shows the possible seasonal change in precipitation between scenario and baseline climate in this region, with a substantial rise of wintertime precipitation but significantly-curtailed summertime rainfall. This graph shows the results of four RCM model results undertaken in the framework of the EU-PRUDENCE project; while the absolute projections of seasonal precipitation change vary from one model to another, the sign of change is consistent between models, as discussed by Beniston (2006).

Snow is an essential component of mountain hydrological systems, and any changes in the amount, duration, and timing of the snow-pack can have long-lasting environmental and economic consequences. Snow determines the timing of peak river discharge during the melting of the snow-pack in the spring and, in many instances, maintains river flows even during warm and dry summer periods. The timing of snow-melt is also a major determinant for initiating the vegetation cycle of many Alpine plant species (Keller and Körner, 2003). Furthermore, snow is intimately linked to winter tourism, which numerous mountain resorts depend upon for a substantial part of their income (Abegg and Froesch, 1994; Beniston, 2003).

The two principal determinants of snow and ice are temperature and precipitation. As climate changes, subsequently modifying temperature distributions and precipitation patterns, so does snow amount and duration. In mountain regions, an average rise of  $1^{\circ}\text{C}$  is accompanied by a general rise of about 150 m in the altitude of the snowline (Haeberli and Beniston, 1998). Beniston et al. (2003) have shown that the length of the snow season has tended to decrease at many locations in the Alps since the early 1970s, with, however, high inter-annual variability. This is particularly the case for elevations below about 1500 m above sea level (asl) where precipitation falls more in the form of rain than in the form of snow. In contrast, however, at altitudes above 2500 m asl, snow amount and duration has actually been observed to increase in some parts of the Alps.

In a scenario climate, warmer conditions associated with enhanced precipitation in the Alps are likely to lead to more abundant snowfall in the higher reaches of the mountains, but much

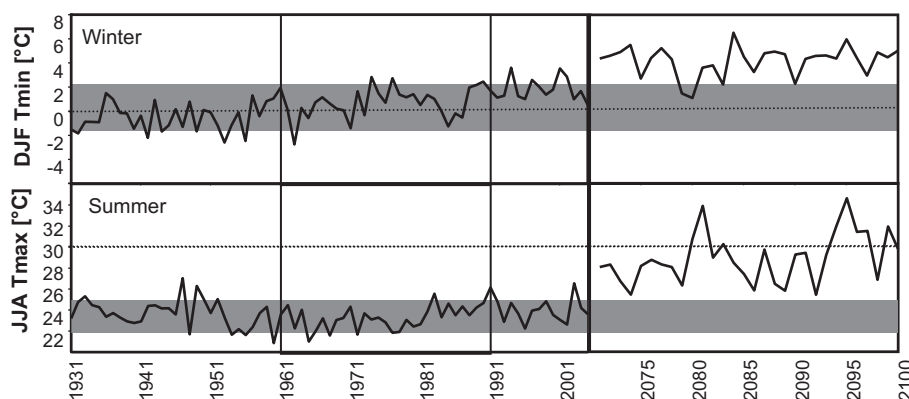
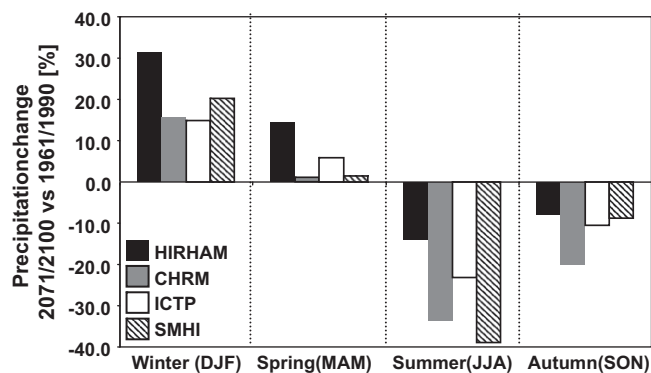


Fig. 2. Observed (1931–2005) and simulated (2071–2100, IPCC A2 emissions scenario) winter (December–January–February, or DJF) minimum and summer (June–July–August, or JJA) maximum temperatures in Montreux, Switzerland. The shaded zone highlights the 95% range of variability for the 1961–1990 observed baseline climate.





**Fig. 3.** Seasonal changes in mean precipitation in the source region of the Rhone river in the central Swiss Alps. The graph shows the percentage change with respect to the 1961–1990 precipitation levels, for 2071–2100 (IPCC A2 emissions scenario). Four different regional climate model realizations used in the framework of the EU-PRUDENCE project are provided to illustrate the inter-model variability, but also the general agreement between models with respect to the sign of change. HIRHAM: Danish Meteorological Institute RCM; CHRM: ETH-Zurich Swiss high-resolution model; ICTP: International Center for Theoretical Physics (Trieste, Italy), RegCM3 model; SMHI: Swedish Meteorological and Hydrological Institute RCM.

reduced snow at lower levels where precipitation is more likely to fall in the form of rain. Beniston et al. (2003) have shown that the crossover level where snow becomes more abundant under milder conditions is located between 1700 and 2000 m above sea level. The same study suggests a dominant influence of temperature on snow duration compared to precipitation, with small shifts in mean winter temperature leading to substantial changes in the length of the season.

In terms of snow volume, which is a key snow-related variable for assessing peak flow from snow-melt in river systems originating in the Alps, Beniston et al. (2003) have computed the shift between current and future values (Fig. 4). The shape of the curve reaches a maximum at about 2000 m asl, and represents the combination of snow depth and surface area that yields the greatest volume of snow. Below that level, even though the surface area considered is greater, the amount of snow that accumulates during the season is much less, and thus the snow-pack volume is reduced. Conversely, above 2000 m, even if the total snow accumulation is greater, the volume is lower because deep snow accumulates on increasingly smaller surface areas. For an increase of mean winter minimum temperatures of 4 °C, it is estimated that snow duration will be reduced by more than 100 days at elevations below 1500–2500 m asl. The increase in winter precipitation only slightly offsets the dominant effect of temperature rise. Warming at low elevations will result in the quasi-disappearance of the

snow-pack during most winters, while the change at very high elevations will be small. This is mainly because even in a warmer world, temperatures at height will remain cold enough to sustain snow for much of the year.

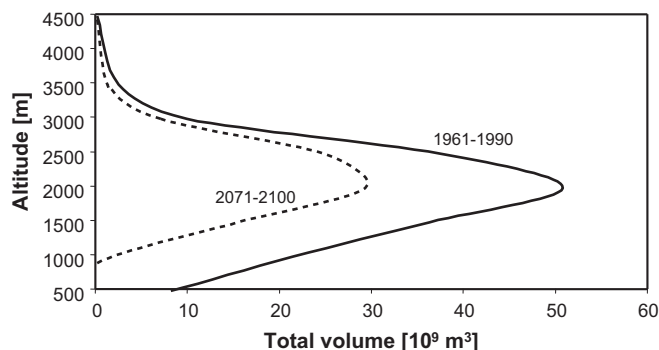
In terms of Alpine ice cover, the glaciers in Switzerland and its neighbors have lost between 30% and 40% of their surface area and about half of their volume (Haeberli and Beniston, 1998) since 1900, a feature that has been observed in numerous other mountain glaciers of the world. Empirical and energy-balance models indicate that 30–50% of existing mountain glacier mass could disappear by 2100 if global warming scenarios in the range of 2–4 °C were to occur (Haeberli, 1995; Haeberli and Beniston, 1998). The smaller the glacier, the faster it will respond to changes in climate. For most mountain glaciers in the temperate parts of the world, there exists a close linear relationship between the equilibrium line altitude of the glacier and the precipitation and temperature controls on glacier mass. Farinotti et al. (2009) estimates that in order to maintain the equilibrium line altitude of a glacier, roughly 300 mm of additional precipitation per degree of warming would be necessary. Projections from regional climate models suggest that in the Alpine region, warming will be accompanied by an average reduction of annual precipitation, thereby implying rapidly waning glaciers until they find perhaps another equilibrium at much higher elevations and with substantially reduced volume and surface area; some may disappear entirely if the equilibrium line altitude is positioned above that of the glacier catchment area.

#### 4. Impacts on water regimes

The Alps in general and Switzerland in particular, have in the past been referred to as “the water tower of Europe” (Mountain Agenda, 1998), as they are the source region for many rivers that flow through Western and central Europe, as well as towards the Mediterranean Sea. Any substantial changes in the mountain snow-pack would have a significant impact on the flow of many major river basins, not only because of changes in the amount and timing of runoff, but also because of the potential for enhanced flooding, erosion, and associated natural hazards.

On average, Switzerland receives close to 1500 mm of precipitation per year, of which one-third is lost through evaporation and close to two-thirds contributes to surface runoff; a small fraction is stored in lakes, dams, and serves to recharge groundwater reserves. Within a 30-km radius in the Gotthard region of central Switzerland, surface runoff feeds river systems that flow into the North Sea (the Rhine river basin, representing about two-thirds of total water exported from Switzerland), the Mediterranean (the Rhone river basin, with about 18% of water exports), the Adriatic (the Ticino that converges with the Po river in Italy and represents 10% of runoff from Switzerland) and the Black Sea (via the Inn that converges with the Danube in Germany, and accounts for about 5% of surface runoff), as described in the Swiss Hydrological Atlas (FOEN, 2007).

Alpine water resources are strongly influenced by mountain climates that govern soil moisture, groundwater recharge, evaporation and runoff. The Rhone river discharges are controlled by evaporation, precipitation, storage of water in artificial reservoirs, and melt water from snow and ice. Precipitation throughout the year, and snow and ice melt waters from May to October provide input to the river basin; in addition, hydropower utilities release water into the catchments and tributaries of the Rhone during the winter half-year in order to generate power during the peak energy demand period of the winter. Water is locked in the winter snow-pack on average from November to May, while evaporation reaches a maximum during the summer months. Dams retain a small part of snow-melt and precipitation during the summer



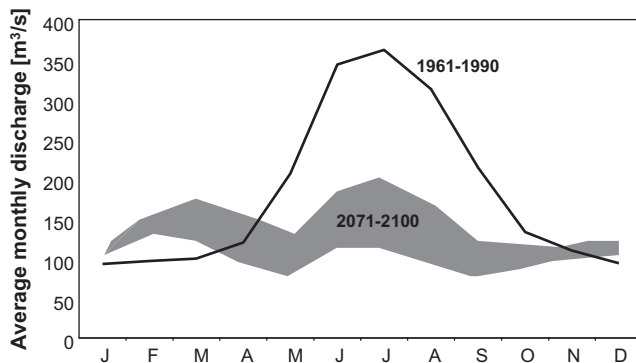
**Fig. 4.** Changes in snow volume in the Alps at different elevations between current and scenario climates, assuming a 4 °C temperature rise during the winter.

months and store this water to prepare for supplying energy later in the year; this storage removes water from the system that would otherwise contribute directly to runoff.

Because precipitation is fairly evenly distributed throughout the year and storage of water in dams represents a small fraction of the total amounts of water involved, the most important seasonal signal in terms of runoff is determined by the Alpine snow-pack, in particular the timing of snow-melt and the amount of melt water which is a function of the quantity of snow accumulated during the preceding winter.

In a scenario climate, runoff by 2100 is seen to change in seasonality and amount compared to current climate (Fig. 5). There is a first peak of discharge that takes place 2–3 months earlier in the year, and according to the level of warming, a second peak of discharge takes place during the summer. This summer peak would occur if the number and volume of remaining glaciers were to be sufficient to contribute to such levels of discharge. At the lower end of the possible range of future discharge, summertime flows are seen to be lower than during the spring; this would be the case with the quasi-disappearance of glaciers in the source region. Whatever the absolute value of future discharge, maximum flows are reduced compared to the reference period because of the smaller contributions of a dwindling winter snow-pack. In addition to changing snow and ice, the modest peak of summertime discharge seen in Fig. 5 is also linked to convective activity that could still occur despite the strong reduction in average summer rainfall highlighted in Fig. 3. Even during summers with convective precipitation, however, the reduction in discharge compared to the baseline conditions ranges from 50% to 75%. The gray shading gives an estimated range of uncertainty of the results, according to the amount of snow and the timing of spring melt, the estimated remaining glacier mass, and shifts in seasonal precipitation. These are typically the quantities that the ACQWA project is seeking to refine for improved estimates of river flows.

Because of the large inter-annual variability of runoff, as a result of the sharply curtailed glacier mass in the mountains and possibly long and dry summers, the volume of summertime glacier melt waters may no longer be sufficient to feed water into river catchments at a time of the year when precipitation amounts are low and the snow-pack has already melted earlier in the year. Consequently, in some years, the Rhone may dry up partially or completely towards the end of the summer and into the early fall. The future characteristics of runoff shown in this figure are more typical of rivers that are currently found in the Mediterranean parts of the Alps, as in the French Provence region and in parts of the Italian-facing slopes of the Alpine arc, for example.



**Fig. 5.** Changes in monthly discharge of the Rhone river close to its mouth in the Lake of Geneva, near Montreux, Switzerland, from current (1961–1990) to future (2071–2100, IPCC A2 emissions scenario). The gray shading gives the possible range of discharge, according to the timing and volume of snow-melt, estimates of glacier retreat, and shifts in seasonal precipitation.

## 5. Impacts on socio-economic systems

A changing climate leading to modifications in hydrological regimes has the potential to increase competition over water that will be available at different times and in different quantities compared to today. Water is difficult to allocate because of its public good features, which are aggravated by upstream potential to capture the resource and by the fact that flowing water may cross internal and international borders. Adding further to the potential for conflict are socio-economic changes that modify existing distribution schemes. Changing land cover and land-use (e.g., Beguería et al., 2006) will generate significant shifts in the amount and seasonality of water resource demands. The crucial role of forests in protecting against erosion and conserving biodiversity and water storage may potentially be threatened. Changes in the distribution of vegetation cover may cause an increase in the average annual discharge, and an acceleration of runoff during rainstorm events, thus enhancing erosion and downstream sediment supply. Changing social patterns and economic incentives have resulted in land-use changes in many mountains of the world, and in some instances have exacerbated the risks associated with excessive runoff, erosion potential, etc. Conflicting water use (e.g., between agriculture and hydropower, or between hydropower and tourism) as the resource diminishes through reduced precipitation in some areas and glacier retreat in others, needs to acknowledge the fact that new water resource management is not just a matter of adjusting to shifts in the physical environment. Such management also needs to be strongly associated with social changes that are generated by shifts in the type and level of water use and new market conditions that are capable of affecting distribution.

These changes will have significant impacts on several critical socio-economic sectors in mountain regions, particularly since these are also subject to various other forces that influence their viability. There will in addition be cascading effects on downstream areas. For example, mountain agriculture has been under pressure from lower-cost production in lowland areas. Potential increases in drought conditions will only serve to increase its vulnerability. As a result of shifting seasonality of precipitation and glacier melt, the reduction in capacity to store water could also diminish the potential for hydroelectric production just as European-wide efforts are being initiated to reduce dependence on fossil-fuel based energy sources, as part of the European post-Kyoto strategy. The entire European electrical grid would thus be affected, and not only in the Alps. Some rivers, such as those that flow from the northern part of the Alps, may dry up partially or completely towards the end of the summer; this is already the case in the Mediterranean mountains, where the drought situation may well worsen.

## 6. Conclusions

Water is relevant in every aspect of mountain systems, in the physical, biological and socio-economic systems. It directly influences the energy supply (hydropower), tourism (snow, water usage, glaciers), forestry and agriculture (productivity changes with changes in water supply, need for irrigation) and services from natural and semi-natural ecosystems. On the other hand changes in any of these compartments will affect water availability. Reforestation and deforestation processes triggered by climate change will likely affect the water balance, the generation of flood runoff and sediment production due to enhanced or reduced erosion. Increased competition for water among many socio-economic sectors may arise, requiring regulatory or market mechanisms to attenuate tension and assure efficient and equitable use. Achieving sustainable water use poses particular challenges for policy mak-

ing because of its nature as a public good and because it often has both upstream/downstream and trans-boundary characteristics. Any changes in climate affecting precipitation and the behaviour of snow and, where relevant, glaciers, will have a major influence on the seasonality, amount, and quality of surface runoff. The main changes are thus expected in the surface water systems, with uneven temporal distribution of the resource throughout the year.

By investigating the challenges of managing crucial but often limited water resources, the ACQWA project aims to provide novel answers to social and economic issues such as changes in social arrangements among mountain populations and their downstream neighbors, energy production in regions where water is underused as a means of helping abate greenhouse-gas emissions, and environmental issues such as the future evolution of water supply for use in domestic, tourist, or agricultural sectors. The future challenges that ACQWA is addressing are significant, especially because of the growing interconnection among regions and economic and social sectors. The relationships with downstream areas are especially critical, notably in cases where upstream and downstream entities concern separate sovereign countries. Critical analysis of upstream–downstream asymmetries and the particular vulnerabilities that arise from both is essential for the development of policy-relevant instruments.

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### References

- Abegg, B., Froesch, R., 1994. Climate change and winter tourism: impact on transport companies in the Swiss Canton of Graubünden. In: Beniston, M. (Ed.), *Mountain Environments in Changing Climates*. Routledge Publishing Company, London and New York, pp. 328–340.
- Beguéría, S., López Moreno, J.I., Gómez Villar, A., Rubio, V., Lana-Renault, N., García Ruiz, J.M., 2006. Fluvial adjustment to soil erosion and plant cover changes in the Central Spanish Pyrenees. *Geografisker Annaler* 88A, 177–186.
- Beniston, M., 2000. *Environmental Change in Mountains and Uplands*. Arnold/Hodder and Stoughton/Chapman and Hall Publishers, London, UK, Oxford University Press, New York, USA. 172 pp.
- Beniston, M., 2006. The August 2005 intense rainfall event in Switzerland: not necessarily an analog for strong convective events in a greenhouse climate. *Geophysical Research Letters* 33, L5701.
- Beniston, M., Keller, F., Koffi, B., Goyette, S., 2003. Estimates of snow accumulation and volume in the Swiss Alps under changing climatic conditions. *Theoretical and Applied Climatology* 76, 125–140.
- Beniston, M., Stephenson, D.B., Christensen, O.B., Ferro, C.A.T., Frei, C., Goyette, S., Halsnaes, K., Holt, T., Jylhä, K., Koffi, B., Palutikoff, J., Schöll, R., Semmler, T., Woth, K., 2007. Future extreme events in European climate; an exploration of regional climate model projections. *Climatic Change* 81, 71–95.
- Beniston, M., 2003. Climatic change in mountain regions: a review of possible impacts. *Climatic Change* 59, 5–31.
- Beniston, M., 2008. Sustainability of the landscape of a UNESCO World Heritage Site in the Lake Geneva region (Switzerland) in a greenhouse climate. *International Journal of Climatology* 28, 1519–1524.
- Christensen, J.H., Christensen, O.B., 2003. Severe summer-time flooding in Europe. *Nature* 421, 805–806.
- Christensen, O.B., Christensen, J.H., Machenhauer, B., Botzet, M., 1998. Very high-resolution regional climate simulations over Scandinavia – present climate. *Journal of Climate* 11, 3204–3229.
- Christensen, J.H., Carter, T.R., Giorgi, F., 2002. PRUDENCE employs new methods to assess European climate change. *EOS (American Geophysical Union Newsletter)* 83, 13.
- Deque, M., Rowell, D.P., Lüthi, D., Giorgi, F., Christensen, J.H., Rockel, B., Jacob, D., Kjellström, E., de Castro, M., van den Hurk, B., 2005. An intercomparison of regional climate simulations for Europe: assessing uncertainties in model projections. *Climatic Change*. doi:10.1007/s10584-0006-9228-x.
- Farinotti, D., Huss, M., Bauder, A., Funk, M., 2009. An estimate of the glacier ice volume in the Swiss Alps. *Global and Planetary Change* 68, 225–231.
- FOEN, 2007. *Swiss Hydrological Atlas*, edited by the Swiss Federal Office of the Environment (FOEN), Berne.
- Giorgi, F., Mearns, L.O., 1999. Regional climate modeling revisited. *Journal of Geophysical Research* 104, 6335–6352.
- Haeberli, W., Beniston, M., 1998. Climate change and its impacts on glaciers and permafrost in the Alps. *Ambio* 27, 258–265.
- Haeberli, W., 1995. Glacier fluctuations and climate change detection – operational elements of a worldwide monitoring strategy. *WMO Bulletin* 44 (1), 23–31.
- IPCC, 2007. *Climatic Change; the Intergovernmental Panel on Climate Change fourth assessment report*. Cambridge University Press, Cambridge (Volume I: Science; Volume II: Impacts; Volume III: Adaptation and Mitigation).
- Keller, F., Körner, C., 2003. The role of photoperiodism in alpine plant development. *Arctic, Antarctic and Alpine Research*.
- Mountain Agenda, 1998. *Mountains of the World. Water Towers for the 21st Century*. Prepared for the United Nations Commission on Sustainable Development. Institute of Geography, University of Berne (Centre for Development and Environment and Group for Hydrology) and Swiss Agency for Development and Cooperation. Paul Haupt Publishers, Bern, Switzerland, 32pp.
- Seneviratne, S.I., Lüthi, D., Litschi, M., Schär, C., 2006. Land-atmosphere coupling and climate change in Europe. *Nature* 443, 205–209.