The authors would like to thank anonymous referee #1 for the detailed revision of our manuscript. We especially appreciate the reference to additional literature to incorporate into the study.

Interactive comment on "The importance of glacier and forest change in hydrological climate-impact studies" by N. Köplin et al.

Anonymous Referee #1, received and published: 1 June 2012

This well-written manuscript analyzes the hydrological effect of glacier retreat and forest cover modification in response to climate change. The impact analysis is based on the ENSEMBLES project climate projections and studies the effect of different glacier retreat and forest cover increase scenarios on 15 mountainous catchments in the Swiss Alps. The impacts are assessed in terms of annual runoff as well as in terms of its distribution throughout the year. From my point of view, this "classical" impact study (injecting a number of climate and land use scenarios into a rainfall-runoff model) lacks a critical view on the value of such studies in general and does not sufficiently discuss the results with respect to existing literature.

Please see the detailed answers to each comment below.

Detailed comments

- The literature review in the introduction seems to be incomplete; while it might be possible that there are no previous studies that compare forest cover and glacier cover scenarios in the context of climate change, there are studies that analyze the one or the other for high mountainous contexts (e.g. Stahl et al., 2008; Huss et al., 2008; Huss et al., 2010; Horton et al., 2006; Finger et al., 2012; Zierl and Bugmann, 2005). They should be reviewed and the methods / results critically be reflected. I also recommend reformulating the last sentence of the introduction, which talks about land use in general whereas it should refer to glacier and forest cover.

We reformulated the last sentence in the introduction following the suggestion and included the following text passage in the introduction:

Most studies assessing the impacts of climate change on hydrological systems neglect the effects of accompanied changes in forest cover (see e.g., Elsner et al., 2010; Gunawardhana and Kazama, 2012; Laghari et al., 2012). Only few studies assessed its impact in an alpine (e.g. Zierl and Bugmann, 2005) or pre-alpine, mid-latitude environment (Gasser et al., 2003). While there are a number of hydrological climate impact studies in mountainous catchments that account for glacier retreat (e.g., Hänggi, 2011; Horton et al., 2006; Schaefli et al., 2007), there are few that particularly assess its effect on the projected runoff (Finger et al., 2012; Huss et al., 2008; Jost et al., 2012; Stahl et al., 2008). There is a growing consensus in the scientific community, though, that land cover impacts have to be accounted for in climate impact studies to reliably assess future availability of water resources (e.g., Bronstert, 2004; Hejazi and Moglen, 2008; Viviroli et al., 2011).

The results of the mentioned studies are compared to our results in the discussion section (see detailed responses below).

- Observed fluctuations of forest cover in the Alps: at p. 5986 it is simply stated that forest cover increased at the end of the last century and that this was for an important part due to land use. It would be interesting to have more details here (what caused the increase?), especially since increase of forest cover might be a rather unexpected phenomenon for readers not familiar with the Alpine context (this only becomes clear in the scenario of land abandonment).

We changed the text passage to:

They attributed this increase to both the change in climate and in land use, the latter of which being primarily land abandonment of unprofitable high elevated areas.

- Hydrological model parameterization: the paper does not discuss the implications / uncertainty of model parameterization on the results. Given that most catchments are ungauged (p. 5988, lines 1-5) and that the model parameters had to be regionalized, it is highly probable that parameter uncertainty plays a major role here (the model probably has a huge number of parameters since it uses 22 land cover types). What evidence does exist that the simulation results are not just "artefacts" depending on the selected parameter sets and that other equally good parameter sets would not have given very different results? What evidence does exist that the selected parameter sets are useful for present day AND future scenarios? Personally, I think that state-of-the-art climate change impact studies should properly discuss / address modeling uncertainties and not simply state without any further justification that "the most important source of uncertainty (..) is the climate scenario" as in the current abstract (see also Blöschl and Montanari, 2010).

In the last sentence of the comment above, the reviewer refers to a statement in the abstract saying the climate scenario is the most important source of uncertainty. This statement was formulated too general so that the meaning was misleading. What we actually meant was: “The most important source of uncertainty *in this study* is the climate scenario […]”, because this sentence – together with the two before – summarizes and ranks the relative importance of forest, glacier and climate change that we studied here. We changed that sentence (i.e. included “in this study”) to make this clear. In the discussion section, the same statement was made (p. 6003, l. 26f.), and referenced with three studies (p. 6004, l. 1f.); in the abstract there are, of course, no references given.
The reviewer is right that hydrological model parameter uncertainty was not assessed in this study. We are aware of the fact that parameter uncertainty of the hydrological model might be a crucial source of uncertainty in hydrological impact studies. Several studies in recent years showed, however, that this model parameter uncertainty is of minor importance compared to the uncertainty introduced through the climate model (e.g. Bosshard et al., 2012; Finger et al., 2012; Horton et al., 2006; Schaefli, 2005). We think it is justified to compare our results to those studies, but one should also clearly state that these studies did not compare the climate scenario uncertainty to that of the glacier and forest scenarios. We changed the respective passage in the discussion section which now reads:

[…]. *The finding that the climate scenario is the most important source of uncertainty in hydrological climate impact studies is supported by several recent studies, for example Bosshard et al. (2012), Finger et al. (2012), Horton et al. (2006) and Schaefli (2005). Although those studies compared the importance of climate model uncertainty to that of the emission scenario (Horton* *et al., 2006), to the hydrological model structure (Schaefli, 2005) as well as the downscaling method (Bosshard et al., 2012) and to different glacier scenarios as well as model parameter uncertainty (Finger et al., 2012), we still compare them to our results. We justify this by the fact that the climate model was the dominant uncertainty source in all cited studies, regardless of the very different kind of uncertainty sources the climate model was compared to.*

The case study catchments in our analysis are a representative sample out of 186 catchments analysed for hydrological change in Switzerland (Köplin et al., 2012). The model parameters of the study catchments were regionalized to assess as much different catchment types as possible (i.e. also catchments that cannot be calibrated on measured natural runoff). In this study, 12 tunable parameters (14 for glaciated catchments) had to be regionalized. We added this information in section 2 where the modeling setup is explained in detail. The regionalization procedure (Köplin et al., 2012; Viviroli et al., 2009) is basically a combination of three different regionalization methods. Seven simulated hydrographs resulting from the different regionalization methods are combined to one hydrograph, which then is analyzed for changes. This means that the projected hydrograph does not correspond to one distinct parameter set and examining model parameter uncertainty is simply not possible within this study setup. Moreover, we do not assess a single catchment but a set of six study catchments in the ANOVA. Sampling model parameter uncertainty through, for example, 10 000 Monte Carlo simulation to obtain several equally good model parameter sets for a catchment is therefore far beyond the means of this study. We agree with the referee, however, that the neglecting of model parameter uncertainty should be clearly stated and critically discussed in the manuscript. We included a respective paragraph at the end of the discussion section, which reads as follows:

Another aspect of the hydrological model that should be critically reflected is parameter uncertainty. If the tuneable parameters of the hydrological model could be calibrated on runoff of future climate and land cover states, then the parameter set is likely to be different from the one calibrated on the control period conditions. This is why assessing model parameter uncertainty is crucial, especially when using the model for climate impact analysis and when studying land cover change. For several reasons this assessment was not included in the present study. For example, the study analysed 15 representative case studies taken from a set of 186 catchments in Switzerland (Köplin et al., 2012; cf. Sect. 2). The model parameters for those catchments were regionalized because most alpine catchments in the study domain could not be calibrated on measured natural runoff. The regionalization procedure, however, entails that the resulting hydrographs cannot be referred to one distinct parameter set (for details please see the description in Sect. 2 and Viviroli et al., 2009c), which hinders assessment of parameter uncertainty in general. A common way to sample parameter uncertainty is to generate 10 000 random parameter sets to run the model and to evaluate these so-called Monte Carlo runs for their goodness of fit. This goes far beyond the means, however, when using a semi-distributed hydrological model like PREVAH and when studying a range of different catchments rather than a single case study. Moreover, applying 10 or 100 equally good parameter sets does not at all guarantee that those parameter sets are better suited for climate and land cover change modelling. Other studies showed that model parameter uncertainty is less important than climate model uncertainty (e.g. Finger et al., 2012, Schaefli, 2005). In summary, although we are aware that we did not assess all sources of uncertainty in the present climate impact study, we are also *confident that we assessed the most important source of uncertainty, i.e. the climate model and compared it to the relative importance of glacier and forest change.*

There is, of course, no objective way to really prove that the model parameters are valid under present day AND future climate conditions, because we have no future measurements. In our opinion, the hydrological projections are physically plausible and can be reasonably interpreted. We therefore are confident that they are not "artefacts" but show a sound signal of hydrological change in Switzerland. Moreover, within the whole set of study catchments (in this study as well as in Köplin et al., 2012), the projected change signals are consistent. If they were artefacts, the projections would be random and would not show such a systematic picture of change as demonstrated in Köplin et al. (2012). Furthermore, the projections depict the same change as found in other studies in the alpine space, even those that accounted for parameter uncertainty (Finger et al., 2012).
To summarize, we applied a regionalization procedure in our study to assess every catchment type that is typical for Switzerland. The regionalization entails that we cannot assess hydrological model parameter uncertainty, and we clearly stated this in the discussion section of the revised manuscript.

- I do not understand the tree line calculation; does the tree line simple follow the temperature, without any scaling? (100 m of increase of the e.g. 10°C annual temperature line = 100m increase of the tree line)? If yes, this should be said in a clear way (instead of " The increase in tree line was calculated according to the average temperature lapse rate of 0.56K per 100m")

We are not sure what the reviewer means with "scaling", but we try to explain the tree line calculation in more detail. The added text in the paragraph explaining the tree line calculation is marked in italics:

[...] The increase in tree line was calculated according to the average temperature lapse rate of 0.56 K per 100 m (Körner, 1998; Theurillat and Guisan, 2001). *First the upper tree line of the control period was determined for every catchment. Then the catchment-specific low, moderate and high temperature increase (cf. Sect. 2.1.1) was used to calculate the potential scenario tree line.* For a climate scenario with a rather low temperature increase *(e.g. 2.6 K)*, the scenario tree line would be 465 m higher than the actual catchment-specific control period's tree line (2.6 K / 0.56 K * 100 m).

- The scenarios are designed for comparison with existing studies, but such a comparison seems to be almost absent

The reviewer is right, please see the detailed response below on page 6 of this document.

- Forest scenarios: scenario 1 corresponds to an increase of the tree line with the expected temperature change but what governs the extend of "forest ingrowth" in scenario 2?

On p. 5992, l. 8–11, we explained: "Within the control period's range of lower and upper tree line, first the coniferous forest grows on the allowed areas, then deciduous forest grows and again replaces coniferous within the deciduous forest's tree line boundaries." That is, the size of the "allowed area" (i.e. subalpine meadows, alpine meadow, alpine vegetation, etc., cf. p.

5990, l. 17–20) governs the extent of forest ingrowth. To better highlight that ingrowth occurs *within* the control periods tree line boundaries, we included this information again in the sentence on p. 5992, l. 11:

[…] That is, this scenario reflects a sideways forest expansion *within the control period's tree line boundaries and* in addition to the previous *pure* upwards expansion *in* FC_1.

- ANOVA: the scenarios are of "additive" nature, i.e. one scenario includes the effect of all previous scenarios. This means that variance explained by scenario FC3 includes variance explained by FC1. How can we know how much additional variance is explained by FC3? How can you complete a proper analysis of variance in this context? This should be better explained.

It is correct that the scenarios are of additive nature, but this does not affect the ANOVA, because the ANOVA does not aim at explaining the variance of a single *level* of a factor (i.e. FC_3, for example). It facilitates to assess that part of the variance of a target variable that can be attributed to the total variation of a factor (i.e. the range from F_{CTRL} to FC_3).
The description of the ANOVA and especially the interpretation of the results were however not precise enough before, the other reviewers commented on that, too. Therefore we rephrased the respective text passages. Please see the detailed response to the comments of reviewer #2 and #4.

- In the current manuscript version, the plots give all the water balance components but there is almost no quantitative discussion of these components (and no table summarizing them), which does not help the reader to have a clear picture of the overall changes.

We added a table (also shown at the end of this document, p. 9) summarizing the annual changes in the water balance components for the two extreme case studies catchment 5 (large increase in forest area, no glacier) and catchment 9 (Strong glacier retreat and small increase in forest cover).

- ANOVA results analysis: the text states in 4.3 that "the interaction term is rather small which indicates independence of the scenarios with respect to the considered target variables." This seems rather strange, the glacier retreat scenarios depends on the climate, the same holds for the first forest cover scenario. What explains this independence?

Yes, the reviewer is right. The interpretation of the interaction term was not completely correct. We revised the interpretation of the whole ANOVA meanwhile, motivated by the suggestions of referee #2 and #4. The mentioned text passage now reads:

For all panels, the interaction term is rather small which indicates that the variation in the target variables does not depend on combined effects of the scenarios. In other words, the respective variation can be unambiguously attributed to the variation in each of the single factors.

- p. 6002, line 1-2: something seems to be wrong here ("evaporation (..) comprises (..) evaporation").

We changed the sentence to:

[...] evaporation from snow and ice comprises a non-neglectable amount of the total catchment evapotranspiration in high-altitude catchments.

-The current and future water balance components are almost not compared to previous studies; on p. 6003, line 17 the results are said to be in line with results from Hundecha and Bardossy and Fohrer; both studies apply however to low mountain ranges and do not just analyze forest cover change; the relative importance of glacier retreat and forest cover change are compared to the study of Cuo et al (p. 6003, line 24) who analyzed an estuarine catchment in the US (i.e. with a rather different hydrometeorological context). I would have expected here a more in depth comparison to results from the Alps.

We changed the references and discussed the results in detail. We would like to refer to the revised manuscript for the changed discussion of our results (discussion section, paragraphs 2–4). We did not include the updated text passages in this reply, because it is two pages long.

- At the same location in the manuscript (p. 6003 / 6004), there is the very general comment that climate change is the most important source of uncertainty; which part of the study analyzed this uncertainty? Reference for this statement are two studies in the UK, which are not of direct relevance and one in Switzerland. Please refer here to recent studies from the Alps.

The statement is based in the ANOVA that analysed the variation (i.e. the uncertainty) introduced to the projections through the climate, glacier and forest scenarios. The statement the reviewer refers to is a comparison and ranking of the three kinds of scenarios and their importance for the projected target variables. The complete quote reads: "Climate change, in turn, proved to be the most important source of uncertainty in this study, by far, and dominates the changes in the target variables to a large extent." The referee is right, however, criticizing the choice of the references, and we changed the references (for the updated version, please see the reply on p. 2f. of this document).

- p. 6004: " Evapotranspiration, on the other hand, is of minor importance in this region": as far as I can see, for catchment 5, the future scenarios has 1350 mm of total precip. and 450 mm of evaporation. This seems to be a contradiction with the above statement. A table summarizing the water balance components for all catchments would certainly be helpful (perhaps as suppl. material).

The reviewer is right, the statement was to general. As suggested, we included a table (p. 9 of this document) summarizing the annual water balance components but only for the two case study catchments shown in Figs. 5 and 6.

- p. 6005, line 5: "we question the frequently proposed strong interactions of climate and land cover, at least for the studied climate region"; what is the purpose of questioning the interaction of climate and land cover here? of course, the selected climate simulation conditions the glacier cover; the forest scenario 1 is driven by climate!

This statement is misleading and does not say what we actually meant, so the reviewer is right. We deleted the sentence.

- Conclusion (p. 6005, line 25): which part of your study analyzes the effect of using an ensemble of climate simulations rather than a single simulation? are there results referring to this? furthermore: what do you mean by "assess the impact on lower and higher hydrograph quantiles?" on extreme values?

In the ANOVA analysis, we assessed the uncertainty of the climate model by evaluating the variation in the target variable that is introduced by the full range of climate changes assessed in this study. Regarding the second question, the reviewer is right, we meant extreme values. To make this clear, we rephrased the sentence:

[…] assess the impact of the climate-induced land cover scenarios *on projected low or high flows*.

- Fig. 4: I like the idea of visualizing the scenarios but I find the upper right side difficult to understand

Actually, the upper half of the figure visualizes the information that is already given in Table 1 (of the discussion paper). We decided to just display the scenario coupling for the ANOVA (i.e. the lower part of Fig. 4) to avoid redundancies.

- Fig. 5: this figure is too dense; having temperature, PET, ET, SME and P, for control and future median climate, and for the forest scenarios, in a same plot does not help the reader to actually see what is going on here. I suggest to regroup similar plots with similar symbols in a new figure (1 plot for inputs, 1 with evaporation and soil moisture, 1 with runoff and runoff coefficient). By the way: since the graphs are too dense, things that are said in the text cannot be seen (e.g. " In July and August, even a slight decrease of actual evapotranspiration is observed")

We agree that there was a lot of information in Figs. 5 and 6. We reduced the displayed variables (i.e. removed T, P_{sol}, ETP, RC) and only show the annual cycle of monthly values in the revised version. The annual values are given in the table at the end of this manuscript (p. 9). We followed the suggestion and regrouped the different variables to single panels and we furthermore display now both catchments on a combined figure which should ease comparison. Please see the updated figure at the end of this manuscript (p. 10)

- Fig. 5: the input part shows liquid precipitation as well as solid precipitation and snow melt. This accounts twice for solid precipitation (since snowmelt was solid precipitation before); the plot should show actual liquid input to the system (melt and rain) OR total input to the system (precipitation + glacier melt if there is)

The review is right, we changed that. Please see the updated figure at the end of this document.

- Fig. 6: the inputs should also include ice melt

The reviewer is right. We now show the total melt, i.e. the sum of snow- and ice-melt.

References

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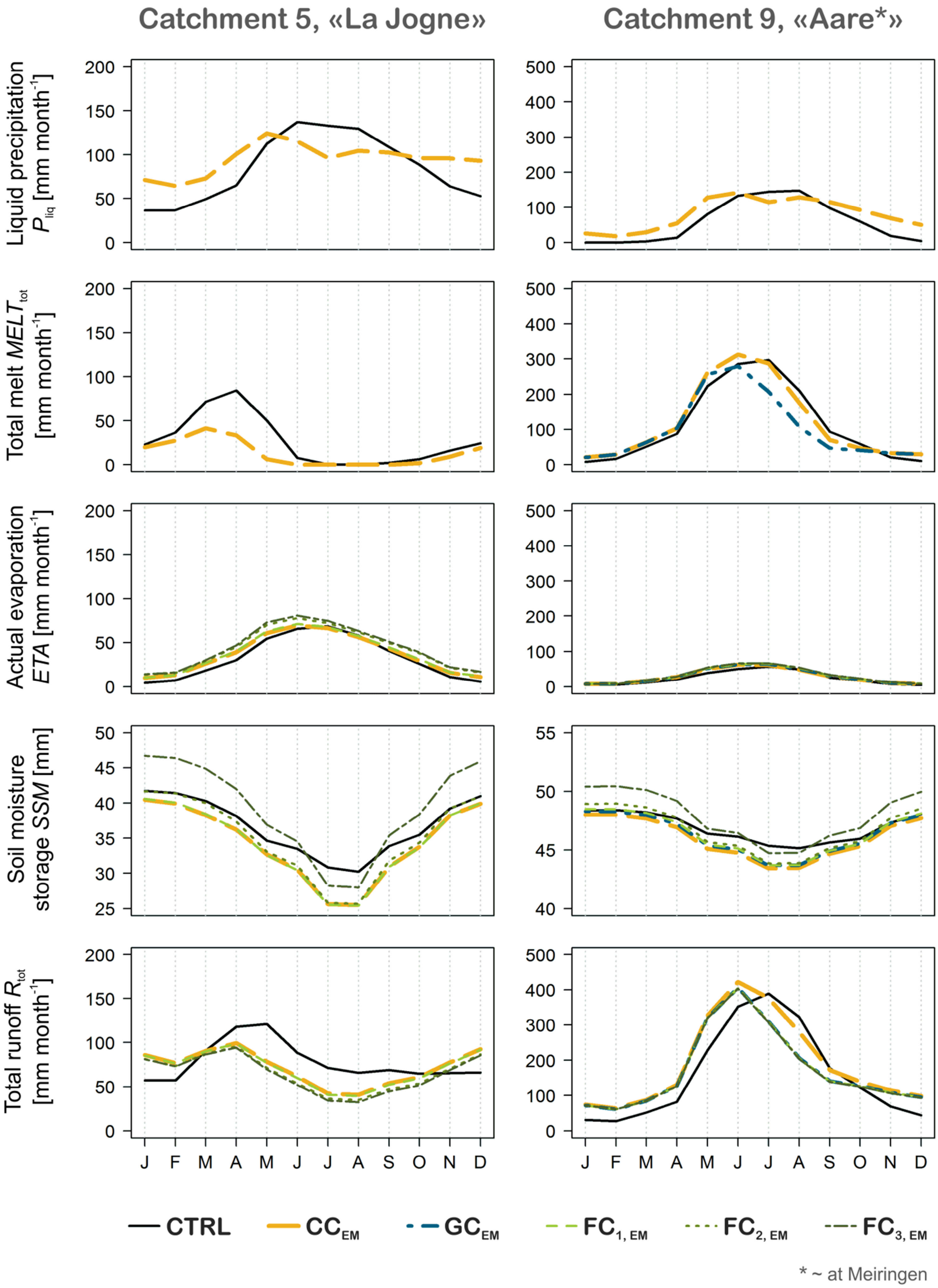
Zierl, B., and Bugmann, H.: Global change impacts on hydrological processes in Alpine catchments, Water Resources Research, 41, W02028, 10.1029/2004WR003447, 2005.

Table 3. Annual values of water balance components for catchments 5 (La Jogne) and 9 (Aare at Meiringen) shown in Fig. 5. The values in brackets are the changes in % relative to the control period, except for temperature where it is the absolute change in K

Catchment 5, La Jogne	CTRL	CC	GC	FC_1	FC_2	FC_3
T [°C]	5	8 (+3)	-	-	-	-
P_{tot} [mm y^{-1}]	1327	1304 (–2)	-	-	-	-
P_{sol} [mm y^{-1}]	335	165 (–51)	-	-	-	-
P_{liq} [mm y^{-1}]	992	1139 (+15)	-	-	-	-
$MELT_{tot}$* [mm y^{-1}]	322	158 (–51)	-	-	-	-
ETP [mm y^{-1}]	416	481 (+16)	-	488 (+17)	538 (+29)	552 (+33)
ETA [mm y^{-1}]	390	442 (+13)	-	455 (+17)	511 (+31)	528 (+35)
SSM [mm]	37	34 (–6)	-	34 (–6)	35 (–4)	39 (+7)
R_{tot} [mm y^{-1}]	935	861 (–8)	-	847 (–9)	792 (–15)	774 (–17)
Catchment 9, Aare at Meiringen						
T [°C]	1	4 (+3)	-	-	-	-
P_{tot} [mm y^{-1}]	2380	2359 (–1)	-	-	-	-
P_{sol} [mm y^{-1}]	1600	1266 (–21)	-	-	-	-
P_{liq} [mm y^{-1}]	780	1093 (+40)	-	-	-	-
$MELT_{tot}$* [mm y^{-1}]	1364	1433 (+5)	1217 (–11)	-	-	-
ETP [mm y^{-1}]	340	478 (+41)	484 (+42)	489 (+44)	497 (+46)	503 (+48)
ETA [mm y^{-1}]	297	353 (+19)	361 (+21)	368 (+24)	376 (+27)	383 (+29)
SSM [mm]	47	46 (–2)	46 (–1)	46 (–1)	47 (0)	48 (+2)
R_{tot} [mm y^{-1}]	1897	2286 (+21)	2062 (+9)	2055 (+8)	2047 (+8)	2040 (+8)

* $MELT_{tot}$ includes both snow- and glacier melt. Catchment 5 is not glaciated, therefore there are no values in column GC, and $MELT_{tot}$ only represents snowmelt.



Catchment 5, «La Jogne»
Catchment 9, «Aare*»
Liquid precipitation
P_liq [mm month-1]
Total melt MELT_tot
[mm month-1]
Actual evaporation
ETA [mm month-1]
Soil moisture
storage SSM [mm]
Total runoff R_tot
[mm month-1]
J F M A M J J A S O N D
CTRL
CC_EM
GC_EM
FC_1, EM
FC_2, EM
FC_3, EM
* ~ at Meiringen

Fig. 5.