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Hydrology and Earth System Sciences Discussions

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Interactive Comment

Interactive comment on "Elevational dependence of climate change impacts on water resources in an Alpine catchment" *by* S. Fatichi et al.

S. Fatichi et al.

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Dear Editor Bettina Schaefli,

Please find below our reply to the comments of reviewer-3. This is intended as rebuttal and to further stimulate the ongoing discussion.

Sincerely,

S. Fatichi, S. Rimkus, P. Burlando, R. Bordoy, and P. Molnar

Responses to reviewer 3

Referee: *The paper describes the modelling of the Rhone river basin under changing*

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climate conditions, based on a distributed rainfall-runoff simulation model. The main idea is to use climate scenarios based on the A1B emission scenario, which are used to drive the rainfall-runoff model. This hydrological model integrates different hydrological processes, such as surface runoff, infiltration, snow melt and glacier melt. Moreover, the model integrates other anthropical effects, such as water diversion and storage by hydropower plants. In general, the major processes affecting the water cycle are considerred in this study at a sufficient detail level.

The major results of this contribution can be summarized as follows: 1. The greatest changes in water balance occur at higher elevations 2. The changes in water cycle of the main stream (Rhone river in the Rhone valley) are almost negligible because of the limited part of glacierized areas (the most influenced areas)

In general, it can be observed that these results are not surprising and not new, because they are directly linked to the assumptions of the climate scenarios. 1. A large amount of studies showed that the water cycle in glacierized regions would change with an increasing average temperature. In general, the annual quantity of water would increase and finally decrease due to the loss of glacier mass. 2. The annual influence of the glacier decreases with its relative surface in the catchment area. 3. The increase of evaporation is limited, because the general evaporation is low in high elevation regions such as the Rhone river basin upstream of lake Geneva.

As long as the climate scenarios tell us that the changes in precipitation are limited, the changes in the water balance will be limited as well!

Reply: We summarize below what are in our opinion the novel contributions of the manuscript. While, on the one hand, we agree that qualitatively several results could have been expected following the arguments expressed by the reviewer, we consider, on the other hand, their explicit and extensive quantification for the entire upper Rhone across a large range of spatial scales to represent a novel and noticeable contribution with respect to qualitative speculations and precedent works. In particular, some of the

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results would have been difficult to predict (e.g., the distributed impact of anthropogenic infrastructure and its interaction with the changes, changes in minimum and maximum flow and their uncertainty) without the analysis carried out in this paper. In summary:

- We provide a quantification of the effect of climate change on a typical catchment of the Alpine region by means of simulations carried out through a fully distributed hydrological model. The simulations describe the basin response across the entire river network, from small headwater glacierized catchments to large catchments downstream, and thus allow to investigate *the differential effect of climate change with elevation and basin size* as measured by streamflow characteristics and other hydrological variables. Hence, the title of the manuscript.

- We provide, across more than 290 control points in the catchment (characterized by different elevation, drainage area, topography and fraction of glacierized area) *an estimate of changes of many metrics that were not typically presented before*, for instance, projected changes in maximum and minimum discharge, at various temporal scales up to the hourly one.

- We provide *an estimate of the uncertainty related to the stochastic variability of climate*, which we argue to be, by far, the most important source of uncertainty in the analysis of "distributed" climate change effects on streamflow regime.

- We provide *an implementation of the anthropogenic infrastructure and physical characteristics of the upper Rhone at unprecedented level of detail*, from which we can simulate both the natural hydrological regime and that altered by the operation of hydropower systems (see Figure 4 in the manuscript), thus being able to investigate the net effect of the imposed human alteration and how this could be affected by climate change.

To our knowledge all these points make this paper a very distinct and unique contribution in terms of both methodological approach and level of detail of the results.

Referee: Comments on the general focus of the study

Choice of climate scenarios

The general sensitivity of the system (climate + river basin) cannot be sufficiently estimated by the use of a single emission scenario. Other scenarios could have been tested, with limited number of stochastic realizations. For example: - Prolongation of the reference scenario (persistance) –> what will happen if the next 50 years are similar to the last 30 years (reference period) ? In that case, the difference between the chose climate scenario and the persistance could already show (or not) any difference - Scenario with emissions having a strong influence on precipitations –> could show other types of possible realizations, maybe much more critical.

Reply: While we limited the analysis to A1B emission scenario, we stated in the manuscript that the choice does not represent a serious limitation since future climate simulations are limited to the year 2050 (P 3748 LL 12-16). There is a certain amount of literature (e.g., Hawking and Sutton, 2009; Prein et al., 2011) that demonstrate that all of the emission scenarios are producing very similar trajectories of climate change for the first half of the 21th century. We agree with the reviewer that for analyses beyond the year 2050 (which were outside of the scope of the study that led to this paper), the use of additional emission scenarios could have been important. With regard to the possibility to explore the "persistence" of the control scenario, please refer to our reply at the end of the document.

Referee: *Influence of hydroelectric installations*

The influence of hydroelectric installations is in general correctly modelled (with a water level average filling curve for large reservoirs), for the current situation. However, electricity market will change, and there is no reason to believe that the filling curves will stay similar to the current ones. In this study, it is showed that hydroelectric schemes strongly influence the hydrological regime. But it could be interesting to highlight how more it could change with other filling curves –> are they cumulative and negative

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effects ?

–> I suggest an additionnal analyse showing the influence of anthropogenic effects compared to climate change effects to highlight the most important ones.

Reply: We fully agree that future energy demand (and market controls) might have an impact on reservoir operations and we will emphasize this point in the discussion of the manuscript. However, we consider the assumption of unchanged operational rules for the reservoirs the only possible at the moment, without venturing into a speculative exercise. We could have hypothesized different strategies of reservoir management, but how realistic could they have been? In order to get future operational rules we will need to know changes in the electricity market and changes in the energy policy of Switzerland (both rather uncertain). These modifications will further interact with changes in the resource that our study has investigated. In the EU-ACQWA project, which has funded this study, there are partners that on the basis of our results will work to anticipate possible changes in hydropower operations. We are confident that on the basis of their results, additional investigations will make possible to address the combined effect of climate change and changes in reservoir operations as well as feedback mechanisms.

Referee: *Comments on the modeling*

Glacier model

I see a problem with the assumption of uniform thickness for each glacier. With this assumption, you might underestimate the celerity of ice melt during the first decades, because the thickness is normally smaller at elevations ranging from 2500m to 3000m (glacier tongue). These regions might melt very quickly. However, as the model don't take into account the glacier flow from top to bottom (mass transfer inside the glacier), you might tell that both effects compensate each other. So please tell it.

Reply: The assumption related to the initialization of the ice thickness at the beginning of the simulations is indeed “critical” and we will emphasize the importance of this assumption in the revised manuscript. Ice thickness can have important consequences on the timing of glacier thinning (retreat) and ice melt reduction and in the occurrence of a more or less abrupt transition. If we overestimated the initial ice thickness we have delayed the glacier retreat. If we underestimated it, we have accelerated the process. The latter might be the case in our simulations but as shown by Gabbi et al., (HESS 16, 4543–4556, 2012) the acceleration is likely to be less than 10-15 years. In both cases, all the conclusions of the manuscript remain valid but are just shifted in time by some years. We will expand the discussion of the problem in the revised manuscript, to make sure that this limitation and its implication are clear to every reader.

Moreover, we would like to emphasize here that the size of the basic computational elements (grid elements), which were used in the hydrological simulations, is 250m x 250m. While this resolution can be considered very detailed for distributed catchment hydrology, especially for simulations at the scale of the entire upper Rhone (5338 km2), it is still far from allowing to solve features such as the heterogeneity of the ice thickness distribution. The use of this approximation for ice thickness seems therefore to be justified. After discussing the problem with glaciologist working on this specific topic, and considering that detailed distributed maps of ice thickness for all the glaciers of the upper Rhone were basically unavailable (at least to us), we adopted what was considered the best compromise solution.

Referee: *p.3747 "Simulations of natural and regulated flows also allow us to ...". See CCHydro project. I would write "for one of the first times" or someting similar.*

Reply: To the best of our knowledge the CCHydro project did not present results where the presence of infrastructure is explicitly accounted for and nothing about the change induced by anthropogenic disturbances in the natural flow regime. Furthermore, the methodology used for the hydrological modeling and, particularly, for the climate forcing in the CCHydro project seems to be rather different from the methods used in this study.

Referee: *p.3752 "This represents a much more realistic precipitation forcing ...". Please... Some clever people use precipitation forcing including altimetric precipitation gradient. Try it and compare, it may provide similar results. You are right to use the RhiresD, as it is now existing (what was not the case a few years ago). But other are not stupid. Please read (Tobin et Rinaldo al., 2012) in Journal of hydrology, they tested an interpolation method using external data (altimetric gradient) and it worked.*

Reply: We agree on the fact that when RhiresD was not existing (until recently) other solutions should have been adopted to interpolate the precipitation in complex topographic regions such as the upper Rhone catchment. However, we want to emphasize that using elevation precipitation gradients can help in matching the total amount of precipitation, but it is absolutely not equivalent to having a product such as RhiresD, which actually shows a rather scatter plot between elevation and precipitation. The final spatial distribution of precipitation obtained by using precipitation gradients connected to elevation would be rather different and likely less accurate in many regions. Furthermore, the use of elevation precipitation gradients implies a calibration coefficient (precisely the gradient) to apply to the precipitation input, which might be lead, if adjusted in the calibration procedure, to masking of model deficiencies in simulating other processes. We strongly believe that RhiresD was a very significant factor for the overall good performance that we obtain in the observational period (Table 1). On page 3752, LL 3-7 we simply emphasized the added value of having a rather “precise” precipitation input with comparison to past studies that could not use it, simply because it was not available yet.

We found the study of Tobin et al., 2011 (J. of Hydrology 401 77–89) rather unrelated to our discussion. These authors tested several interpolation techniques at the event scale, providing the comparison of the performance as measured at a single streamflow station, and for three extreme events only. Precipitation spatial patterns of extreme events is likely to be very different from the overall long-term spatial distribution, and from their study we cannot conclude that IDW or Kriging technique would have led to good performance at several stations and for a 18 year periods.

Referee: *p. 3768 "We provided for the first time..." –> No, (Meile et al; Jordan et al.) already discussed these points (regarding the hydropeaking processes and flood processes). The water budget is also considerred by (Huss et al.). –> Please suppress the "first time" and focus the sentence on influence on water budget only, other effects of anthropogenic activity were already analyzed.*

Reply: We wrote on P 3768 LL 7 "We provided for the first time a quantification of present day anthropogenic disturbances in the hydrological budget of the upper Rhone basin", because we did not find in the literature a modeling study able to lead to a plot such as the one we presented in Figure 4 of the manuscript. Jordan, (2007, EPFL PhD thesis), Jordan et al. (2012, International Journal of River Basin Management) focused on the effect of reservoirs for flood risk management but no analysis of the hydrological budget are presented. Indeed, Meile et al. (2011, Aquat. Sci.) showed changes in discharge characteristics induced by the anthropogenic disturbances but a rather different analysis of the results was carried out. We are not aware of any work of Huss et al., which has considered anthropogenic disturbances of the upper Rhone basin but if the referee wants to be more specific in the reference we are open to investigate and consider any relevant reference.

In the revised paper, we will refer explicitly to Meile et al., (2011).

Referee: *p. 3769 "However, the fact that interannual variability of discharge was well simulated..." I do not agree. Interannual variability depends on temperature only, as in your model the ice melt is depending on surface in (m2) of the glacier. You cannot assess the correctness of glacier mass, even by using trends over 18 years. Indeed, ice melt trend is a gradient, and you could obtain the same result with much more ice mass in your model. To check, you need to simulate longer periods up to 2100 to check when your glacier disappear. Please formulate your sentence differently –> the verification of the ice thickness must be achieved by other cross-validation (Funk et al.,*

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etc...)

Reply: We agree with the reviewer in the sense that if the glacierized area remains the same in the 18 years of simulation corresponding to the "observational period", a good simulation of interannual variability is to be attributed to a correct simulations of the basin response to precipitation and temperature rather than being related to the effect of the glacierized area. However, if a fraction of glacierized area is lost during this period, then changes in annual runoff are also due to different glacier cover and to a good initialization of ice thickness (at least in the lower area). We will check this and in case we find a similar glacierized area between the beginning and end of the simulation in the observational period, we will remove the sentence in page 3769 LL 17-19.

Referee: *p. 3771 "These results lead us to argue that broad impacts..." -> I don't agree. The studies focused on sensitive regions and the impacts are significant there. I don't think that the authors of these studies have extrapolated there results for larger basins.*

Reply: Our aim was to underline the fact that since most of the previous studies focused on high-elevation glaciarized catchments, a summary of the state-of-the-art climate change studies on the Alps would have been biased toward showing stronger impacts than the ones could be expected when a larger area is considered. We did not intend to say that the authors extrapolated their findings but simply that the previous literature was biased toward a specific type and size of "Alpine catchment". Through this statement, we intended to underline the importance of studies like the one we present in this paper, where a broader spatial and distributed view to the problem is taken. However, we will modify the sentence in the revised manuscript in order to avoid possible misunderstandings.

Referee: *Additionnal analyzis needed:*

In order to fullfill the analyze, it is recommended to extend it with the following experi-

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ments:

1. Simulate the past 30 years, based on the today's initial condition of the model (particularly the glacier mass), and compare it to the climate scenarios you already presented. In that case, it will really highlight the influence of climate change in comparison with the reference scenario, which for future is not the past years, but the climatology and the actual situation.

Reply: We think that running simulations with the control scenario climate projected up to 2050, could simply tell us which is the acceleration of glacier melting induced by climate change. Being all forcing climates equal to the control scenario the hydrological response would be exactly equivalent to the ensemble of streamflow obtained for the control scenario (1992-2010). The only effects that we could appreciate, are those related to model initialization issues, typically in the soil moisture compartment and in the ice thickness. However, the initialization of soil moisture plays typically a role only for a few months, whereas the initialization of ice thickness is critical and has a long-term role, as we already discussed above. Given the uncertainty and approximation of the initialization of ice thickness, we think that an attempt to quantify the differential acceleration of ice melting induced by future projected climate versus the control scenario climate would be very speculative and thus does not deserve additional and time consuming computations. However, as stated above we will significantly expand the discussion on the implication of assuming a constant ice-thickness for each glacier.

Referee: *2. Compare the reference scenario "without hydropower installations" with the future scenarios "without hydropower installations". Then you might highlight more differences due to climate change, not in water balance, but in seasonal averages discharge. The problem is that in you current analyze, the uncertainty due to anthropogenic influence is too high. Then you might see that anthropogenic activity has a stabilizing influence on the seasonal water regime.*

Reply: Consistently with the reviewer's suggestion, we originally planned to carry out

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an ensemble of simulations with projected future climate but without the influence of the hydraulic infrastructure, i.e., in natural flow regime. However, we came to the conclusion that its outcome would have been very unrealistic and of limited use. The actual anthropogenic disturbances created by river diversions and reservoirs will be in place (very likely) for at least the next 50 years. We thus asked, also within the ACQWA project, who could have interest in an ensemble of simulations for unregulated streamflow in a projected future climate, and concluded that there was no practical or even speculative interest for such a simulation. Therefore, in order to optimize the very large computational requirements of running stochastic ensembles at the selected spatial and temporal scales, we decided to limit our simulations to a more realistic (and useful, in the light of the increased pressure on the hydropower sector due to the future Swiss energy strategy) future climate projections with the presence of hydraulic infrastructure.

Interactive comment on Hydrol. Earth Syst. Sci. Discuss., 10, 3743, 2013.

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