The authors would like to thank anonymous Referee #2 for the very detailed, constructive and valuable comments on the paper. We think, they really helped to improve the paper and made it a sounder study. We particularly appreciate all the effort that the referee put in improving the language where it was unclear or not precise.

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

Anonymous Referee #2, received and published: 21 June 2012

The manuscript by Köplin et al. investigates and compares the influence of climate and additional land cover (here: glacier cover and forest cover) changes on the hydrology of 15 catchments in the Swiss Alps. The hydrological model PREVAH is applied to each catchment for a control period and for several scenarios, successively incorporating climate, glacier and forest changes. The effects on water balance components are analyzed. The relative importance of uncertainties in the different types of scenarios are assessed by an ANOVA.

The authors obviously put great efforts into their work. The study is well organized, the methods are mostly well described, and the results are presented in a clear and well organized way. Most of the conclusions are justified by the results presented. To my knowledge, this is the first study that investigates the joint effects of climate and land cover changes in such a systematic and comprehensive manner. In general, I consider the study very relevant for the hydrological climate impact community. It puts different kinds of scenario assumptions into a mutual perspective and allows to draw important conclusions (at least for the sample of investigated alpine catchments). Weaknesses of the study mainly relate to the interpretation of the results of the ANOVA analysis. Some figures are rather overloaden and could be simplified. A literature review on climate land cover interactions (both directions) is missing but should be included. Possible implications of considering additional precipitation changes for the land cover scenarios are not discussed. A number of further issues should be improved as well, see the details below. After accounting for these points, which I'd classify as minor revisions, I consider the study as well-suited for publication. I congratulate the authors for their very nice piece of work.

Please see the detailed answers to each comment below.

MAIN POINTS

- Consideration of precipitation changes: When deriving the glacier and forest scenarios, only the projected temperature changes are taken into account, precipitation changes are not considered. I agree with the authors that temperature changes are probably the most important factor for both glacier retreat and forest cover change in alpine environments. But a more explicit mentioning of this simplification and a brief qualitative discussion about possible implications would be valuable. The projected increase of winter precipitation might lead to a somewhat less pronounced reduction of glacier area (increased accumulation), whereas a decrease of summer precipitation might limit forest growth in dry inner-alpine environments. Furthermore, additionally accounting for precipitation changes (which differ between the climate scenarios) might increase the importance of the CC factor in the ANOVA (if the GC and FC scenarios are indeed calculated separately or each CC scenario; see

1

below). I leave it completely up to the authors to decide whether incorporating such a qualitative discussion or not. It is not absolutely necessary, but might enhance the quality of the manuscript.

We discussed several aspects that might have hindered such extreme forest increases (as assumed in the study) in the discussion section. We think this is the right place to include an additional discussion on the neglected precipitation change and its possible impact on the calculated forest scenarios. We added the following section (highlighted by italics) after l. 12, p. 6004 of the discussion paper:

[…] several additional changes of environmental factors are expected to determine tree line, such as rising CO_2 concentrations, increasing deposition of nitrogen (Grace et al., 2002) and soil water availability (Henne et al., 2011). *Regarding the aspect of water availability, another important feature that was not accounted for is the change in precipitation; the forest scenarios solely depend on temperature increase. Enhanced drought stress in summer caused by decreasing precipitation, however, could lead to a decline of forests, especially in the dry inneralpine valleys (Dobbertin et al., 2006).* Moreover, we neglected natural hazards like avalanches or mudflows […]

Regarding the impact of precipitation change on glacier retreat, we think the relationship is less clear. Surely, the increasing winter precipitation could lead to an increased accumulation. But if the solid precipitation decreases in the scenario (see also the table on page 14 of this reply) then the resulting glacier retreat would be even more severe, regardless of an absolute increase of winter precipitation. This was shown in a study by Zemp et al. (2006) who analysed projected changes in the accumulation areas of 14 alpine glaciers for given temperature and precipitation changes. For a temperature increase of 3 °C in the summer half and an increase of 10 % in annual precipitation the accumulation area would be reduced by 75 % at the end of the 21st century. Most of the applied scenarios in our study are extremer, i.e. hotter and drier. Therefore, we prefer not to discuss this topic in the manuscript.

- page 5989, lines 17-18: "… with scenario-specific temperature changes": It rather seems that the glacier retreat scenarios are not "scenario-specific" (i.e. different retreat scenarios for each climate change scenario), but that some mean temperature change is assumed for GC (see e.g. Figure 4). Please correct me if I'm wrong. The same applies to the FC scenarios (section 2.3). Are forest cover changes calculated separately for each climate change scenario? If so, it might be helpful to mention this fact more explicitly and to modify Figure 2 (which suggests that the same GC and FC scenarios are applied to each CC scenario).

Our description of the GC and FC scenarios derived from the CC scenarios was not precise enough. The ten climate scenarios were assigned to three groups of different temperature increases (a low, a moderate and a high increase), first. Depending on the classified temperature increase, three different scenarios of glacier retreat were then calculated (Linsbauer et al. 2012) as well as three different forest extents for each FC scenario (Sect. 2.3). For every hydrological model run forced with a certain climate scenario (either with a low, moderate or high *T*-increase), the respective GC and FC scenarios were chosen (i.e. low, moderate or high). In this respect, GC and FC are indeed "scenario-specific". To clarify this in the manuscript, we integrated a subsection 2.1.1 "Grouping of climate scenarios", into Sect. 2.1 ("Climate scenarios"):

2

To derive the scenarios of glacier retreat (Sect. 2.2) and forest increase (Sect. 2.3), the ten climate scenarios were assigned to three groups of different temperature increases (a low, a moderate and a high increase, cf. Table 1). For every catchment, the mean annual delta T was calculated and those values were then averaged within a group so that each catchment has a specific low, moderate and high delta T. Depending on these temperature increases, three different scenarios of glacier retreat were calculated (Linsbauer et al. 2012, Sect. 2.2) as well as three different forest extents per forest scenario (Sect. 2.3). For every hydrological model-run forced with a certain climate scenario (i.e. with one of the group low, moderate or high T-increase), the appropriate glacier and forest scenarios were chosen (i.e. low, moderate or high).

To prevent any confusion with Fig. 4 (referee #1 also commented on that), we decided to delete the upper part of Fig. 4, because the information is redundant anyway because Table 1 (of the discussion paper, in the revised version it is Table 2) gives the same information. We did not integrate additional glacier and forest cover extents in Fig. 2, because this would result in rather confusing graphs. Instead, we now clearly state in the caption of Fig. 2 that only the mean glacier and forest extents are displayed, and we refer to the added subsection above as follows:

[...] *Please note that only the mean glacier and forest extents are shown and not the extents corresponding to a low und a high temperature increase (cf. also Sect. 2.1.1).*

- Ensemble mean analysis (descriptive analysis) versus ANOVA: I assume that the authors are aware of the different nature of their two analyses (descriptive vs. ANOVA), but these differences are somewhat hidden in the manuscript and should be pointed out much more clearly. The ANOVA is not just a more quantitative version of the descriptive analysis (as it could easily be understood from the text), but produces an entirely different kind of information. While the descriptive analysis of water balance components is based on ensemble mean values and allows to compare the average effects of CC alone, CC+GC and CC+GC+FC on the water balance, the ANOVA assesses the importance of variations (here: uncertainties) WITHIN the different scenarios (CC, GC, FC) for changes in the investigated target variables. The descriptive analysis, for instance, shows that CC is in many cases the most important factor and that considering additional effects (GC and FC) has only little influence. This does not mean, however, that CC needs to be the most important factor in the ANOVA. If the ten CC scenarios were very close to each other, the influence of variations in GC and/or FC could still be dominant (this is not the case, however). Of course, if the descriptive analysis shows that a certain scenario/factor has only little influence in the ensemble mean, it is very unlikely that variations in this factor will have a strong effect. Still, the different kind of information the two analyses provide needs to be better emphasized in the manuscript. In this respect, it also very important to point out that the ten CC scenarios do not sample the full uncertainty range of future climate change. For instance, only the A1B emission scenario is considered. See e.g. Bosshard et al. (2011) and CH2011 (2011). GC, on the other hand, possibly samples the full range of uncertainties as it ranges from GC_CTRL to GC_NO. Hence, the importance of CC in the ANOVA is very probably underestimated. The fact that the ANOVA focuses on uncertainties within the individual scenarios/factors can partly be clarified by incorporating the following modifications: Page 5996, line 15: Change to "... the relative impacts of uncertainties in ...". Page 5996, line 27: Change to "... the relative importance that uncertainties in the scenarios ...". page 5997, line 2: "variations" instead of "changes".

The authors would like to thank the referee for the valuable comments on the ANOVA and its interpretation. We included the suggested text modifications and revised our presentation of the ANOVA methods and results. We would like to refer to the respective sections in the revised manuscript. The reviewer is right that the different numbers of levels could have an impact on the outcome of the ANOVA; referee #4 commented on that, too. We decided to reduce the ANOVA setup to a 3x3x3 matrix which is explained in the methods Sect. 2.3 "Analysis of variance (ANOVA)" of the revised manuscript (see also Fig. 7 on p. 16 of this document):

[...] *Because the different levels of the factors might influence the outcome of the ANOVA (i.e. a high proportion of variance explained might be an artefact of a high number of levels; it would be 10 for CC, 3 for GC, 4 for FC), we reduced the setup to a 3C × 3G × 3F matrix: the climate scenarios with the lowest, a moderate and the highest annual temperature increase (cf. Table 1) were combined with the three glacier extents (GCTRL, GC, GNO) and three of the four forest extents (FCTRL, FC1, FC3). Moreover, the climate scenarios are driven by three different GCMs. This setup entails that we sample the full range of uncertainties related to the glacier, a large range related to forest change and the full range related to the climate scenarios applied in this study. This full range of CC, however, represents only a certain part of climate change, because the scenarios are based on just one emission scenario, for example. Hence, the CC variation in the ANOVA is very likely underestimated, which has to be considered interpreting the results.*

- climate-land cover interactions: The author's correctly highlight that climate and land cover are linked to each other by various interactions. These, however, are not investigated in their study and should not be confused with the interaction terms of the ANOVA. The study addresses the separate and combined effects of climate and land cover changes on catchment hydrology, but climate-land cover interactions are basically neglected. None of the ten RCMs applied includes a dynamic vegetation scheme or a dynamic glacier scheme, the land cover characteristics are fixed. Assuming a vegetation or glacier response in a fully interactive manner would involve RCM experiments that make use of such schemes and that could account for land cover feedbacks onto the climate. In other words: If a forest change scenario other than F_CTRL (i.e., F_1, F_2, or F_3) is linked to a certain CC scenario, there is some inconsistency as the climate change signal would be different if the climate model would interactively account for forest changes. The same applies for the glacier change scenarios. It is surely beyond the scope of the present study to investigate these effects in detail, but the authors should at least mention this simplification. There's quite some literature available on climate-vegetation interactions (e.g. on recent GCMs and RCMs involving dynamic vegetation modules), and also a few studies on glacier-climate interactions. Some of these could be cited. In this respect, also the statement on page 6005, lines 5-6 is very misleading, as these interactions have not been investigated at all. The authors refer to the interaction terms in the ANOVA, which should be clearly stated.

The reviewer is right, the statement on page 6005 is not only misleading, it is actually wrong. We wanted to say that the additional, climate-driven effect of a changed land cover is small compared to the importance of the climate scenario. When revising the interpretation of the ANOVA results (see above), we deleted the whole paragraph. Furthermore, we added the following statement in the discussion section:

[...] It has to be stated that the importance of glacier and forest cover change could be different, however, if the applied climate scenarios would account for feedbacks between the land cover and the climate. Smith et al. (2010) found for example that the lowering of the albedo through projected increases of the tree line in an alpine environment would lead to a positive feedback on the climate system, which means that the temperature increase would be intensified. Another study (Cox et al., 2000) showed that the vegetation in general would act as a carbon sink until 2050, but turn into a source in the second half of the 21st century which also implies an intensified temperature increase, and which in turn would further alter the land cover. The soil moisture is another important variable influencing summer climate variability through feedbacks with precipitation and temperature (Seneviratne et al., 2006). The climate scenarios applied in the present study do not account for feedbacks between the climate and the land cover, however, and our results show therefore only the one-way (i.e. top-down) effects of climate change and altered glacier and forest cover on the hydrology.

- Figures 5 and 6: These two figures are very complex and not easily accessible. It requires quite some effort to get the essential points out of them. The figures contain a lot of information, some of it very useful, other not immediately relevant. The authors should consider simplifying these figures. For instance, the right hand side panels (JJA, DJF and annual means) could be skipped in my opinion. The same is true for the mean annual cycles of temperature (red symbols in the uppermost panel). In any case, the two yellowish colors for ETP and ETA should be better separated (chose two different colors if possible). Concerning the "input into the simulated water balance" (grey and green bars) it is not clear to me why P_sol and SME are both represented. Isn't that a double accounting and shouldn't it just be SME? (P_sol is stored for some time after it appears again as SME).

Displaying both snow melt and accumulated snow in Figs. 5 and 6 is indeed misleading and does not help to compare the results. We rearranged and simplified the two figures and combined it to one figure (see p. 15 of this document). We followed the suggestions and deleted the annual and seasonal values (right hand side panels) and we removed the variables T, P_{sol}, ETP and RC. We summarized the annual values for all previously shown variables instead in an additional Table 3 (see p. 14).

FURTHER ISSUES

- abstract, line 8: "were derived from" instead of "consist".

We changed that.

- abstract, line 9: I'd suggest to use "changes" here instead of "deltas", as the delta change methodology has not yet been introduced.

We changed that.

- abstract, line 16: "as changes in evaporation ..." instead of "as evaporation ..."; "are concerned" instead of "is concerned".

We changed that.

- abstract, line 22: This statement, referring to hydrological climate impacts studies in general, is too strong. A generalization of the findings is not possible at this point, as correctly mentioned in the following sentence. Better replace "in hydrological climate impact studies" by "in this study".

   We changed that.

- page 5985, line 7: "runoff generation and concentration processes" would be more appropriate.

   We changed that.

- page 5985, lines 9-11: Phenological changes (for a given species) might be another aspect, that could be mentioned here.

   We added *phenological change* to the list.

- page 5985, line 23: "factors" instead of "conditions".

   We changed that.

- page 5986, line 22: "might change" instead of "will change".

   We changed that.

- page 5986, line 23: "... hydrological change when considering only changes in atmospheric conditions?"

   We changed the sentence to:

   [...] hydrological change caused by changes in climate.

- page 5987, line 6: "... the output of ten regional climate models" instead of "... ten regional climate models".

   We changed that.

- page 5987, line 20: Figure 1 also shows the clusters C1 and C7. Does this mean that C1 and C7 are not sensitive to climate change? If yes, why? It might be helpful to clarify this point.

   It is indicated in the legend of Fig. 1, that C2 to C6 are the most sensitive clusters. To explain this more clearly, we changed the caption of Fig. 1 to:

   Spatial (a) and altitudinal (b) distribution of case study catchments. The clustering according to Köplin et al. (2012) is displayed. Out of the seven clusters, C2 to C6 showed the most sensitive response to climate change in the study by Köplin et al. (2012) and we sampled those five sensitive clusters through three catchments each resulting in 15 case studies for further analysis.

- page 5988, lines 1-2: I'd suggest to rephrase this sentence. Not the catchments were parameterized, but the parameters of the hydrological model were regionalized.

We reformulated the sentence, it now reads:

The hydrological model parameters for the study catchments were regionalized from calibrated parameter sets, for details see Köplin et al. (2010, 2012) and Viviroli et al. (2009b, 2009c).

- page 5988, line 6: I'd suggest to add "... neglecting the influence of hydropower production" after ".. land cover change ...".

We included that.

- section 2.1: It is not entirely clear, how the climate scenarios were applied to the PREVAH model. Some more information might be helpful. Did the authors apply areal mean changes of T and P at daily resolution for each catchment? Or was the climate change information applied to individual stations within the catchments and then interpolated to the catchment area? Furthermore, the control period should be mentioned in this section as well as in the abstract. Currently, it is only contained in the caption of Table 1.

We stated the control period in the abstract and Sect. 2.1 of the revised manuscript. Furthermore, we added the following paragraph in Sect. 2.1:

To run the hydrological model with these climate scenarios, we first scaled the observed precipitation and temperature time series of every meteorological station with the station-specific annual cycle of daily change values. Then, the scaled time series were interpolated to the catchment scale with a spatial resolution of 500 × 500 m². Afterwards, the spatially distributed climate data was averaged to 100 m elevation zones. See also Köplin et al. (2010) for a detailed description of the interpolation of climate input data to the catchment scale.

- page 5988, line 13: Change to "... all of them assuming the A1B emission scenario and driven by 5 different GCMs."

We changed that.

- page 5988, line 15: Change to "... of daily changes, yielding a continuous ...".

We changed that.

- page 5988, lines 16-17: Change to "The mean annual cycles of temperature and precipitation for the control period XXX to XXX were provided ...".

The reference to the control period is not correct in the context here. The sentence should explain that the mean annual cycles of the change signals were available for every meteorological station in Switzerland. Our description was obviously ambiguous and we changed the sentence to:

The specific mean annual cycles of temperature and precipitation change were provided for every meteorological station in Switzerland [...].

- page 5988, lines 19-22: Please mention explicitly, that the delta change approach does not account for changes in variability, which might be a strong simplification.

We added the suggested statement as follows (added text in italics):

[...] Because the climate scenarios are based on the Delta Change approach that assesses changes in the long-term mean annual cycle of the climate variables, all of the subsequent analyses of hydrological response variables are based on the mean annual cycle, too (i.e. mean monthly, seasonal and annual values, respectively). *This post-processing method does not account for changes in the variability of the climate variables, though, which might be a strong simplification.*

- page 5988, lines 23-28: A further reference to Bosshard et al. (2011) or the CH2011 report might be helpful here, since more details on the projected temperature and precipitation changes are given therein.

We included both references at the end of the mentioned paragraph.

- page 5989, line 3: "changes" instead of "deltas".

We changed that.

- page 5989, line 7: The correct number is probably 150 m/K, not 100 m/K. Please check.

Yes, you are right, thank you!

- page 5989, line 19: Change to "In PREVAH, the surface that is ...".

We changed that to: "In our study, the surface...".

- page 5990, lines 5-6: Change to "... if no specific retreat scenarios were available.".

We changed that.

- page 5992, line 3: "reduced" instead of "changed".

We changed that.

- page 5992, lines 5-14: Even after having read this section several times, it is still not entirely clear to me how FC1 and FC2 differ. Does FC2 assume that areas that are used for alpine farming within the limits of the tree line today are additionally converted to forests? The authors might think about rephrasing this paragraph to make it clearer.

Yes, this is exactly the difference. In FC_1 trees can only grow *above* the control periods' tree line, in FC_2, the trees grow *within* the boundaries of the control period's tree line. We rephrased the paragraph (changes highlighted in italics):

[...] 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, 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*.

- page 5993, line 20: Change to "... the increased soil depth under FC3. An increased ...".

We changed that.

- page 5994, lines 21-24: Not clear.

Since we decided to delete RC from the whole analysis, the mentioned paragraph was removed from the manuscript.

- page 5995, line 15: Strongest increase of WHAT?

Increase of forest cover. We changed the sentence to:

Catchment 5 shows *both* the strongest increase *and* highest degree of forest cover under FC_2 (CTRL: 32 %; FC2: 87 %) and is not glaciated.

- Section 3.2: Does the ANOVA applied here account for the fact that the three factors contain different levels? Please specify. If this is not the case, one would expect CC to be dominant simply due to the fact that it contains 10 levels as opposed to 3 levels for GC and 4 for FC.

No, the ANOVA did not account therefor. Referee #4 also mentioned this point and we rearranged the ANOVA setup. We now assess a matrix of 3x3x3, i.e.
- 3 climate models (one of the category "low T increase", one "moderate" and one "high", cf. Table 1 on p. 13 of this document),
- the 3 glacier extents and
- only three forest extents (the control extent, the "increase in tree line only" and the extreme scenario "additional ingrowth + soil genesis").
Thereby we sample every factor equally and test the full range of the applied scenarios at the same time. Please see also the detailed response to the comments of referee #4 on this topic.

- page 5998, line 3: I'd suggest to introduce the (very complex) Figures 5 and 6 already at the beginning of this section.

We refer to Fig. 5 (in the revised version it is only one figure) already in the first sentence. As this figure is essentially simplified in the revised version, we think this is sufficient.

- page 5999, line 15: "exactly superimposed": is this really true? Are the values identical?

The referee is right, we were not precise (or wrong) here, and there are indeed slight differences. We changed the text to:

For the target variable Rtot a difference of the four land cover curves is hardly visible.

- page 6000, lines 5-6: "the degree of forest cover CHANGE"!

We changed that.

- page 6000, lines 10-12: No, probably not. As the shown changes are changes w.r.t. the previous scenario, the overall change of ETA is probably still negative (but less negative than for CC alone).

The referee is right; the figure does not unambiguously support this general statement. It is true, however, for the extreme forest scenario FC_3. Then, one has to sum up all three forest net changes. We adjusted the statement in the text:

[...] Remarkable are catchments 13 and 14, where the net change of ETA due to the climate scenario is negative in summer, but it is converted into a positive signal under *the most extreme forest change FC_3 (when summing up the three forest net changes)*.

- page 6000, lines 12-15: Section 4.1 investigated two different catchments (5 and 9), which partly showed an increase of summer ETA due to CC alone (as derived from Figures 5 and 6). Only in catchment no. 5 summer ETA partly decreased (in July and August). I'd therefore suggest to remove this sentence.

We think it is useful to refer to the results from catchment 5, here, because it allows explaining this observation. However, we adjusted the text to make it clear that this was only observed for catchment 5. See the added text in italics:

[...] This effect was observed *for catchment 5* in the previous section, where the climate signal alone yielded slightly decreasing summer *ETA,* whereas it increased under forest change, *particularly under FC_3.* This contrary signal *in catchment 5* was attributed to the strong increase in soil moisture storage under forest change and therefore a higher amount of water available for evapotranspiration.

- page 6001, line 13: Change to "... the present-day forest extents...".

We changed that.

- page 6001, lines 14-17: Not really. For the ANOVA, the degree of forest cover CHANGE is probably most important.

The referee is right, we did not express ourselves clearly, here. The text passage now reads as:

[...] From top to bottom, the present-day forest extents decrease, whereas the glacier extents increase. At same time, the degree of forest cover change decreases from top to bottom and glacier retreat increases (except for catchments 9 and 12, cf. Fig. 7). If there was a causal relationship between the degree of change in land cover and the respective variation in the target variable, the variance fractions of the forest scenarios should decrease from top to bottom, whereas the variance fractions of the glacier scenarios should increase in the same direction.

Furthermore, we added also the

- page 6001, lines 21-23: Similar as above. I guess both the effects of present-day forest cover and forest cover CHANGE can be seen here (which go hand in hand as catchments with a large forest cover fraction also experience the largest forest cover changes).

The referee is right and we adjusted the text saying

- page 6002, line 2: Change to "... of evaporation in high-altitude catchments".

We changed that.

- page 6002, lines 14-18: The authors should consider to remove the target variable RC entirely from the analysis. In my opinion, not much insight is gained by its consideration. Figure 8 would be streamlined.

We followed the suggestion and removed the runoff coefficient RC from the whole analysis in this study. Of course, we initially expected additional insight into the changing processes considering changes in RC. After carefully re-evaluating the insights we gained from the analysis of RC, one has to admit that the main information is an increasing proportion of direct runoff in winter and decreasing direct runoff in summer (see also the comments of referee #4 on this topic). This information, however, is already explained when comparing the change in precipitation and in runoff alone (more liquid, i.e. 'direct' precipitation in winter and less in summer). We think, the reviewer's suggestion helped to accentuate the main results of the study.

- page 6003, line 13: One or two introductory sentences for the discussion section would facilitate the reading. Also, I'd suggest to replace the first sentence of the discussion by "We demonstrated the importance of forest cover changes on the projected evapotranspiration." (see comments above).

This is the revised beginning of the discussion section:

The results presented in the previous section will be compared to existing studies that analysed the effect of glacier or forest change on projected hydrological change. Furthermore, the findings as well as the applied methods will be critically reflected and possible extensions of the study will be discussed.

- page 6003, line 14: "of more than" instead of "on more than".

We changed that.

References (that were not already given in the original manuscript)

Cox, P., Betts, R., Jones, C., Spall, S. and Trotterdell, I.: Acceleration of global warming due to carbon-cycle feedbacks in a coupled climate model, 408, 184–187, 2000.

Seneviratne, S. I., Lüthi, D., Litschi, M. and Schär, C.: Land–atmosphere coupling and climate change in Europe, Nature, 443, 205–209, doi: 10.1038/nature05095, 2006.

Smith, B., Samuelsson, P., Wramneby, A. and Rummukainen, M.: A model of the coupled dynamics of climate, vegetation and terrestrial ecosystem biogeochemistry for regional applications, 63, 87–106, doi: 10.1111/j.1600-0870.2010.00477.x, 2011.

Zemp, M., Haeberli, W., Hoelzle, M. and Paul, F.: Alpine glaciers to disappear within decades?, Geophys. Res. Lett., 33, L13504, doi: 10.1029/2006GL026319, 2006.

Table 1. Annual delta *T* and *P* for every climate model chain. The mean (MEAN), minimum (MIN) and maximum (MAX) values characterize the distribution of the catchment-specific annual change values. The precipitation change signal is given for additional information, but the grouping of climate model chains to the three different classes of mean annual temperature increase (low, moderate, high) is solely based on delta *T*.

Climate model name	Delta *T*			Delta *P*			*T*-increase
(Institution_GCM_RCM)	MEAN	MIN	MAX	MEAN	MIN	MAX	grouping
SMHI_BCM_RCA*	2.3	1.9	2.6	0.98	0.89	1.07	low*
DMI_ECHAM5_HIRHAM	2.6	2.0	2.9	1.00	0.94	1.04	low
ICTP_ECHAM_REGCM	2.9	2.8	3.0	1.03	0.98	1.08	low
CNRM_ARPEGE_ALADIN	3.0	2.7	3.4	0.91	0.88	0.95	moderate
SMHI_HadCM3Q3_RCA	3.3	2.9	3.6	1.07	1.03	1.13	moderate
KNMI_ECHAM_RACMO*	3.3	3.1	3.5	1.04	0.93	1.12	moderate*
MPI_ECHAM_REMO	3.4	3.1	3.9	1.03	1.00	1.06	moderate
SMHI_ECHAM_RCA	3.4	2.9	3.8	0.99	0.94	1.07	moderate
ETHZ_HadCM3Q0_CLM	3.9	3.7	4.0	0.96	0.89	1.08	high
HC_HadCM3Q0_HadRM3Q0*	4.2	4.0	4.4	0.95	0.93	0.99	high*

* These three climate model chains are applied in the ANOVA.

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.

Fig. 5
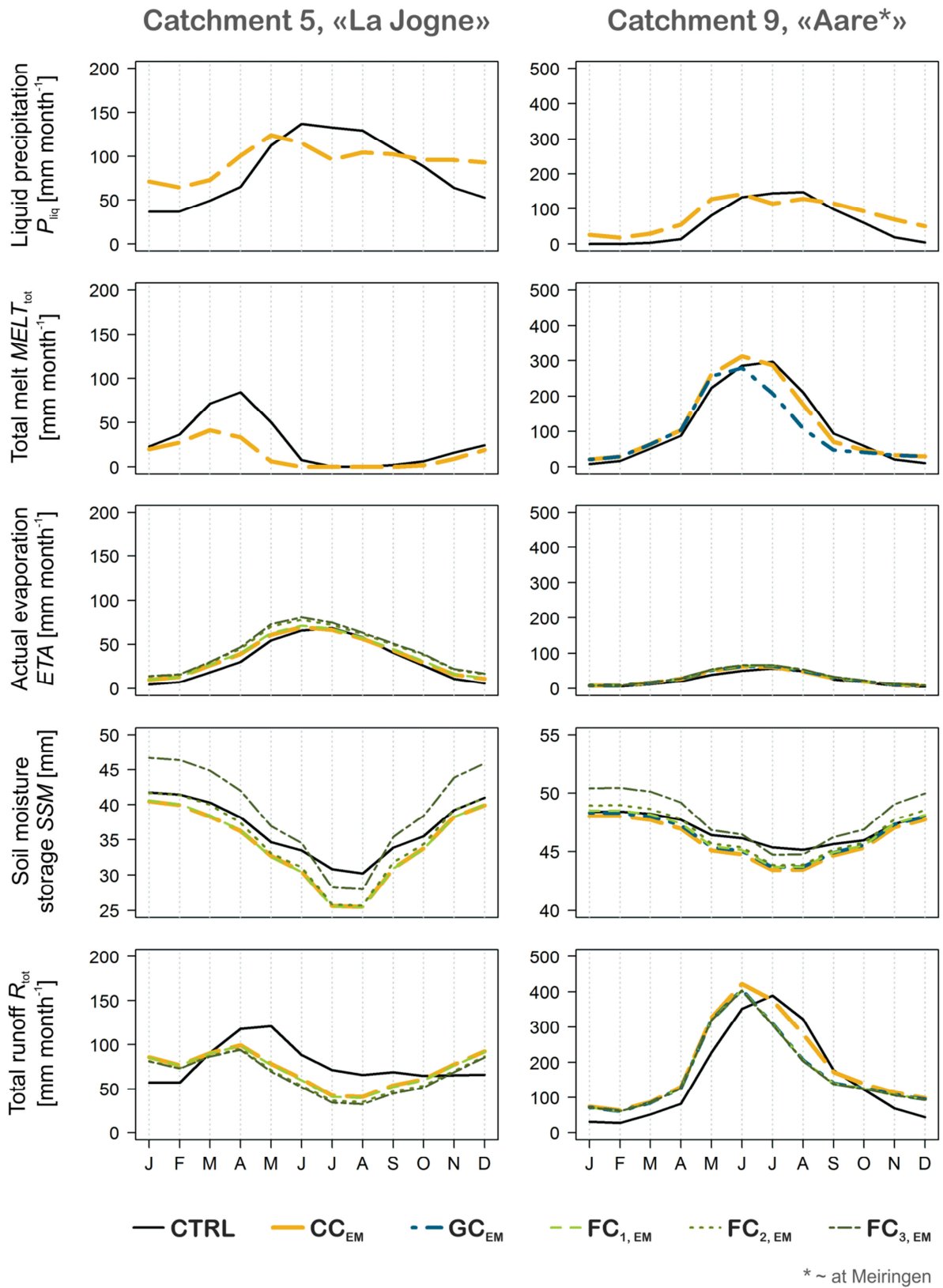
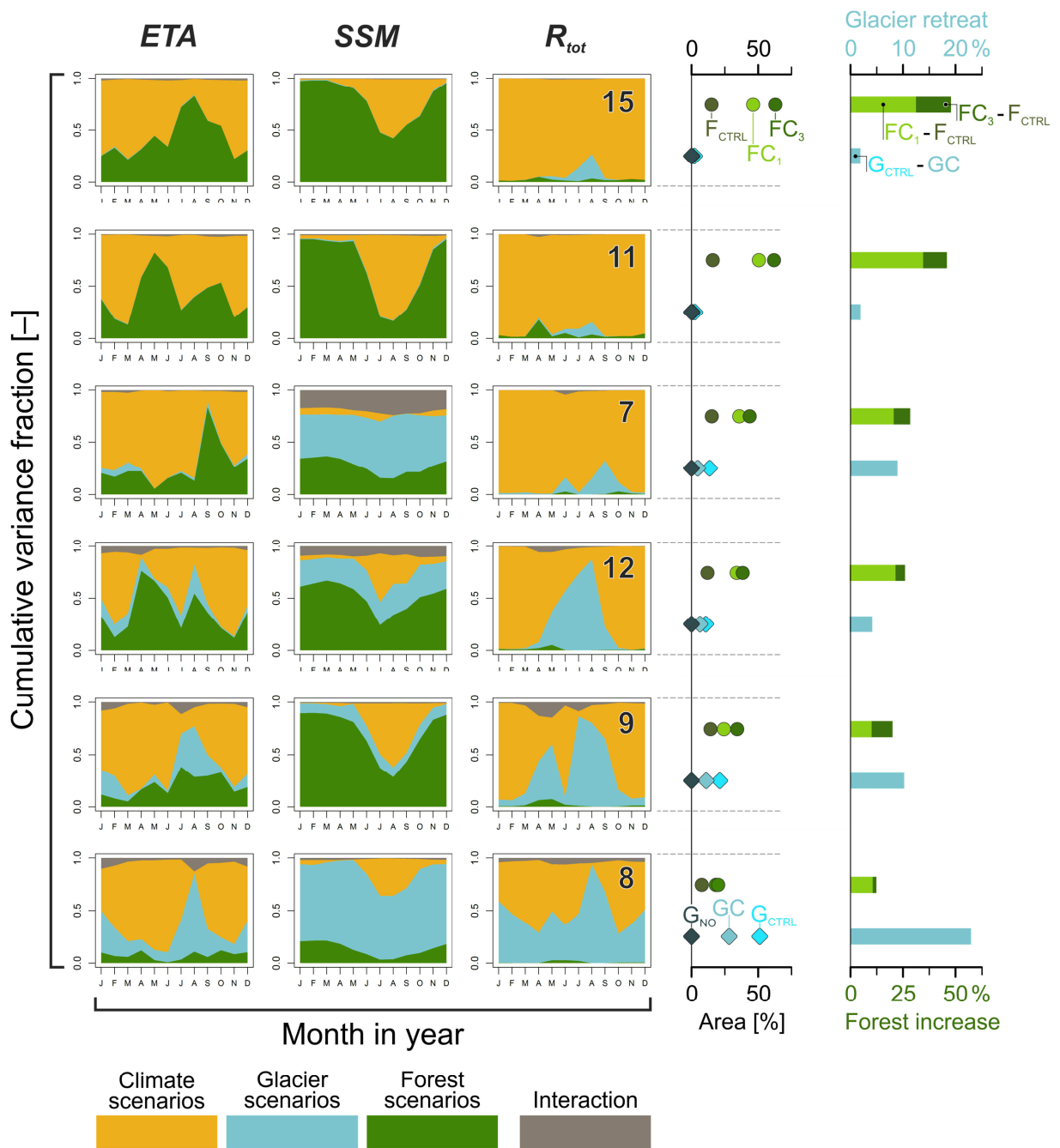Fig. 7