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Editorial

Assessing the impacts of climatic change on mountain water resources

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ABSTRACT

As the evidence for human induced climate change becomes clearer, so too does the realization that its effects will have impacts on numerous environmental and socio-economic systems. Mountains are recognized as very sensitive physical environments with populations whose histories and current social positions often strain their capacity to accommodate intense and rapid changes to their resource base. It is thus essential to assess the impacts of a changing climate, focusing on the quantity of water originating in mountain regions, particularly where snow and ice melt represent a large streamflow component as well as a local resource in terms of freshwater supply, hydropower generation, or irrigation. Increasing evidence of glacier retreat, permafrost degradation and reduced mountain snowpack has been observed in many regions, thereby suggesting that climate change may seriously affect streamflow regimes. These changes could in turn threaten the availability of water resources for many environmental and economic systems, and exacerbate a range of natural hazards that would compound these impacts. As a consequence, socio-economic structures of downstream living populations would be also impacted, calling for better preparedness and strategies to avoid conflicts of interest between water-dependent economic actors. This paper is thus an introduction to the Special Issue of this journal dedicated to the European Union Seventh Framework Program (EU-FP7) project ACQWA (Assessing Climate Impacts on the Quantity and Quality of WAter), a major European network of scientists that was coordinated by the University of Geneva from 2008 to 2014. The goal of ACQWA has been to address a number of these issues and propose a range of solutions for adaptation to change and to help improve water governance in regions where quantity, seasonality, and perhaps quality of water may substantially change in coming decades.

1. Introduction

The importance of mountain regions as a provider of numerous ecosystem services was recognized at the United Nations Conference on Environment and Development (Rio de Janeiro, Brazil, 1992); mountain regions were included under Agenda 21 of the UNCED conference, which mentions under its Article 13 (UN, 1992) that "*Mountains are important sources of water, energy, minerals, forest and agricultural products and areas of recreation. They are storehouses of biological diversity, home to endangered species and an essential part of the global ecosystem. From the Andes to the Himalayas, and from Southeast Asia to East and Central Africa, there is serious ecological deterioration. Most mountain areas are experiencing environmental degradation.*"

Mountains are today unanimously recognized as "sentinels for environmental change", in the sense that they exhibit dynamics in physical and biological systems that are often more readily identifiable than in other geographical entities of the globe (Beniston, 2003; Loarie et al., 2009; Engler et al., 2011; Gobiet et al., 2014). The study of cryospheric, hydrologic, geomorphic and socio-economic change in sensitive mountain regions enables to further our understanding of how an important part of the terrestrial environment responds to, is affected by, and may adapt to rapid and sustained changes in temperature and precipitation regimes (Beniston, 2009; Barriopedro et al., 2011; IPCC, 2013).

Among these visible impacts, changes in glacier length and volume are perhaps the most spectacular manifestations of climate impacts in mountains; currently and with few exceptions, mountain glaciers from the equatorial to the high latitudes experience glacier shrinkage (Paul, 2011; Bolch et al., 2012; Sorg et al., 2012; Pellicciotti et al., this issue-a), highlighting the fact that this is a global phenomenon. Shifts in mountain snow-pack behavior in the past decades have also been observed, with collateral impacts on the timing of snow-pack melting and thus of surface runoff (e.g., Stewart, 2009; Beniston, 2010, 2012; Rohrer et al., 2013), and also an influence on the start of the vegetation period for certain mountain plant species (Keller et al., 2005; Moser et al., 2009; Beier et al., 2012; Gottfried et al., 2012).

More subtle changes are reported for mountain ecosystems, in part because of the longer timescales involved in biological systems compared to mountain cryospheric systems, for example, and also because certain species are more adaptable than others (Dubuis et al., 2013), thus resulting in greater difficulties in attributing cause-to-effect relationships of climate change. In mountains, the transitions between biological entities and vegetation (ecotones) can occur over short

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distances, contrarily to what takes place in lowland plains (e.g., Gosz, 1993). Many changes in vegetation patterns related to sustained shifts in environmental conditions can be identified in these ecotone transition zones, as shown for example by Gottfried et al. (2012) at the boundary between high alpine vegetation and the snowline. Invasive species moving into and upwards from lowland regions are also an indicator of change, since the endemic nature of many upland ecosystems is related to the relative isolation of mountains that can be considered as islands surrounded by lowlands (Hedberg, 1964), and any new species entering into a mountain region would be indicative of some form of disruption.

Finally, mountains are also the locale for numerous socio-economic activities, in particular tourism, agriculture, industry, mining, and energy (hydropower). These sectors are all sensitive to climate change, since climate exerts the essential controls on the availability of snow for ski tourism (e.g., Uhlmann et al., 2009; Morrison and Pickering, 2013), or of water for mountain agriculture, hydropower, and for mineral exploitation (e.g., Finger et al., 2012; World Bank, 2013; Fuhrer et al., this volume; Gaudard et al., this volume)), for example. However, it should be emphasized here that low priorities to sustainable land-use and natural resource management in many mountain regions in the world imply that changes in forest resources, mountain agriculture and water resources are driven not only by environmental change but also by economic and demographic factors (Beniston, 2003).

It is in this context of rapid dynamics of change in mountain regions that the ACQWA project (Assessing Climate impacts on the Quantity and quality of WAter; Beniston et al., 2011, 2012) was constructed, in response to the first call for climate-relevant projects under the European Union Framework Program (EU-FP7) and coordinated by the University of Geneva (01.10.2008–31.03.2014). It has been one of the largest climate-related projects coordinated by Switzerland under FP7, both in terms of funding and the number of partner institutions, i.e., 30 in 10 countries and three continents for a total of 37 different research, public, or private research entities representing over 100 scientists.

The overarching goal of the project was to assess the vulnerability of water resources in mountain regions where snow and ice represent a major input of water for rivers originating in mountains, and where declining snow amounts and receding glaciers in a warmer climate are likely to have profound impacts on hydrological regimes. Future shifts in temperature and precipitation patterns, and changes in the behavior of snow and ice in many mountain regions will change the quantity, seasonality, and possibly also the quality of water originating in mountains and uplands (Sorg et al., 2012; Immerzeel et al., 2013; Collins et al., 2013). As a result, changing water availability will affect both upland and populated lowland areas (Hill et al., in press-a,b; Sorg et al., 2014). The challenge of the ACQWA project has thus been to estimate as accurately as possible future changes in water availability, and the impacts these changes may impose on a range of water-dependent economic systems (Fig. 1).

The flow diagram in Fig. 1 illustrates the broad structure of the ACQWA project. Current generation of state-of-the-art models (e.g., Themessl et al., 2010; Cane et al., 2013; Heinrich et al., 2013; Gobiet et al., 2014) was applied to various interacting elements of the climate system, that include regional atmospheric processes in complex terrain, snow and ice, vegetation, and hydrology in order to project shifts in water regimes in a warmer climate in mountain regions as diverse as the European Alps, the Central Andes of Chile and Argentina, and the mountains of Central Asia (Kyrgyzstan). Observations, targeted models, and methodologies from both the social and the natural sciences were then applied to conduct analyses of climate impacts on sectors such as tourism, agriculture and hydropower which could be strongly influenced by changing water regimes. Because these economic sectors and other water-dependent industries may well enter experience conflicts of interests and rivalries if water is no longer available in sufficient quantities or at the right time of the year, a further goal of the ACQWA project was thus to define a portfolio of proposals to pave the way for appropriate adaptation strategies and improved water governance (Hill and Allan, in press; Hill and Engle, 2013; Hill et al., in press-b). These are designed to help alleviate the more negative impacts of climatic change on water resources and to reduce the risks of conflict between the economic actors most affected by these changes.

The aim of this introductory paper to the Special Issue of Science of the Total Environment is not only to summarize the principal highlights of the ACQWA project, but also to emphasize some of the elements of inter-comparison between this project and other research initiatives that in recent years have also been dedicated to water and climate issues.

2. The ACQWA case-study regions

Fig. 2 shows the main case-study areas investigated in the context of the ACQWA project. The Rhone and Po river basins in the European Alps have been used as a common “test ground” for model investigations,

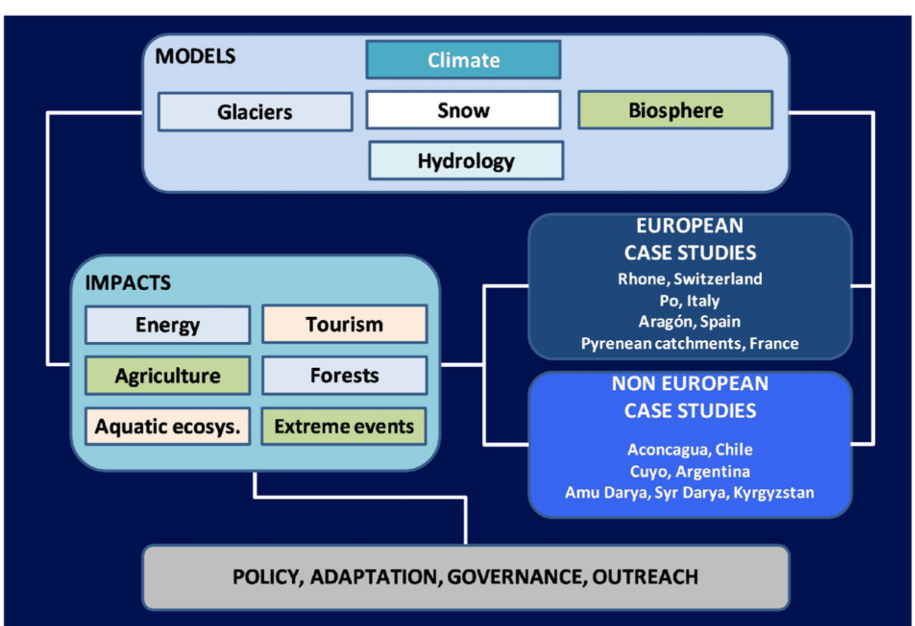

Fig. 1. Structure of the ACQWA project and its main components.

Fig. 2. The principal ACQWA case-study regions: the Swiss Rhone and Italian Po basins, the Chilean Aconcagua basin, and the Kyrgyz catchments of Central Asia.

where the different methodological approaches have converged to the basin scale through appropriate up- or down-scaling techniques. Both basins represent ideal case-study areas, as they comprise all the elements of the natural environment that have been modeled (snow, ice, vegetation, hydrology) and have a wealth of data to enable models to be validated. At the same time, these are highly regulated watersheds, where economic activities related to hydropower generation, irrigated agriculture, and tourism take place in the context of a climate that is at the borderline between Mediterranean and Continental, and are therefore particularly vulnerable to climatic change (Beniston, 2003). The boundaries of the Rhone catchment study-area include the alpine segment, running from the Rhone Glacier in Central Switzerland to Lake Geneva. The boundaries of the Po case-study area used in the ACQWA project do not extend as far as the Adriatic Sea, for reasons of data access and hydrological model constraints. The investigations have thus focused more on the flows from the Alps of Piemonte and Valle d'Aosta, with the "ACQWA Po" boundary that is limited to Cremona, on the Po River south of Milan and the western segment of the basin (Coppola et al., this volume; Fatichi et al., this volume). Regional climate model results, however, cover the entire basin as illustrated in the map in Fig. 2.

Some of the methodologies developed in the intensive investigations of the European alpine catchments have been applied to the Aconcagua Basin in Chile, where receding glaciers already today pose a genuine threat to water availability (Pellicciotti et al., 2014). Investigating the coping strategies of Chilean economic sectors affected by changes in the quantity and seasonality of water resources can help highlight the types of problems that could arise in the Alps in coming decades (Hill et al., in press-a). In Central Asia (Kyrgyzstan), on the other hand, the same processes of ice-mass wasting in the headwaters of the Syr Darya or Amu Darya rivers involve much larger glaciers (Sorg et al., 2012). During the 21st century, the meltwaters from the Tien Shan could potentially represent a source of economic opportunity, for example through the development of hydropower as a source of foreign revenue, but also a risk in view of the political instability and rivalries between different independent states of former USSR (Sorg et al., 2014).

Other research-specific case-study areas comprise the Aragón Basin in Spain for interdisciplinary investigations pertaining to agriculture and energy in a context of changing land-use and climate (Lopez-Moreno et al., 2014); and French Pyrenean watersheds for aquatic ecosystem studies in a hydrology, habitat and biota framework (Khamis et al., 2013a, 2014). These are located in the Cauterets region in the vicinity of the French Pyrenees National Park. By analogy with the other non-Alpine case study regions, some of the issues addressed in the Pyrenees in today's world are likely to be those that will arise in the European Alps in tomorrow's world.

3. Climate change in the ACQWA case-study regions

The high-resolution simulations carried out within the EU-FP6 ENSEMBLES project (www.ensembles-eu.org) formed the basis for the focused modeling work and climate impacts assessments within ACQWA. Two principal simulations were chosen from the ENSEMBLES multi-model dataset (namely ICTP_RegCM and MPI_REMO, both driven by ECHAM5-r3) and used by all teams. In addition, several impacts studies used the entire ENSEMBLES dataset in order to identify more completely climate-induced uncertainties. The IPCC (2001) A1B greenhouse-gas scenario through to the mid-21st century was applied across all the individual case studies to have a common scenario referenced period for all projections and impacts studies. The 2050s was set as the principal time horizon for the project, as this is a period in the future which is not too

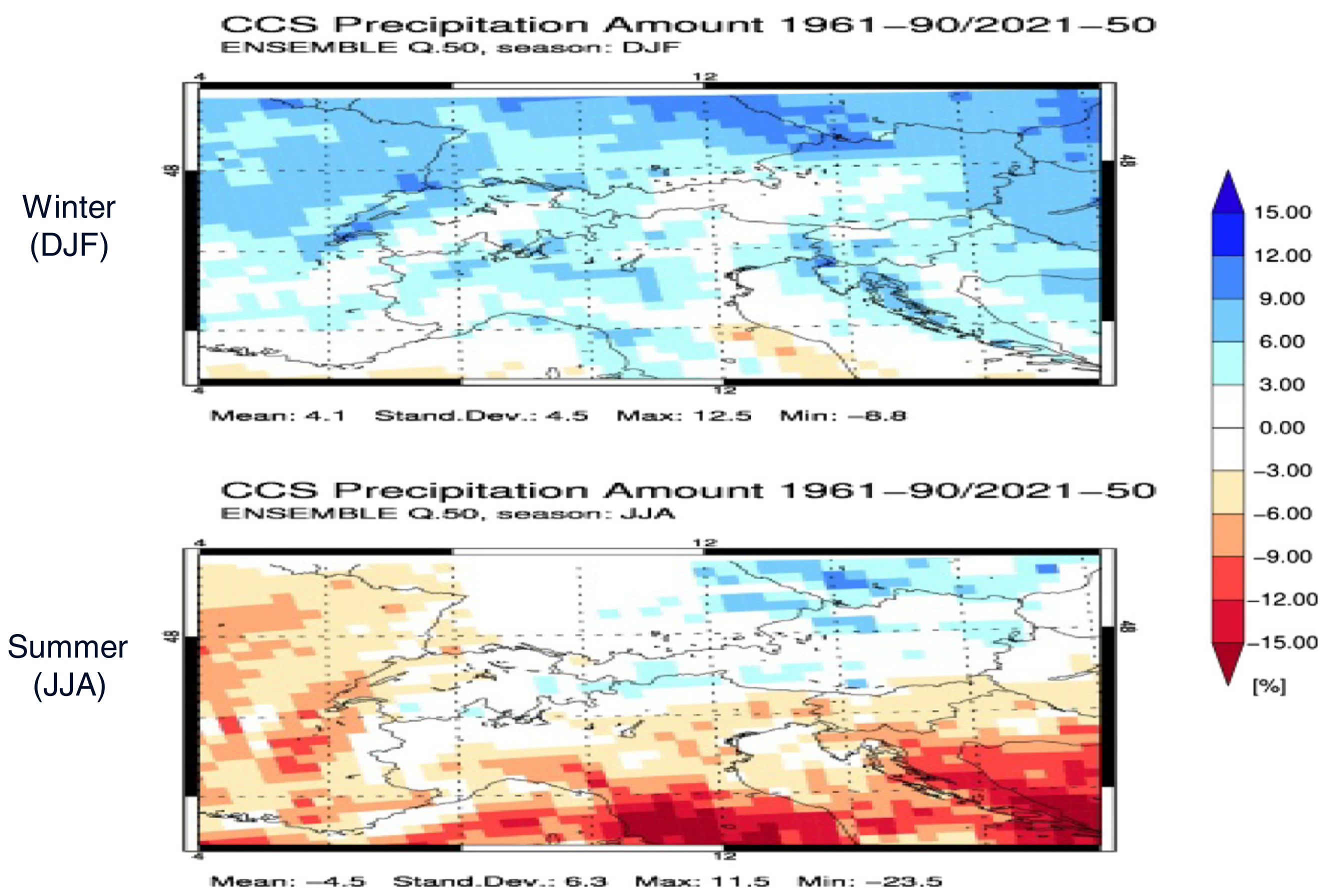

Fig. 3. Alpine-scale precipitation change in winter and summer by 2050.
Source: A. Gobiet, University of Graz, Austria.

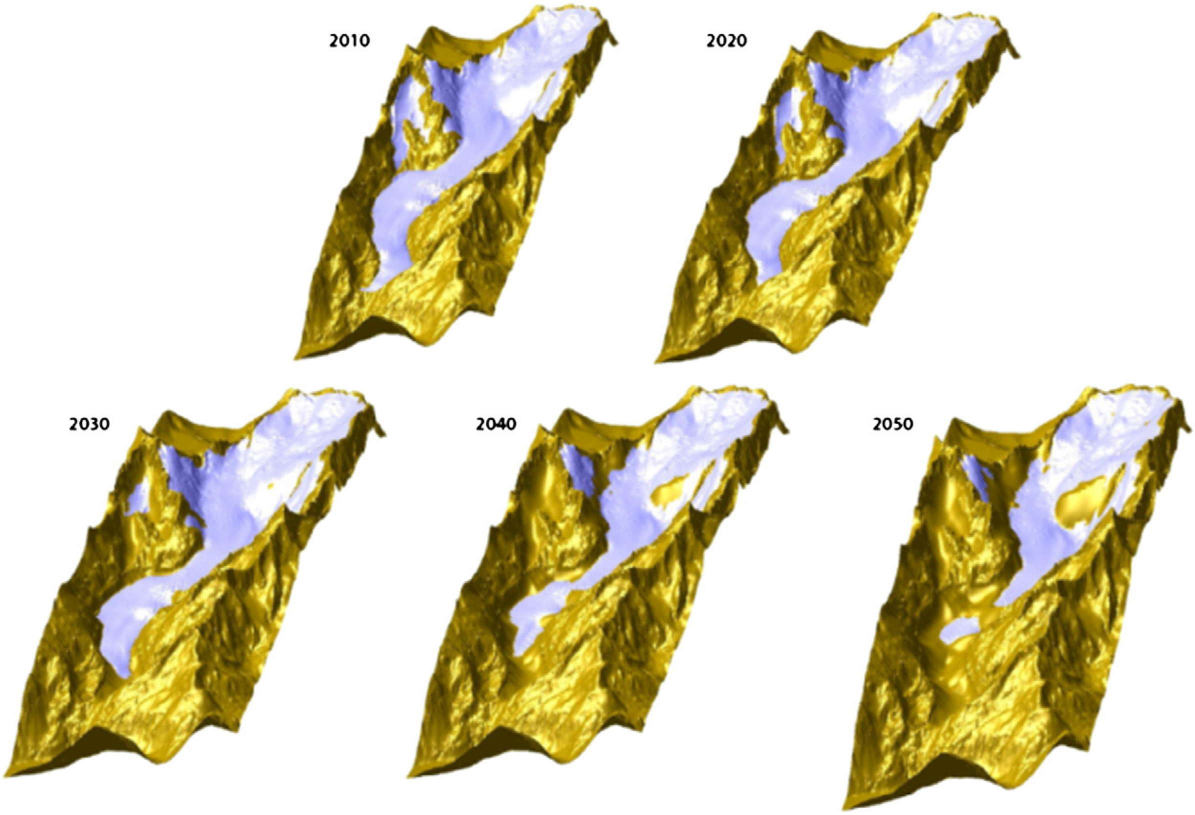

Fig. 4. A pseudo-3D representation of the retreat of the Rhone Glacier by 2050 (Fatichi et al., 2014).

far removed from the time-scales typical of forward economic planning and decision-making. Using the ENSEMBLES simulations from a set of 22 high resolution regional climate models (RCMs), climate data in the regions of interest was compiled up to 2050. The ENSEMBLES RCMs were used with a horizontal grid spacing of 25 km, and the lateral boundary conditions were provided by eight different global climate models (GCMs). The restriction of using only the A1B emission scenario, rather than other scenarios or a range of emission futures, is of minor importance since the uncertainty due to the choice of emission scenario remains fairly small in the first half of the 21st century (Gobiet et al., 2014).

Results by 2050 using the multi-model mean climate change signals exhibit stronger warming along the Alpine ridge, especially in summer. The high sensitivity of the Alps becomes even more evident in the rather small Rhone case-study region located in the Valais region of south-

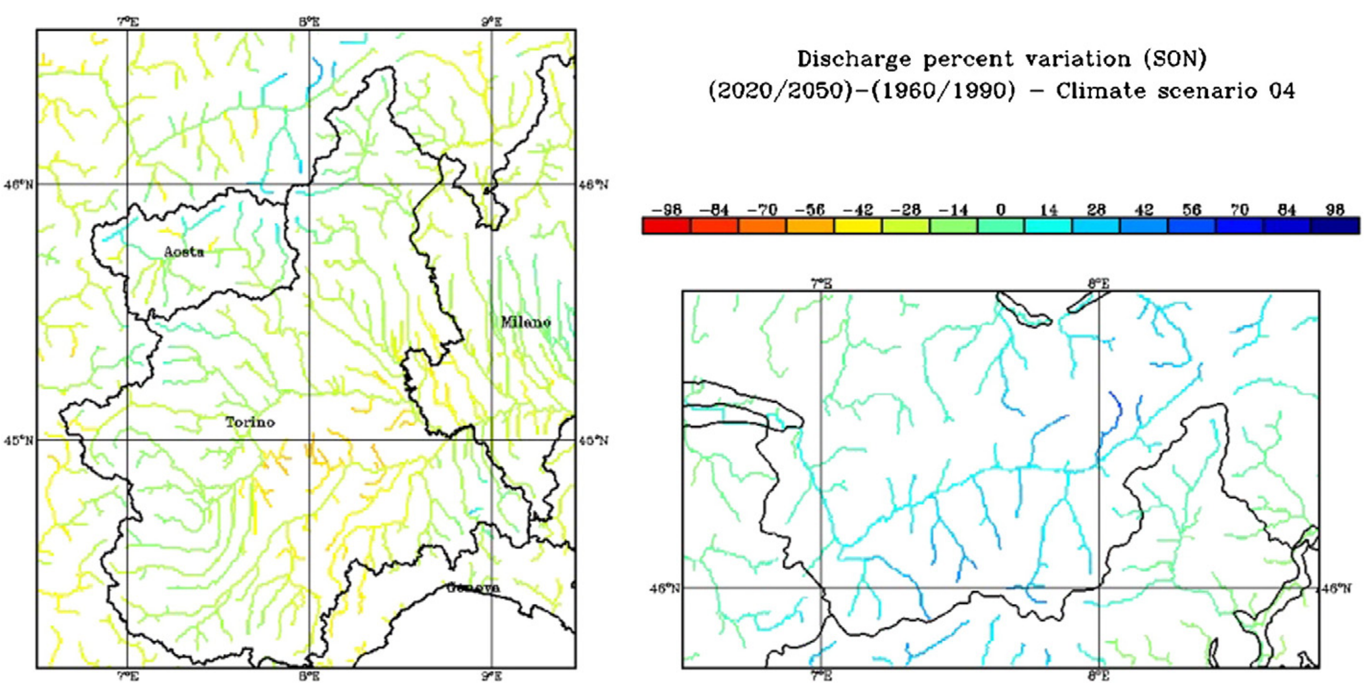

Fig. 5. Changes in discharge in the Po (left) and Rhone (right) catchments between the reference climate 1961–1990 and the scenario climate 2021–2050 (Coppola et al., 2014).

central Switzerland, with projected median warming over 1.5 °C in winter (DJF) and close to 2 °C in summer (JJA). Warming is projected by all models of the dataset and for all seasons; the uncertainty of the projected changes is larger in summer and autumn than in winter and spring (Gobiet et al., 2014). In-depth analyses of this data suggest that the choice of the GCM that drives the RCM initial and boundary conditions has by far the largest effect on the total uncertainty, contributing more than 75% to the overall variance in most cases (Im et al., 2010a, b; Deser et al., 2012; Gobiet et al., 2014).

The massive presence of the Alpine ridge as a dividing feature between Mediterranean and Atlantic or Continental climates clearly influences the spatial distribution of precipitation and the projections of change, as seen in Fig. 3. In the Rhone catchment, the summer decrease and winter increase are small through to 2050, although these changes may well amplify into the second half of the 21st century as shown by a number of earlier studies (e.g., Beniston, 2006). In the Po catchment, temperature and precipitation changes are somewhat more marked than in the Rhone catchment to the north. Between the decades 2001–2010 and 2041–2050, increases of temperature according to different RCM simulations range between 2 and 3 °C, and the variation of mean annual precipitation ranges from 1 to 10%, mainly in the winter and early spring period. Accelerated melting periods, earlier in the year, and likely increases in summertime evapotranspiration will inevitably counter the influence of the larger amounts of summer precipitation on river discharge that are projected for the region.

In the Andean zone, of central Chile, the Aconcagua catchment is projected to experience warmer winters and decreasing precipitation which, as in other mountain regions, will affect the behavior of the mountain snowpack and lead to changes in the timing of snow and glacier melt (Pellicciotti et al., 2014). In the Central Asian republic of Kyrgyzstan, available climate simulations project by 2050 decreases in summer precipitation by around 5% and increases in winter precipitation around 8%. Temperature increases of between 2.5 and 4.5 °C are projected for all seasons in the region. Overall, extreme events will tend to increase, in particular at both ends of the moisture spectrum with more summer droughts and winter or spring flood events (Sorg et al., 2012, 2014).

4. Impacts of a changing climate on natural and socio-economic systems

Changes in snow, ice and water will have impacts on natural systems (such as forests) and managed systems (such as hydropower and agriculture).

4.1. Changes in mountain cryosphere and hydrological systems

Alpine snow cover will decline due to temperature increases that will change the liquid-to-solid precipitation ratio, with higher risks of winter rainfall rather than snow-fall particularly at mid-latitude locations in the range from 1000 to 2000 m asl (Dedieu et al., 2014). The speed at which individual glacier retreat may be reduced at locations where glaciers become confined to high elevations characterized by high totals of accumulated winter snow fall. State of the art, continuous mass balance models project a high variability of progressive glacier retreat for 2001–2050 and a related ice volume reduction for a number of alpine glaciers. For the Rhone Glacier, source of the Rhone River, Fig. 4 shows the progressive decade-by-decade retreat of the ice until 2050 (Fatichi et al., 2014).

Numerical model results, that include the intricacies of water flow in drainage networks beneath the glacier base, suggest that the stability of a number of alpine glaciers could be altered significantly by atmospheric warming trends (e.g., Faillettaz et al., 2012; Worni et al., 2013). Debris-free glaciers are projected to have a faster negative mass balance in comparison to those covered by a thick layer of debris. Higher spring and summer melting occurs in 2031–2050. Overall, the contribution of ice melt to runoff in glacierized catchments will gradually disappear as the size of the glaciers dwindles.

In the Alpine region, the application of distributed hydrological models emphasizes the fact that the impacts of climatic change on the hydrological cycle will probably be less marked in the higher mountain domains (e.g., for the upper part of the Rhone catchment) than for lower elevations (e.g., on the Italian side of the Alps and in the Padan Plain of the Po catchment). Fig. 5 illustrates the contrasting shifts in water amount in the two catchments according to elevation and distance from the mountains (Coppola et al., 2014).

RCM-projected impacts of climate change on flow duration curves of mountain tributaries for the Po River exhibit a general decrease of discharge for low flows and an increase in discharge for high flows. The decrease of flow discharge is estimated to be more than 50% of the seasonal average for a large portion of the drainage network. In the Rhone catchment, stochastic climate variability is a fundamental source of uncertainty that is often larger than the magnitude of projected climate change. In a highly managed catchment like the Swiss part of the Rhone River, changes in the natural hydrological regime imposed by the existing hydraulic infrastructure are larger than those imposed by the magnitude of climate change expected by 2050 (Finger et al., 2012; Fatichi et al., 2014; Gaudard et al., 2014).

In all the mountain regions studied, climate change impacts on stream flow are elevation-dependant, with a sharp reduction at high elevations due to the missing contribution of water from ice melt and a damped effect downstream, with a decrease of water availability in summer and an increase of discharge in winter (Fatichi et al., 2013).

4.2. Mountain forests

Mountain forests are considered to provide a number of services; beyond their purely aesthetic value, the wood they provide can be used for various purposes (Leuzinger et al., 2011). Above all, however, they act as natural protection against rockfalls and other slope instabilities (Stoffel et al., 2006), and in addition filter the water that runs along the surface or infiltrates into the soils. Any changes in the distribution of mountain forests could change the protective role that they play against natural hazards (Stoffel et al., 2005, Gottfried et al., 2011). In the ACQWA project, it was found using the LPJ-GUESS biosphere model that the sensitivity of Alpine forest ecosystem services to a 2 °C warmer world depends heavily on the current climatic conditions of a region, the strong elevation gradients within a region, and the specific ecosystem services in question (Wolf et al., 2012). These include carbon storage, modulation of surface runoff, timber production, biological diversity, and protection from natural hazards. At higher elevations and in regions that are initially cool and moist, simulations suggest that forest ecosystem services may be comparatively resistant to a 2 °C temperature rise. At low and intermediate elevations large negative impacts may occur in dryer–warmer regions, where relatively small climatic shifts could result in negative drought-related impacts on forest ecosystem services. Some services such as protection against rockfall and avalanches are seen to be sensitive to a sustained 2 °C change in mean temperature, but other services such as carbon storage remain reasonably resistant. The study concludes that a 2 °C increase of global mean temperature, which is the “EU Policy” threshold to which a number of other countries such as Switzerland adhere to, cannot be seen as a universally “safe” boundary for the maintenance of mountain forest ecosystem services (Elkin et al., 2013).

4.3. Aquatic ecosystems

Mountain lakes are often considered to be sentinels of change, because they are located in sensitive or extreme environments, where small shifts in environmental conditions or direct human interference can result in rapid dynamics in the functioning of aquatic ecosystems (Tiberti et al., 2013). Increased temperature, seasonal precipitation shifts, reduced ice cover and ice melt are likely to have significant implications for aquatic biodiversity, in particular increased abundance of larger predator species, increased primary and secondary productivity, increased local diversity, and decreased regional diversity. Case studies from the Pyrenees and the Swiss Alps highlight that although climate signals are broadly similar, the predicted responses that relate hydrology to habitat to ecology are varied and are a function of cryospheric river flow buffering potential, i.e., glacier size (Khamis et al., 2014, submitted for publication). In order to enhance conservation of mountain lake ecosystems, three key paradigm shifts are proposed; these involve moving from simply focusing on direct and point source impacts to diffuse threats, to recognize flexibility and dynamism in the system, rather than aiming to control static ecosystems, and finally to improve integration and synergies across different policy frameworks that impact conservation (Khamis et al., 2013b).

4.4. Agriculture

In many of the ACQWA case-study regions, problems for agricultural yields by 2050 are likely to be linked more to high temperatures than to increased droughts (Fuhrer et al., 2014); elevated temperatures, particularly if they are sustained over time, are known to have negative effects on both crop and livestock production (Smith et al., 2012). With increasing temperatures, water consumption through the increases in crop evapotranspiration is likely to lead to additional irrigation demands (for example 10% or more in the Swiss segment of the Rhone Valley) in order to maintain optimal yields (Fuhrer et al., 2014). High demand for water for irrigation will in turn place additional pressure on small rivers in catchments with little or no water supply from glaciers (Finger et al., 2011; Fatichi et al., 2014), while larger water sources in valley may not be subject to the same extent of variability. In drier areas with low summer precipitation (e.g., in the Po Basin), potential water shortages for crop growth would be likely, requiring more irrigation to maintain optimal crop yields. The amount of water for irrigation purposes could increase by as much as 35%. Improved water management should include both regulations regarding the allocation of water to different users of the same source, installation and management of reservoirs (Gaudard et al., this volume), and technical measures to improve the efficiency of irrigation by avoiding losses of distribution systems, evaporative losses, and excessive runoff due to over-application of water.

4.5. Hydropower

In terms of hydropower, the changes in the behavior of snow and ice in a warmer climate will affect the management of hydropower plants and dams (Finger et al., 2012). As these are particularly dependent on snow and ice melt for their primary supply of water, the variability in glacier retreat patterns, that are dependent on the size, aspect, and shape, of the glacier, will be a strong determinant for dams. The reduction in surface water flows and seasonal shifts in water availability that model studies suggest, i.e., more availability of water in the earlier months of the year and a longer summer period with lower run-off or drought, will impact hydropower. Climate change may also indirectly affect electricity loads because energy consumption varies with air temperature. Storage-hydropower plants are a more flexible technology with modifiable production periods, whose revenues are less vulnerable to shifts in seasonality than run-of-river power plants. While a more uniform contribution from runoff might be an advantage for reservoir management, a decrease in total annual runoff expected for reservoirs fed by ice melt is likely to negatively affect production. While the changes to the physical determinants of water availability for hydropower operation are important, technological, economic and behavioral changes in the electricity system are, however, expected to exert an even stronger impact than climatic change, at least in the first half of the 21st century (Gaudard et al., 2014).

4.6. Extreme events

Changes in air temperature and precipitation are considered likely to have a range of secondary effects, including on the subsurface temperature and three-dimensional distribution of permafrost as well as on the stability of slopes (Stoffel and Huggel, 2012). However, while there is a theoretical understanding for increased mass-movement activity as a result of predicted climate change in mountain environments, changes in activity are difficult to detect in observational records. In addition, uncertainty remains considerable as a result of error margins inherent in scenario-driven global predictions, and due to the lack of spatial resolution of downscaled projections (Crozier, 2010).

For the southern valleys of the Swiss Rhone valley, indications exist that changes in the frequency of high-elevation debris flows from permafrost environments might not be affected significantly by climatic changes, but that the overall magnitude of debris flows could be larger due to larger amounts of sediment delivered to the channels and an increase in extreme precipitation events (Stoffel et al., in press). Events are likely to occur less frequently during summer, whereas the anticipated increase of rainfalls in spring and fall will likely alter debris-flow activity during the shoulder seasons (March, April, November, December; e.g., Stoffel et al., 2008, 2011; Schneuwly-Bollschweiler and Stoffel, 2012; Toreti et al., 2013). The volume of entrained debris will crucially depend on the stability and/or accelerations of permafrost bodies, as destabilized rock glacier can lead to debris flows without historic precedents in the future (Lugon and Stoffel, 2010; Stoffel, 2010). The frequency of rock slope failures is likely to increase in the future, as excessively warm air temperatures, glacier shrinkage or downwasting, as well as permafrost warming and thawing will affect and reduce rock slope stability in the direction that adversely affects rock slope stability (e.g., Ravanel and Deline, 2011; Allen and Huggel, 2013). Changes in landslide activity in the Alps will likely depend on differences in elevation. Above 1500 m asl, the projected decrease in snow depth in future winters and springs will likely affect the frequency, number and seasonality of landslide (re-) activations. In the French Alps (Lopez Saez et al., 2013a,b) and in the Piemonte region (Tiranti et al., 2013), 21st century landslides have been demonstrated to occur more frequently in early spring and tend to be triggered by moderate rainfalls, but also to occur in smaller numbers. On the contrary, and in line with recent observations, fall events, characterized by a large spatial 34 density of landslide occurrences, might become increasingly scarce (Stoffel et al., 2014).

5. Conclusions and outlook

Climate change in the mountain regions studied in the ACQWA project is leading to modifications in quantity and timing of water resources that have potentially significant ramifications for water governance and management. Water managers will need to adapt to potential increases in runoff in late winter and autumn and potential decreases in spring and late summer. Snow-melt is likely to take place earlier, with increased melt in spring, but less change will be noticed at lower elevations compared to the higher ones. One of the strongest effects is the significant reduction in the glacier melt contribution expected by the middle of the 21st century, and a constriction of the period with high glacier melt that will have repercussions for the management of hydropower reservoirs. At present, glaciers and snow pack provide a valuable buffer of additional water during dry summers, which will be less and less the case in the future. While increased glacial runoff from melting glaciers will at first lead to surface runoff surpluses, continued reductions in glacier volume will eventually result in a decrease of summer runoff. In some of the ACQWA case areas, particularly in the Andes and the uplands of Central Asia, this phenomenon is already occurring (Pellicciotti et al., 2014; Sorg et al., 2012).

The ACQWA project has thus developed climate information for a set of mountain regions downscaled to temporal and spatial scales that are intended to be of use to the challenges decision-makers face. ACQWA policy work focused on three principal domains, namely the identification of underlying water governance challenges in the mountain case-study regions, assessing the adaptive capacity of these regions, and identifying governance mechanisms to better implement adaptive and integrative water resources management.

Climate change impacts in a number of basins dominated by snow and ice melt that water managers and users will need to adapt to change in the quantity and timing of water resources. This is not only relevant to local and regional scales, but also to communities and economic sectors downstream who are reliant on a range of goods from mountain regions and their resources, in particular for electricity, water, and water storage.

A certain level of uncertainty has always existed in water resources planning due to climate variability. Climate change represents an increase in uncertainty, in part due to the speed and magnitude of change compared to earlier periods in the past. Water policy and management frameworks need to cope with both existing and increasing levels of uncertainty from climate variability and climate change impacts. While principles in the management, conservation and adaptation of water resources and ecosystems abound, there still remains a lack of clear policy guidance on practical governance mechanisms and actionable measures, especially in the context of mountain areas (Hill et al., in press-a,b).

Synergies or conflicts across different sectoral policies are particularly relevant in mountain areas, where fragile ecosystems provide valuable economic services such as energy for hydropower, water towers and natural storage systems of water, tourism uses, etc. Existing tensions across economic sectors are likely to be further heightened by impacts from climate change, underlining the need for not only integrative but also adaptive water resources governance and management. There is a clear need for a more integrated and comprehensive approach to water use and management. In particular, beyond the conventional water basin management perspective, there is a need to consider other socio-economic factors and the manner in which water policies interact with, or are affected by, other policies at the local, national, and supra-national levels. It is indeed currently unclear whether current EU water policies are consistent with energy, agriculture, and other industrial policies.

Large integrating projects generally represent a step forward in furthering our understanding of various complex processes and interactions between environmental, economic, social, and technological systems. The ACQWA project is no exception to this rule, and the five years of research has indeed enabled a number of issues to be refined and clarified, but has also identified problem areas that would need to be addressed in future investigations of this nature. Among these, issues pertaining to access to data for research purposes has often been identified as a key barrier to the successful outcome of a project. Policies aimed at ensuring free and unrestricted access to data, especially those generated by the numerous research projects that focus on issues of water availability, quality and management have been recommended (Beniston et al., 2011, 2012).

Finally, many scientists working in large integrated projects highlight a large gap between Science and Policy, as emphasized by Beniston et al. (2012). This is certainly at least partly due to problems of communicating in an appropriate manner the key research results that would be of use to policy-relevant strategies. Awareness of this problem is increasing within the EC and other policy institutions, and hopefully this new momentum will be sustained over time so that conclusions from EU and other water-relevant projects will be widely incorporated into future policies at the local, national, and supra-national levels. Ultimately, the implementation of guidelines, maybe even an EU Directive, on the good governance of data (sharing) could be envisaged as a possible framework, providing advice and general rules on data formats and standards, data storage after project completion or the general terms of access.

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