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High-resolution distributed analysis of climate and anthropogenic changes on the hydrology of an Alpine catchment

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SUMMARY

A fully distributed hydrological analysis at scales significant for water management for present-day, and projected future climate conditions is presented for a catchment in the Alps. We selected the upper Rhone basin (Switzerland) as a test case for understanding anthropogenic impacts including climate change on water resources and flood risk in the Alpine area. The upper Rhone basin contains reservoirs, river diversions and irrigated areas offering the opportunity to study the interaction between climate change effects and hydraulic infrastructure. Anthropogenic disturbances of the flow regime were implemented in detail in the hydrological analysis. We downscaled climate model realizations using a methodology that accounts for the uncertainty in climate change projections related to the stochastic variability of precipitation and air temperature. We showed how climate change effects on streamflow propagate from high elevation headwater catchments to the river in the main valley by analyzing changes in several hydrological metrics and at various temporal scales across 297 control sections. Changes in the natural hydrological regime imposed by the existing hydraulic infrastructure are likely larger than climate change signals expected by the middle of the 21st century in most of the river network. Despite a strong uncertainty induced by stochastic climate variability, we identified an elevational dependence of climate change impacts with a severe reduction in streamflow due to the missing contribution of water from ice melt at high-elevation and a dampened effect downstream. Reduced ice cover and ice melt are likely to have significant implications for hydropower production. The impacts can emerge without any additional climate warming. A decrease of August–September discharge and an increase of hourly and daily maximum flows appear as plausible projected change for the most part of the catchment. However, it is unlikely that major changes in total runoff for the entire upper Rhone basin will occur in the next four decades.

1. Introduction

The Alpine region has been identified as an area particularly vulnerable to climate change in a series of sectors such as flood risk, water resources, ecological services, and tourism (Koenig and Abegg, 1997; Theurillat and Guisan, 2001; Elsasser and Bürki, 2002; Zierl and Bugmann, 2005; Fuhrer et al., 2006; Beniston, 2006; Schädler and Weingartner, 2010; Viviroli et al., 2011; Rixen et al., 2011; Dobler et al., 2012; Beniston, 2012). The European Alps have been, moreover, represented as the "water tower of Europe" (Viviroli et al., 2007; Beniston, 2012) since important rivers flowing through central Europe (Inn, Danube), western Europe (Rhine) as well as toward the Mediterranean sea (Rhone, Po) originate from this region. Moreover, the Alpine region contributes an important fraction of their runoff, especially in summer months (Huss, 2011). Given the importance of the Alps for local and downstream water related activities, there is a pressing need from stakeholders and public authorities for studies addressing implications of climate change on this area (Hill et al., 2010; Beniston et al., 2011). These studies are required to provide information on different characteristics of the flow regime such as amount, seasonality, minima and maxima, as well as estimates of other hydrological variables, e.g. soil moisture and snow cover. The research presented here aims at refining and improving quantitative projections of changes in river flows in the upper Rhone basin and represents the driver for additional impact studies within the European project "ACQWA", Assessing Climate change impacts on the Quantity and quality of WAter (Beniston et al., 2011; Hill-Clarvis et al., 2014).

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The upper Rhone catchment constitutes an optimal test case to investigate climate change impacts in the Alpine region since it includes most of the characteristics of Alpine mountain catchments, such as glacierized areas, a large range of elevations, the presence of numerous river diversions and reservoirs for hydropower operations, and river intakes for irrigation. Furthermore, the upper Rhone is influenced by both mediterranean and continental climate, making the basin particularly interesting to study in a changing climate (Beniston, 2012). For these reasons, several sub-catchments of the upper Rhone basin have already been the subject of studies of climate change effects on the hydrological regime (Zierl and Bugmann, 2005; Horton et al., 2006; Schaefli et al., 2007; Rössler et al., 2012; Uhlmann et al., 2013; Finger et al., 2012; Farinotti et al., 2012). These studies analyzed impacts of climate change at specific locations providing insights on the possible future hydrological regime and related vulnerabilities. They generally found a significant impact of climate change on the runoff regime with a shift toward an earlier onset of snow melt in spring, a reduction of summer streamflow due to glacier retreat, and an increase in dry conditions (Zierl and Bugmann, 2005; Rössler et al., 2012). These changes were found to negatively affect hydropower operations (Schaefli et al., 2007; Finger et al., 2012). Because of their focus on upper tributaries, previous studies did not provide any general, distributed and cross-scale overview of changes in the entire upper Rhone basin. At the same time, the spatial scale at which water managers and policy makers are requested to take decisions is the scale of the entire upper Rhone river basin. Local changes are important but they need to be identified throughout the entire basin since their propagation within the river network might reveal critical aspects for management.

In order to fill this information gap, this study presents a distributed investigation of the propagation of climate change effects on streamflow at fine spatial and temporal scales using a comprehensive hydrological model. Climate change effects are investigated throughout the entire range of elevations, i.e., from the headwater catchments to the main streams in the valleys. We are particularly interested in understanding if the effect of climate change on a number of streamflow characteristics (e.g., mean, seasonality, maxima, minima) has an elevation and stream order dependence and if there are significant geographical differences within the upper Rhone basin. Existing studies are strongly biased toward high-elevation catchments, mostly fed by glacier sources (e.g., Rössler et al., 2012, Uhlmann et al., 2013, Finger et al., 2012, Farinotti et al., 2012), or look only at the basin outlet (Addor et al., 2014). These studies focus on catchments that are not influenced by anthropogenic infrastructure, in order to use their streamflow observations for calibration of hydrological models that simulate the natural flow regime. We argue that results obtained from these studies might provide a partial perspective whereas a more balanced approach to climate change impacts in mountainous catchments should be based on a larger scale and fully distributed analysis, which is the goal of this study.

A significant part of the upper Rhone basin river network is highly regulated through river diversions and reservoirs, which requires the inclusion of this infrastructure and of its operation. This represents a challenge as testified by previous studies in which the hydrology of the entire upper Rhone catchment is simulated (García Hernández et al., 2009; Hingray et al., 2010; Meile et al., 2011). Because the technical data of existing infrastructure are not always available, we adopted a very pragmatic engineering approach to simplify the representation of hydraulic infrastructure whenever this was needed (Section 2.2.4). Numerical simulations were performed with the hydrological model Topkapi-ETH, that is a substantial evolution of the original rainfall–runoff model Topkapi (Ciarapica and Todini, 2002; Liu and Todini, 2002) and of successive updates (e.g. Ragettli and Pellicciotti, 2012). The model was modified for running long-term hydrological analysis in complex topographic environments and to explicitly account for anthropogenic influences. Despite several simplifications, we demonstrated that the adopted methodology provided satisfactorily results in reproducing present day (1990–2008) and natural flow regimes (before 1950). The upper Rhone basin is an excellent case study to evaluate model simulations in reproducing both natural and regulated flows because discharge observations were available at a few streamgauges from the beginning of the 20th century, i.e. before reservoirs and river diversions were constructed. Simulations of natural and regulated flows also allow us to quantify the anthropogenic impact induced by the presence of infrastructure and to compare it with modifications induced by climate change. The presence of hydraulic infrastructure and its operation is assumed to remain unmodified for simulations of future climate, in order to isolate the effects of climate change from any adaptation imposed by altered energy market or demand. However, we acknowledge that reservoir operations could be adapted to respond to future changes. Despite the working hypothesis of unmodified operational rules for the reservoirs, the interaction of climate change with the existing hydraulic infrastructure provides an important perspective in climate change impact studies (Minville et al., 2010; Koch et al., 2011).

In order to simulate future climate scenarios at the catchment scale, climate model realizations have to be transferred to spatial and temporal scales suitable for hydrological modeling. We used a combination of dynamic and stochastic downscaling. Realizations from three climate models, one Global Climate Model (GCM), ECHAM5, and two Regional Climate Models (RCMs), REMO and RegCM3 driven by ECHAM5 were used to derive factors of change for different climate statistics. The factors of change were derived independently for each decade from 2011 to 2050, using the period of 1991 through 2010 as a control scenario. Successively, they were used as input into a stochastic downscaling procedure, which produces an ensemble of realizations for the three driving climate models (Bordoy, 2013; Bordoy and Burlando, 2014a). Each future decade and the control scenario were assumed to be stationary. We limited the analysis to the A1B emission scenario (IPCC, 2000). Since future climate simulations are limited to the year 2050, this choice does not represent a serious limitation because all of the emission scenarios are very similar for the first half of the 21th century (Hawking and Sutton, 2009; Prein et al., 2011).

We acknowledge that using only one GCM and two RCMs could significantly underestimate the uncertainty of climate change projections, since the variability among model realizations is considered as one of the principal sources of uncertainty (Déqué et al., 2005; Räisänen, 2007; Knutti, 2008; Christensen et al., 2010; Hawking and Sutton, 2011). However, the stochastic downscaling approach allows us to alleviate this problem and account for the uncertainty due to the internal variability (stochasticity) of the climate system (Burton et al., 2010; Deser et al., 2012a; Fatichi et al., 2013). A recent analysis of a GCM has demonstrated that internal climate variability can account for more than half of the spread of the CMIP3 multi-model ensemble for several climatic variables, and gives a comparable variability for precipitation (Deser et al., 2012b). Another stochastic downscaling methodology showed that climate stochasticity for precipitation is likely to cover a large fraction (although not all) of the uncertainty generated by considering a multi-model ensemble (Fatichi et al., 2013). Our own analysis (Fig. 1) shows that the range of variability of annual changes for mean air temperature and mean precipitation obtained from the stochastic downscaling (combination of stochastic realizations driven by REMO, RegCM3 and ECHAM5) over the upper Rhone basin is comparable to the range of variability obtained from the ensemble of 20 RCMs used in the ENSEMBLES project (van der Linden and