Dear Prof. Bronstert,

We thank you and the reviewers for acknowledging the value of our work and appreciate the constructive comments and suggestions for improvement. The revised version of our manuscript addresses the main point of criticism regarding the use of a control vs. the use of a reference regime. We agree with the reviewers that the use of reference regime estimates derived from the 39 GCM-RCM combinations is indeed more suitable than the use of a control regime derived based on observed meteorology. The methodology and results were adjusted accordingly.

Below, we address the points risen by the two anonymous reviewers and state how we would like to address them in a revised version of the manuscript. Our replies to the reviewers' comments are written in blue and italic to distinct them from the reviewers' comments.

On the behalf of all co-authors,

Yours sincerely,

Manuela Brunner

Reviewer 1

General comments (overall quality of the discussion paper)

The authors have presented a nicely prepared study that applies hydrological simulations driven by different meteorological forcings for past and future climate conditions to estimate changes in high- and low-flow conditions for different rain- and melt-dominated catchments in Switzerland. Thereby, different approaches for estimating high- and lowflow regimes are applied and compared, discussing the individual strengths and weaknesses of each approach. A total number of 39 realizations of three different IPCC representative concentration pathways (8 x RCP2.6, 13 x RCP4.5 and 18 x RCP8.5) is compared to reflect the bandwidth of potential change in future discharge conditions in the catchments considered. As the knowledge on potential changes in highland low-flow conditions is of high societal, economic and ecological importance, the present study is of high scientific relevance with the thematic focus fitting nicely in the thematic scope of HESS. The formal requirements for publishing are almost fully met as reflected in the low number of technical corrections suggested in the following.

My major concerns relate to the comparisons of current and future discharge conditions. While the hydrological simulations representing the data basis for the estimation of current flow conditions are driven by meteorological observations, the simulations for future discharge conditions are based on climate conditions simulated by different GCM-RCM combinations. Although the downscaling approach of quantile mapping has been applied to statistically correct biases in the climate simulations for past and future conditions, the meteorological conditions in the observational data set applied for the hydrological simulations for the past are still not identical to the RCM simulated climate simulations for the past. This induces biases when it comes to the comparison of past and future discharge conditions calculated on the basis of meteorological data from the two different origins. Differences in the meteorological data sets can be expected to occur at shorter time scales (as highly relevant for extreme weather and hydrological conditions) as well as with respect to the interdependency of various meteorological variables, e.g. temperature, humidity and precipitation (such inter-variable consistency is not conserved applying quantile mapping). The existing differences in the meteorological observations and climate simulations with their respective hydrological effects for the past become clearly evident looking at the differences between the hydrological simulations achieved using meteorological observations and simulations in the case of both mean and extreme conditions in Figure 6. Moreover, calibration of the hydrological model seems to be carried out using meteorological observations for the past. While less important compared to the issue described before, calibration can indirectly compensate deficiencies in the meteorological input applied during calibration. Applying the same calibrated parameter set using different meteorological input (with very likely different deficiencies, e.g. those related to the quantification of precipitation) might lead to inconsistencies in the model results. A way to avoid the inconsistencies arising from different meteorological input for the past and future would be to correct the RCM simulations for the past and future statistically (as done in the present study) and later only compare the differences between the hydrological simulations for the past and the future using past and future climate simulations as input for the hydrological simulations. Figure 6 follows this direction but all other results seem to compare current and future conditions generated on the basis of different meteorological input (station observations vs RCM simulations). Using the just outlined approach the hydrological simulations would be better comparable as (hopefully) the same systematic biases are found in the simulations for the past and future. As a large number of RCM simulations are providing meteorological conditions for the past in this study, this would require defining some sort of "one hydrological reference" (e.g., the multimodel mean) the different scenario simulations can then be compared to. Apart from this main point of criticism, some further points for improvement remain, which are described in the "Specific comments" and mostly represent suggestions for clarification as well as options to make the contents of the study easier transportable to the reader.

A final issue to be mentioned is, that at some point a closer linkage of the hydrological results to the climate change signal in the applied climate scenarios for Switzerland (e.g., by showing and discussing the temperature and precipitation change) would be beneficial to interpret the presented hydrological changes. However, considering the large number of scenarios and realizations this is probably beyond the scope of the article and should hence not be an issue that needs to be addressed in the revision.

As a final recommendation, I suggest to accept the article for publication in HESS given all issues have been addressed properly (major revisions)

Reply: *Thank you for your suggestion of replacing the regimes derived from a control run (observed meteorology) by regimes derived from a reference run (simulated meteorology). We followed your suggestion and replaced the regimes derived from the control run by a multi-model mean computed from the 39 reference runs. All the figures affected were updated accordingly.*

Modification: p:9, l:7-9, Figures 7-10

Specific comments (individual scientific questions/issues)

1) p.3, l.24: The authors describe existing approaches for the generation of discharge time series and then name the approach chosen in their study. Although more detailed information is provided in the "Methods section", it might be valuable for the reader to receive some brief description, in how far the applied approach differs from or matches the ones described shortly before. Maybe the authors could add some information on this here?

Reply: *We added a brief description of the differences of the simulation approach employed here as compared to existing approaches. As opposed to classical phase randomization approaches, this approach does not rely on the empirical distribution but uses the flexible, four-parameter kappa distribution (Hosking, 1994), which allows for the generation of a wide range of realizations of high and low discharge values.*

Modification: p:3, l:28-30

2) p.4, Figure 1: This figure is considered very important for the reader to get an overview of the study regions. However, apart from the outlines of the study regions, the map seems rather general and would benefit from some additional detail. Maybe it would be possible to support orientation for non-EU readers e.g., by modifying Figure 1, including a larger scale overview map linked to the original map as well as by adding some more details e.g., the names of larger rivers, lakes or cities?

Reply: *We added an inlet map of Europe, showing the location of Switzerland within Europe. Since the map is already quite busy restricted the labels to the ones already present.*

Modification: Figure 1

3) p.4, l.7: The authors include the information "second step" in brackets - this approach helps to structure the workflow and might be a good extension also for the first and following steps, which are currently referred to as part of the describing text. Having all the steps in brackets would make it easier to navigate through the workflow for the reader.

Reply: *We added the number of the step in brackets.*

Modification: p:4, l:11&14

4) p.4, l.9: The discharge series used for the estimation of extreme regimes are based on hydrological simulations using observed meteorological conditions for past discharge conditions and simulated meteorological conditions (climate model output) for future

discharge conditions. Given the biases in currently available climate simulations the reader here wonders if some correction has been applied before the application of the climate simulations for past and future in this study. Although this is later explained adding "bias-corrected" and "downscaled" might satisfy the readers curiosity at this early point.
Reply: *The information was added to the text.*
Modification: p:4, l:17

5) p. 5, Figure 2: Number 1 in the workflow (comparison procedures) leads to some confusion from my point of view. I understand from the workflow description starting on p.4, l.5 that the different methods for estimating extreme flow regimes were tested, however this comparison seems to require the hydrological simulations of the left side of Figure 2 as input already, which somehow conflicts with the rank in the overall workflow.

Some further confusion in Figure 2 from my point of view arises in the context of the "Data" column. The caption says "A" introduces the simulated data used, however the two plots rather seem to show the meteorological input applied (climate simulations and observations) for the discharge simulations. On the other hand, the data flow from "A" to "C" (the "Estimation" box), as well as that from "A" to "B" requires the two data inputs from "A" to be the discharge simulations achieved on the basis of the two different meteorological data sources (climate simulations and observations). Maybe the authors could clarify these issues in an updated version of Figure 2. It thereby would be an option to use different colors for meteorological input and hydrological model results - while white and orange are used in the figure, the caption does not clarify whether the colors are used in this sense. Maybe it would also be beneficial to use different signatures/colors for the current and future estimates in box "C" and more clearly link them to the discharge simulations based on meteorological observations and climate simulations following the argumentation on p.4, l.9? Maybe also the PREVAH model, which is later mentioned to be used for the hydrological simulations, should be already integrated in the figure to complete the workflow?
Reply: *Thank you for your suggestions. Figure 2 is divided into two parts. The "Data" part and the "Estimates" part. We consider the model simulations to be part of the data generation since the main focus and innovation of our manuscript lies on the "Estimation" part. We did therefore not include the hydrological model into the figure. When we talk about data in this figure, we refer to discharge data, be it observed or simulated. This was specified to avoid confusion.*
Modification: Figure 2

6) p.5, l.12: The authors describe that validation was performed for the period 1983-2005, presumably using meteorological observations as input for the PREVAH model. As climate simulations are used for the model runs for future conditions, I wonder if any validation using climate simulations for the past has been carried out beside the results shown in Figure 6 (e.g., by using hindcast simulations that reproduce weather conditions and allow a comparison of simulated and observed discharge at daily basis)?

Reply: *The hydrological model was indeed validated using meteorological observations as input for the PREVAH model (see p. 6, l:7-9). As suggested in one of the next comments, we compared the FDCs for the reference period 1981-2010 derived based on observed meteorology to FDCs derived for the same period using the simulated meteorological data generated by the 39 GCM-RCM combinations. This analysis showed that the FDCs are reproduced well in most catchments, except for the catchment Engadin. As shown in Figure 6, the model was also validated with respect to the reproduction of past low- and high-flow regimes as these were the focus of this study. We extended Figure 6 by including the high-flow results.*

Modification: Figure 6

7) p.5, l.12: The authors explain that the applied hydrological model has been calibrated for the period 1993-1997. Assuming that the model was driven by meteorological observations while calibrating, the question of systematic biases due to calibration under observed meteorological conditions as well as the application of different meteorological input for the past and future arises. From my perspective both the application of different meteorological input for the past and future (meteorological stations vs climate model simulations) as well as the fact that calibration has been carried out for past observed climate conditions, whereas the simulations are presumably carried out with the same parameter set for future simulated climate conditions, need some discussion.

Reply: *It has been confirmed by Krysanova et al. (2018) who did a review study on the performance of hydrological models under climate change that a good performance of hydrological models in the historical period increases confidence in projected impacts under climate change. We found that the hydrological model well reproduces the hydrological regimes analyzed in this study in the reference period and therefore assume that it will also reliably simulate hydrological regimes under future conditions. A short discussion about this issue was added to the manuscript.*

Modification: p:6, l:9-13

It might be the case that calibration compensates for some of the biases in the observed meteorological input data (e.g. an undercatch in precipitation), which are not present or at least different in the case of meteorological simulations. Particularly in snow dominated regions differences in temperature and precipitation between the two data sources can lead to different water storage in the snow pack affecting the simulated discharge conditions. A comparison of the statistical discharge characteristics achieved for the past using meteorological observations (for which the model was calibrated) to those achieved for the past using climate simulations (which were not used in the calibration) over a climatological period of time could show the differences in the discharge characteristics (e.g., using flow duration curves), which might somehow also affect the comparability of past and future discharge simulations in the present study. Maybe the authors could add some discussion on these issues to the manuscript.

Reply: *As shown in Figure 6 in the manuscript, the water balance of most catchments is well represented by using the simulated meteorological data instead of the observed ones. We* *followed your suggestion and did the validation also on the FDCs directly (Figure 1). The results show that the FDCs are mostly well reproduced by using the simulated meteorological data to simulate discharge. An exception is, as in Figure 6, the Engadin, where high flows are slightly overrepresented. We now discuss in the manuscript that this overestimation might be related to the univariate bias correction applied which might not perfectly reflect the interplay between temperature and precipitation and therefore the timing of snowmelt processes* (Meyer et al., 2019).

Modification: p:12, l:8-10

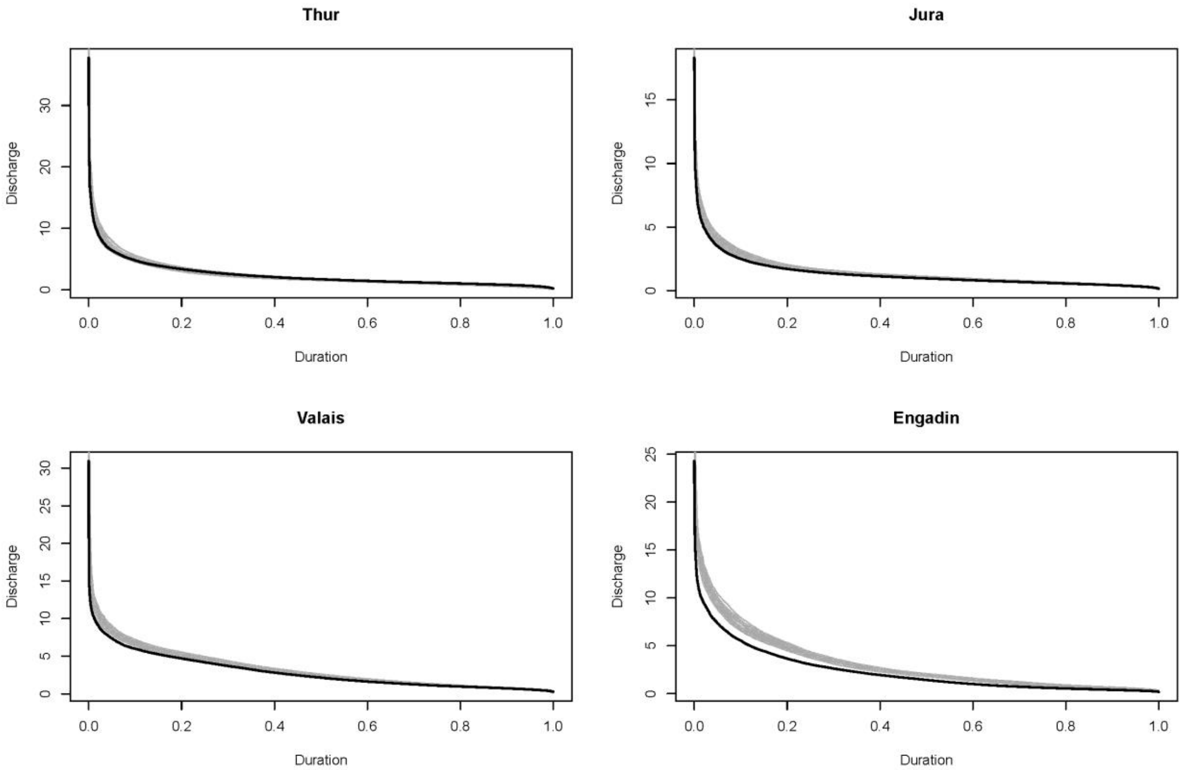

Figure 1: FDCs derived from the control run over the period 1981-2010 (black line) and the 39 reference simulations for the same period (grey lines) for the four catchments Thur, Jura, Valais, and Engadin.

8) p.6, l.2: Two glacier models are applied depending on the length of the glacier considered. It would be interesting why the extended GloGEMflow model is not applied to smaller glaciers (I understand that glacier flow is less important in this case but are there any reasons applying only the GloGEMflow model for all lengths is inadequate?) and what the differences between the results of both models would be - the latter might give an impression of the impact on the overall results induced by using the two different glacier models.

Reply: *For small glaciers a simplified glacier model is indeed used (vs. ice-dynamic model for glaciers >1 km). As shown in the original publication describing the glacier model* (Zekollari et al., 2019)*, for small glaciers the difference between the modeled glacier evolution with the simplified model and the ice-dynamic model is very small though - the difference is found to increase with increasing glacier elevation range (see Figure 12 in* Zekollari et al., 2019*).*

9) p.6, l.11: Does radiation refer to shortwave or longwave radiation or both? Please clarify.
Reply: *We clarified that radiation refers to shortwave radiation.*
Modification: p:6, l:22

10) p.6, l.11 and l.17: Has the approach of Quantile Mapping been applied for all meteorological variables listed in l. 11? Particularly short- and longwave radiation recordings are often not available far back in the past, reducing the possibility to statistically correct the simulations for these variables. Not correcting all variables used as input for the hydrological model would explain differences between the hydrological model results achieved using meteorological observations and those based on meteorological simulations.
Reply: *The quantile mapping approach was applied for all the variables. This was specified in the text. Neglecting the dependence between the variables leads to some deviations between the hydrological model results achieved using the meteorological observations and those using meteorological simulations.*
Modification: p:6, l:32

11) p.6., l.18: Does "model chains" here refer to "GCM-RCM combinations" - if yes, this term would be more precise and should be used alternatively. Or are "GCM-RCM combinations for different scenarios and realizations" the content behind the "model chains" - in any case, please be more precise and avoid the use of "model chains" as it can include quite a lot of pre- and postprocessing steps when used without further clarification.
Reply: *We replaced the term model chain by GCM-RCM combinations for different scenarios since a chain in our case encompasses an RCP, a GCM, and an RCM.*
Modification: the term model chain was replaced throughout the text

12) p.6, l.19: Please rephrase to "for the locations of various meteorological stations".
Reply: *We rephrased the sentence.*
Modification: p:6, l:34

13) p.6, l.23: Please add "for topographic corrections" or a similar completion to "was additionally used".
Reply: *We completed the sentence as suggested.*
Modification: p:7, l:5

14) p.6, l.34: Although later specified, it is not clear whether the applied discharge series is that observed for the gauging stations or the hydrological simulations - maybe adding "(here the simulated discharge for past and future conditions)" would make this clear as early as possible.
Reply: *We specified this in the text.*
Modification: p:7, l:16

15) p.6, eq. 1: What does "i" stand for?
Reply: *We specified that i represents the imaginary unit.*
Modification: p:7, l:20

16) p.6. l.14: "Model chains" is not really precise (see comment 11), please provide additional information.
Reply: *We replaced the term model chain throughout the text and made it more specific.*

17) p. 7, l.24: Here the reader wonders how these unrealistic estimates are handled and how they affect the robustness of the study findings - would it be an option to already point out here that the univariate technique will not find further consideration in the study as later mentioned (see p. 11, l. 2)?
Reply: *This information was added to the text at this early point of the manuscript.*
Modification: p:8, l:10-11

18) p. 7, l.3: Does this mean the typical flow regime assumed is allowed to be different for past and future conditions depending on the simulated discharge time series - this is an important point and needs to be included.
Reply: *This point was included.*
Modification: p:8, l:21-22

19) p. 8, l. 6: Is the number necessarily as high as 1500 years to apply this approach or is it 1500 years because the authors carried out simulations for 1500 years (see p.7, l. 11)? Maybe adding "here" before 1500 would avoid any speculation.
Reply: *The approach is very flexible as to how many simulations are performed. We here run the simulation procedure for 1500 years, which was pointed out in the text.*
Modification: p:8, l:25

20) p.8, l. 13: The authors describe that a "control regime" was generated on the basis of discharge simulations achieved using meteorological observations as input for the hydrological model and that a number of "reference regimes" have been derived from the hydrological simulations based on the different GCM-RCM combinations, resulting in a range of current regime estimates. This is not fully in line with previous statements that describe that the discharge simulations representing past discharge conditions are based on meteorological observations (see p.4, l. 9) so it would be beneficial to modify the statements at p.4, l. 9 accordingly.
Reply: *We extended the statement by saying that we also simulated discharge for current conditions using meteorological input from a set of climate models.*
Modification: p:9, l:5-6

21) p.8, Figure 3: Please add to the caption that this figure is just a schematic illustration of the comparison approach to make clear the underlying data is not generated in this study and should not be interpreted.
Reply: *We added to the caption that the figure is just an illustration.*
Modification: Caption Figure 3

22) Figure 4 & 5: For me it is not quite clear whether the extreme regime estimates for this control setting are derived based on simulated discharge (see p.8, l.13) or on the discharge

observations also illustrated in Figure 4 and 5. However this makes a difference, as using discharge observations for the extreme regime estimation would represent a "perfect setup" to only quantify the uncertainties in the estimation approaches, while using discharge simulations based on meteorological observations (previously defined as "control conditions") would rather illustrate the uncertainty in the whole control setting (which according to the described study design includes the uncertainties from the hydrological modelling using meteorological observations as input) as well as the uncertainties from the individual regime estimation method. Ideally, the extreme regime estimation methods would also be tested using the reference simulations (achieved using climate model data for the past as input for the hydrological model) to show the uncertainty additionally induced by applying climate simulations as hydrological model input (as done for low-flow conditions in Figure 6 using only the FDC method).
Reply: *Figures 4 and 5 are based on discharge derived from observed meteorological data in order to assess the usefulness of the different estimation approaches. This will be specified in the Figures and their captions. The choice of the extreme-regime estimation method was taken based on this comparison. The suitable methods (FDC and stochastic simulation) were afterwards applied to the reference simulations (hydrological model driven with simulated meteorological data). The uncertainty coming from this is shown in Figure 6. We extended the Figure by the high-flow conditions to provide some information on the method's performances for high-flow conditions.*
Modification: Figures 4-6

23) p. 11, Figure 6: This figure is nice as it for the first and only time compares the results achieved for meteorological observations (control simulations) and the climate simulations - is there any reason this is only done for low-flow conditions? There also is some room for improvement with respect to the graphical realization: The different signatures show the "control simulations" (observed meteorological input for the hydrological model) and "reference simulations" (data from different GCM-RCM combinations as input for the hydrological model). The description "Control simulation" and "Climate simulations" is a little confusing, as for the control simulations the word simulations represents hydrological simulations, while in the case of the climate simulations the word simulations refers to the meteorological input applied. I therefore suggest denoting the signatures "control simulations" and "reference simulations" with a detailed description (as already provided) in the figure caption. Moreover, I would suggest to choose a dashed-type of signature for the upper and lower borders of the reference simulations (climate simulations) similar to the future range in Figure 7) to make them distinguishable from the control simulations.
Reply: *We complemented the figure with the high-flow regime estimates. The Figure legend was adjusted as suggested by the reviewer. The borders of the polygons were converted to dashed lines.*
Modification: Figure 6

24) p. 11, l.5: I would in general avoid the word "model chain" and replace it with something more precise (e.g. GCM-RCM combination). "Model chain" is a rather wide term that can

include a hydrological model, the extreme regime estimation or the downscaling and bias-correction procedure (see also comment 11).
Reply: *As mentioned previously, we replaced the term model chain by a more specific term throughout the document.*

25) p. 11, l. 8: Better replace "observed data" with "meteorological observations" to be more precise. I would also replace "means" with "suggests" as it is rather a hint in that direction and not a fact (also the line is in the spread range, the individual reference simulations can be quite far from the line).
Reply: *We replaced the words as suggested by the reviewer.*
Modification: p:12, l:6

26) p. 11, l. 9: The authors explain the overestimation in summer with an overestimation in RCM-simulated precipitation. This is plausible, but shouldn't the precipitation statistics in the RCM data match that of the observations after application of the quantile mapping approach? Maybe the authors could deepen the discussion on this issue in the updated version of the manuscript.
Reply: *The overall precipitation should indeed match the observations. However, precipitation and temperature have been bias corrected in a univariate manner.* Meyer et al. (2019) *recently showed that bivariate (temperature and precipitation) bias correction might be preferable in mountainous catchments where the interplay between temperature and precipitation has a significant impact on snow accumulation and therefore on the seasonality of discharge. This discussion point was added to the manuscript.*
Modification: p:12, l:8-9

27) p. 12, Figure 7: I assume that the current regime is based on the hydrological simulations achieved using meteorological observations as input for the hydrological model (as described earlier in the text, see p.4, l.9). I see a certain weakness of this study in directly comparing the hydrological simulations achieved with meteorological observations (current) and climate simulations (future). While the applied bias correction fits the statistics of the climate simulations for the past to those of the observations (but also only in case of those meteorological variables that are bias corrected, see comment 10), the data sets still are not identical for the past and can be expected to induce different hydrological reactions, particularly when it comes to extreme events. I think the study would have benefitted from using a control regime that is also based on climate simulations, in this case for the past (e.g., multi-model mean of all hydrological model results achieved using different GCM-RCM combinations). Otherwise the systematic differences in the driving data make the results hard to compare. This at least needs to be discussed in the updated manuscript.
Reply: *Thank you for this suggestion. We agree that a comparison of the future regime estimates with an estimate derived using the control run is not ideal. We followed your suggestion and used a multi-model mean derived from the 39 GCM-RCM combinations instead as a reference for the current climate. This multi-model mean was used in the updated figures and to compute the differences between future and current regime*

estimates.

Modification: Figures 7-10

28) p.12, Figure 7: The solid (current) and dashed lines (surrounding the shaded areas) in the case of the "mean conditions" are black in the legend but seem to be grey in the charts - this should be corrected. The caption indicates that the "normal" regimes are provided as a reference in grey, but are these the same as the “mean conditions”, if yes please try to avoid using different words for the same content to make the figure easier to understand. The legend should in this case also be modified to link a grey solid line to the current state and grey dashed lines to the boundaries surrounding the grey areas as described in the caption. Finally, the areas where orange and light-blue areas overlap are extremely hard to distinguish from light-grey areas making the plots extremely hard to read. Please try to update the plots to make them easier to read - maybe there is simply too much information in them? Separating mean and extreme conditions would already make a big difference. Moreover, rather or additionally discussing the multi-model mean instead of the spread in future discharge achieved from all GCMRCM simulations could reduce the displayed information for the sake of readability and interpretability.

Reply: *The legend was corrected. We used the term mean instead of normal consistently throughout the manuscript. The readability of the figure was improved by removing redundant axis labels to save space and by replacing the thick dashed lines around the polygons by thin dashed lines. We did not separate normal from extreme conditions since the regimes derived for mean conditions serve as a reference.*

Modification: Figure 7

29) p.12, l.3: I would suggest to rephrase "These chains" to "Here, the different realizations".

Reply: *The sentence was rephrased.*

Modification: p:13, l:6

30) p.12, l.3: There seems to be also a distinct reduction in mean and extreme conditions for FDC in both rain dominated catchments in spring. Apart from RCP4.5 in the Jura catchment this reduction is clearly evident in both rain dominated catchments and all scenarios. Maybe this could also be an issue of discussion.

Reply: *This observation was added to the text.*

Modification: p:13, l:6-8

31) p.12, l.8: Replace "differences in" with "differences between".

Reply: *The replacement was conducted.*

Modification: p:14, l:1

32) p.12, l. 9: Why has RCP4.5 been excluded from Figure 8. If it is because you expect the changes to be in between those resulting from applying RCP2.6 and RCP8.5 please add a short sentence including this information to the text.

Reply: *We did not include the results for RCP 4.5 to increase the readability of the plot. The results indeed lie in between those of RCP 2.6 and RCP 8.5. A short sentence providing this* *information was added to the text.*

Modification: p:14, l:2-3

33) p.13, l. 1: Do you mean "different" instead of "distinct" - "different" would be better from my point of view as you explain how the changes differ in the following lines.

Reply: *Distinct was replaced by different.*

Modification: p:14, l:6

34) p.14, Figure 8: "Mean" is used in the plot and "normal" is used as a describing term in the caption - I would suggest using one of the terms as the counterpart to "extreme consistently in the figures and throughout the manuscript. Please rephrase "the second three rows" to "the last two rows" in the caption as there are only five rows in total.

Reply: *Mean was used instead of normal consistently throughout the document. The caption was rephrased.*

Modification: Caption Figure 8

35) p.14, l.2: I would suggest to include a brief description of the main findings from Figure 9 before moving on to Figure 10.

Reply: *A short sentence was added the make the transition between Figures 9 and 10 more fluent. The detailed results are discussed after having displayed Figure 10 since it is hard to determine actual changes from Figure 9.*

Modification: p:15, l:1

36) p.14, l.3: Are the changes really "independent of the estimation technique used (FDC/stochastic)" or just in a similar order of magnitude or comparable?

Reply: *We agree that similar is more appropriate and will change the wording.*

Modification: p:15, l:4

37) p.15, Figure 9: As Figure 7 and Figure 9 share many characteristics, the options for improvement described for Figure 7 (comment 28) mostly also apply to Figure 9. Moreover, the y-axes in the case of the Thur catchment need adjustment towards higher maximum y-values as the maxima are cut out in the case of all scenarios.

Reply: *We adjusted the figure according to the changes also made for Figure 7 (see response above). The y-axes of the Thur catchment were adjusted.*

Modification: Figure 9

38) p.16, Figure 10: Please rephrase "the second three rows" with "the last two rows" in the caption as there are only five rows in total.

Reply: *The caption was rephrased.*

Modification: Caption Figure 10

39) p.17, l.17: Better change "include future climate scenarios" to "include the assumptions underlying the applied future global climate scenarios". Maybe also change "the choice of a hydrological model" to "the uncertainties inherent in the hydrological model results".

Reply: *The sentences were rephrased.*
Modification: p:18, l:23-24

40) p.17, l.33: Please replace "regions but the low-flow" with "regions but with the low-flow".
Reply: *The passage was rephrased.*
Modification: p:19, l:7

Technical corrections (typing errors, etc.)

1) p.2, l.6: Better rephrase to "... in the future ...".
Reply: *This was rephrased.*
Modification: p:2, l:6

2) p.5, l.9: I think "glacier melt" in two separate words is the most commonly used form.
Reply: *The word was changed.*
Modification: p:6, l:3

3) p.18, l.23: Please replace "which coincides" with "which coincide" and "high flow" with "high-flow".
Reply: *The phrasing was changed.*
Modification: p:19, l:6

Reviewer 2

Overview

This paper considers future changes in 'extreme flow regimes' in 19 hydrological regions in Switzerland as interpreted from annual flow duration curves and annual hydrographs aggregated as monthly average flows. Two novel methods are applied to generate estimates for the 100-year regimes for the current climate (using simulations driven by observed meteorological data) and a future climate (with simulations driven by bias-adjusted climate model output). The methods are illustrated using four example regions, representing both rainfall-dominated and snowmelt-dominated flow regimes, before being applied to the 19 hydrological regions. The results point towards patterns of change which are distinct for rainfall-dominated vs. snowmelt-dominated flow regimes, and which are consistent with previous work and with changes in the hydrometeorological drivers. The authors also propose that the two approaches applied give similar and consistent results.

General comments

Overall, I find the quality of the work presented to be quite high.

The topic addressed has important practical applications, and the introduction and application of alternative methods for interpreting changes in extreme conditions from data series of limited length (30-year) is much needed in climate change impacts research.

The manuscript is well-written, has a structure and figures that are in most cases clear and easy to follow. I am, however, in agreement with Reviewer #1 that the major weakness of the work is the comparisons made between simulations based on observations (for the current climate) with those based on climate model data (for the future climate) in order to interpret expected changes in flow regimes. One can only justify comparisons between reference and future simulations based on climate model data, due to the inevitable discrepancies between simulations based on observed data vs. climate model data. This needs to be corrected before the manuscript can be considered for publication.
Reply: *Thank you very much for pointing this weakness out. We compared, as also suggested by reviewer 1, the future regime estimates to a multi-model mean derived from the 39 reference simulations. The control run simulated using the observed meteorological data were not be used anymore in comparisons to the future conditions. All the affected figures and results were updated accordingly.*
Modification: p:9, l:7-9, Figures 7-10

Secondly, the choice of the use of a direct stochastic simulation method rather than an 'indirect' stochastic method (which is mentioned but not discussed at all) should be presented in more detail. In particular, the use of a direct stochastic simulation of discharge from 'sampled' discharge (either simulated or observed) entails the assumption that events with long return periods come from the same population as those with shorter return periods (and can therefore be extended based on their power spectrum or using other extrapolation techniques). With 'indirect' methods, this constraint is less severe, in that driving factors producing the flows (e.g. precipitation and initial conditions) can be modelled individually and thus will potentially produce a wider range of likely flow conditions and as of yet unobserved combinations. There are nevertheless many drawbacks with the 'indirect' methods, so the authors should use the opportunity to here to highlight why they have chosen their particular stochastic approach.
Reply: *The direct stochastic simulation approach used here uses a very flexible distribution (four-parameter kappa) to model the distribution of daily flows, which allows for the generation of a wide range of flow values including low and high extremes. The statistical model is therefore well able to produce extremes. Furthermore, the focus of this study was not on individual events but rather the whole regime and the reproduction of single events would therefore anyway be less relevant than for other applications especially focusing on extreme events. We think that this simple approach has the advantage of not including many uncertainty sources commonly included in hydrological modeling (e.g. choice of model, parameter equifinality). A justification for having chosen a direct instead of an indirect approach was added to the manuscript.*
Modification: p:3, l:15-19

My final reservation about the manuscript as it is currently presented is that the discussion of the performance of FDC and stochastic methods is limited and rather superficial. I don't see that the two methods give uniformly similar results, particularly for high flow regimes in rainfall-dominated catchments. The magnitude of the change in maximum discharge under a future climate are both higher and lower for the stochastic method than for the FDC method and the projections give different seasons for the maximum.
Reply: *We agree that there are some differences between the two approaches which are now discussed in more detail. We extended the discussion section saying that the differences between the two methods mainly lie in how the seasonality is derived. In the case of the FDC approach, mean seasonality is used. In the case of the stochastic approach, a rather "random" seasonality is used since the regime is chosen according to the annual discharge sum. The direction of changes derived from the two estimates are similar except for changes of minimum discharge in the low flow regime and minimum discharge in the high flow regimes.*
Modification: p:18, l:5-10

In addition, results comparing simulations based on observed vs. climate data for the current climate are not shown for high flows. Given discrepancies between the two methods found in other figures, one would also like to be able to assess the correspondence between the simulations for high flows. A full development and discussion of the results, with reference to the different aspects considered here (i.e. snowmeltvs.rainfall-dominated catchments and high flow vs. low flow regimes) would significantly enhance the contribution of this work to the scientific literature. Overall, I find this to be a valuable piece of work will be worthy of publication, once the issues raised above have been addressed. Otherwise, I have only a few additional minor comments, questions and proposed corrections as given below.
Reply: *The validation results were also shown for high-flow, i.e., Figure 6 in the manuscript was completed by the high-flow regime estimates.*
Modification: Figure 6

Specific comments

P1 – Abstract: Well-presented, but at this point in the manuscript I also needed a clarification as to what is meant by 'flow regime'. Perhaps you should more clearly emphasis that in your end results you are interpreting/analysing 'flow regimes' using annual hydrographs comprised of monthly averaged flows. Particularly, for the case of high flow regimes, the time unit analysed is of interest.
Reply: *A specification was added to the text.*
Modification: p:1, l:3

P2 L24-25 I don't agree with the statement that the focus on an individual characteristic "neglects the pre-conditions of low- and high-flow events", at least in terms of how most climate impact studies consider changes in this variables. For example, if one is evaluating changes in maximum daily flows based on daily simulations of 30-year periods for a present and a future climate, potentially higher flows in the period preceding the largest events are

also represented in those simulations, i.e. they are not neglected. It is true that by considering an index which targets a broader time window or discharge range you are able to more directly interpret why these changes occur, e.g. because discharge is elevated for a longer time period and is thus more susceptible to extreme precipitation. In the 'standard' one characteristic approach, this would require a further analysis. A similar argument can be made for low flow indices, i.e the antecedent conditions are simulated and can be analysed if one requires additional information as to factors responsible for the estimated changes. However, to simply state that pre-conditions are neglected is misleading and incorrect.
Reply: *We did by no means intend to say that the use of climate simulations does not allow for the consideration of extreme events. What we intended to say was that frequency analyses often focus on one hydrological characteristics instead of considering the flow regime as a whole. Flood frequency or low flow frequency analyses typically do not explicitly consider antecedent conditions. The sentence was rephrased to avoid confusion.*
Modification: p:2, l:22

P3 L15-20 As mentioned in the general comments, this paragraph needs to justify why direct stochastic simulation of discharge is used in this work. I would therefore suggest that the paragraph opens with a sentence describing what stochastic simulation is in general, and that this is followed by a more thorough discussion of the advantages and disadvantages of indirect vs. direct approaches, before you jump into a detailed discussion of options for direct simulation. It is important that you place the direct stochastic simulation method you have chosen within its broader context, and argue for why it is preferable and suitable for use here. In particular, there is a wide and growing literature on 'indirect' stochastic simulation which should be covered here with at least 2-3 sentences.
Reply: *We introduced the aim of stochastic simulation and added a short overview on the two different main approaches: direct and indirect. Then, we explained that we chose a direct simulation approach because it's easy to apply and works without having to progress precipitation through a hydrological model.*
Modification: p:3, l:15-19

P6 L17 'regional downscaling approach based on quantile mapping'. . ..more detail is needed. In particular, it is not clear in the description given in L20-L21 at what point the bias correction with quantile mapping is applied. I assume that the same data which is used for the simulations based on observed data is used for the bias correction. . ..is this correct? In addition, what is the time period of the observed data used for bias correction?
Reply: *The quantile mapping was applied to simulated raw model data, which were bilinearly interpolated from the 12 or 50 km RCM resolution to the observational 2 km grid. It was performed on a grid-cell-by-grid-cell basis. The calibration was performed with the observed gridded data on the period 1981-2010, which was used to drive the model in the control run. More detail on the quantile mapping procedure were provided in the updated version of the manuscript.*
Modification: p:6, l:31-32

P6 L18 . . ..'39 model chains (Table A1'. The choice of models used should be discussed, rather than leaving it to the reader to decipher a table in the appendix in order to determine how many different GCMs vs. RCMs vs. RCPs vs. grid resolutions are represented by the 39 simulations. The different models, etc. represented in the ensemble will indeed have an effect on both the mean values estimated and the spread about the mean, and the 39 model chains used here are only a subset of available EUROCORDEX simulations. In particular, it is unclear to me why both EUR-11 and EUR-44 grid resolutions have been used, if the climate model data are used for hydrological simulations at a 200-m grid resolution. I suspect that the EUR-44 simulations have been included to give a larger ensemble; however, this also means that the GCMRCM combinations that are available for both EUR-11 and EUR-44 are more heavily weighted in the ensemble. A brief (2-3 lines) discussion of the composition of the ensemble is therefore needed in the manuscript.

Reply: *The ensemble was more thoroughly described and a discussion on its composition was provided.*

Modification: p:6, l:34-p:7, l:3

P7 L13-14 Need to also generate stochastic series for the current 'conditions' using the hydrological model simulations based on the 39 model chains for the period 1981-2010.

Reply: *We derived stochastic simulations from the reference simulations derived from each of the 39 model chains. These were later on used to estimate the extreme regimes for the reference period and to compute a multi-model mean serving as a reference.*

Modification: p:7, l:29-31

P8 L2 – 'Long-term mean'. . .can be more specific, i.e. the mean regime over the period 1981-2010? I assume from your figures that this is aggregated by month?

Reply: *The long-term mean for the current conditions was computed over the period 1981-2010. The one for future conditions over the period 1971-2100. We specified that the regime varied for current and future conditions and that it was computed at a daily resolution but aggregated to a monthly scale to allow for a comparison between the univariate and FDC estimates.*

Modification: p:8, l:28-29

P8 L14-15 It is this 'reference' simulation which should actually be the 'control' simulation and be further used to evaluate future changes

Reply: *We agree and now use a multi-model mean reference simulation to derive the differences in regime estimates between future and current conditions.*

Modification: p:9, l:11-12

P8 L17 'were treated separately'. . ..not sure what is meant by this. Perhaps simply that the results were grouped by RCP?

Reply: *This was rephrased as suggested.*

Modification: p:9, l:12-13

P10 L5-7 Why is the seasonality so variable between the FDC, Stochastic and Univariate estimates in the rainfall-dominated Thur and Jura catchments? Doesn't this undermine the credibility of these methods for considering high flows in these and other rainfall-dominated catchments?

Reply: *We specified that the univariate approach produces unrealistic results in terms of seasonality, since the predictions of the monthly 100-year flows neglects the dependence between the different months. The FDC and stochastic approaches produce rather similar results excepts for the Thur catchment. While the FDC approach works with a mean seasonality, the stochastic approach uses the seasonality of one specific realization (annual hydrograph), whose discharge sum corresponds to the 100-year discharge sum.*

Modification: p:10, l:2-3, p:18, l:5-10

P10 L10-12 Given my comment above, I am also curious as to what Fig. A1 looks like for high-flow regime estimates? In particular, the stochastic results for Jura in Fig. 5 suggest that the method doesn't perform better than the univariate approach in that case.

Reply: *The stochastic approach is not supposed to exactly reproduce the mean seasonality reflected by the FDC approach. While the seasonality generated by the univariate approach is something completely artificial, the seasonality produced by the stochastic approach could have been observed. Figure A1 was also produced for the high-flow estimates and is provided here for completeness.*

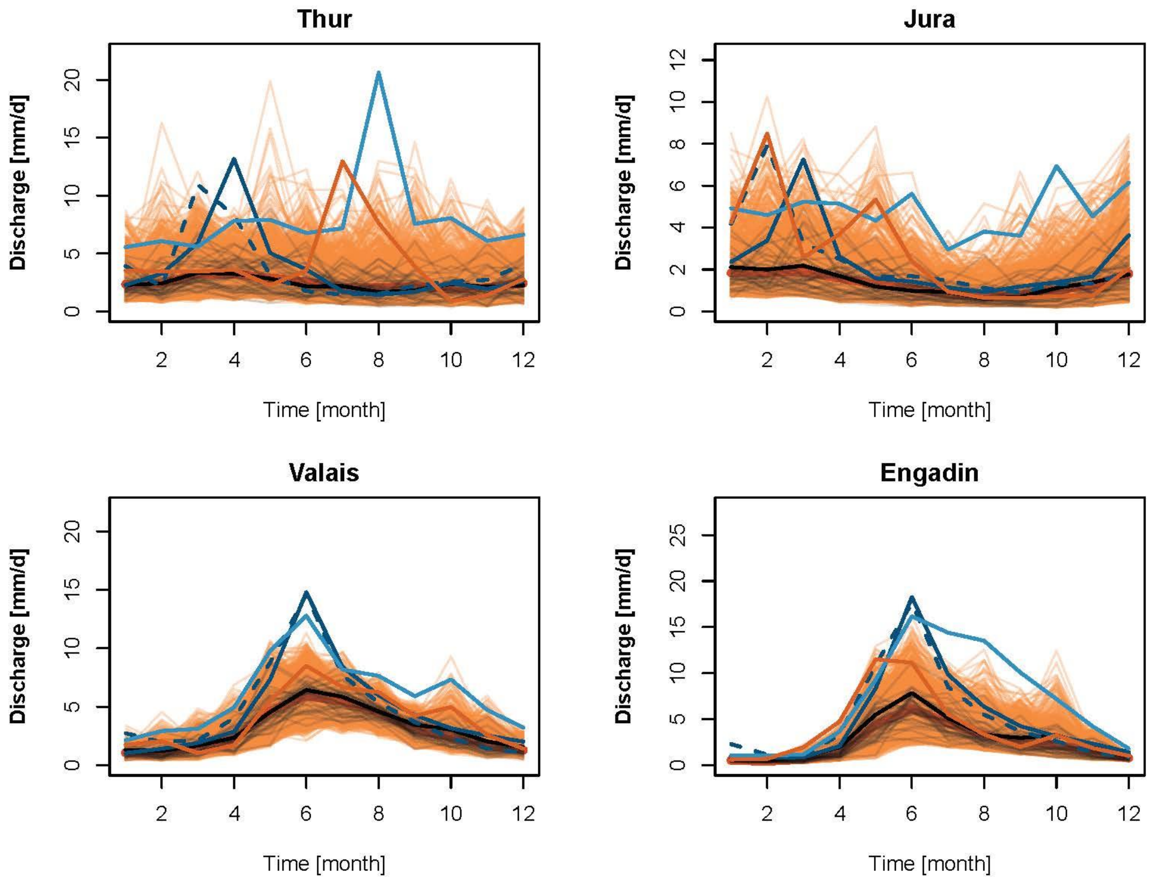

Figure 2: Comparison of the 100-year high-flow estimates, univariate, FDC, and stochastic with stochastically generated hydrographs (orange lines). The legend is equivalent to the one provided for Figure A1 in the manuscript.

P11 Sec 3 Would also like to see a comparison of the climate simulations and the control simulation for high flows, similar to that shown for Fig 6 for low flow regimes.

Reply: *Figure 6 was extended by the high-flow regimes.*

Modification: Figure 6

P12 L10-11: Changes in mean flow of up to 50%, etc. These estimates are not reliable because you are comparing the results of simulations based on climate model data (future) with those based on observations (current), and thus are also including some the error illustrated in Figure 6 in your estimates.

Reply: *We newly computed the differences between current and future regime estimates by using the multi-model mean derived from the 39 reference simulations as a reference estimate. The text was adjusted accordingly.*

Modification: 3.2 current and future low-flow estimates

P17 Section 4.1: In addition to discussing the overall merits of the two methods, it would also be useful to see a discussion of their relative performance for high vs. low flow regimes and for rainfall-dominated vs. snowmelt-dominated catchments. I also find that the second paragraph in this section is too general and should focus on discussing and expanding the results you have presented in more depth. It would also be useful, for example, if you could highlight aspects of the methods you have used which are better for quantifying changes in flow regimes useful for management purposes, relative to those commonly used for climate impact studies.

Reply: *The differences between the estimates derived using the FDC approach and those derived using the stochastic approach were discussed in more detail. However, it is difficult to say which one is the "better" method since the "true" 100-regime estimate is not known.*

Modification: p:18, l:5-10

P18 L15-16: 'Both were found to provide realistic, mutually-agreeing results'. I think that this is bit overstated. In particular, the results for the high flow regimes for the 19 regions (Fig. 10) show a similar direction of change (in most cases), but the magnitude is in some cases much higher with the Stochastic method, and this would have significant implications for their application in practice.

Reply: *The statement was weakened by replacing mutually-agreeing with similar.*

Modification: p:15, l:4

Technical comments

P1 – Keypoints: (L22) – 'are changing' should be 'will change', i.e. you have not examined patterns of change under current conditions, which is what the English used here implies

Reply: *The keypoint was rephrased.*

Modification: Keypoint

P2 L17-18: Considering rephrasing, for example to: For planning purposes and river basin management, however, estimates not only for normal conditions but also for extreme conditions are needed.

Reply: *The sentence was rephrased.*

Modification: p:2, l:17-18

P4 L3. . .should add 'under the current climate' after 'regime.'

Reply: *We specified this.*

Modification: p:4, l:9

P12 L4 Replace 'expressed' with 'pronounced'

Reply: *Expressed will be replaced by pronounced.*

Modification: p:13, l:6

P14 Fig 8; P16 Fig10 caption: In line 3 should be 'The top three rows show relative changes, and the bottom two rows show changes in months'

Reply: *The captions were adjusted.*

Modification: Captions 8 and 10

P18 L8-9: Replace 'We here showed' with 'We have shown here'

Reply: *The sentence was rephrased.*

Modification: p:19, l:15-16

References used in the answers to the reviewers

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Future shifts in extreme flow regimes in Alpine regions

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Abstract. Extreme low and high flows can have negative economic, social, and ecological effects and are expected to become more severe in many regions due to climate change. Besides low and high flows, the whole flow regime, i.e. annual hydrograph comprised of monthly mean flows, is subject to changes. Knowledge on future changes in flow regimes is important since regimes contain information on both extremes and conditions prior to the dry and wet season. Changes in individual low- and high-flow characteristics as well as flow regimes under mean conditions have been thoroughly studied. In contrast, little is known about changes in extreme flow regimes. We here propose two methods for the estimation of extreme flow regimes and apply them to simulated discharge time series for future climate conditions in Switzerland. The first method relies on frequency analysis performed on annual flow duration curves. The second approach performs frequency analysis on the discharge sums of a large set of stochastically generated annual hydrographs. Both approaches were found to produce similar 100-year regime estimates when applied to a data set of 19 hydrological regions in Switzerland. Our results show that changes in both extreme low- and high-flow regimes for rainfall-dominated regions are distinct from those in melt-dominated regions. In rainfall-dominated regions, the minimum discharge of low-flow regimes decreases by up to 50%, whilst the reduction is of 25% for high-flow regimes. In contrast, the maximum discharge of low- and high-flow regimes increases by up to 50%. In melt-dominated regions, the changes point into the other direction than those in rainfall-dominated regions. The minimum and maximum discharge of extreme regimes increase by up to 100% and decrease by less than 50%, respectively. Our findings provide guidance in water resources planning and management and the extreme regime estimates are a valuable basis for climate impact studies.

Keywords: Stochastic simulation, PREVAH model, return period, frequency analysis, extreme value statistics, climate change

Keypoints:

1. Estimation of 100-year low- and high-flow regimes using annual flow duration curves and stochastically simulated discharge time series

2. Both mean and extreme regimes will change under future climate conditions

3. The minimum discharge of extreme regimes will decrease in rainfall-dominated regions but increase in melt-dominated regions

4. The maximum discharge of extreme regimes will increase and decrease in rainfall-dominated and melt-dominated regions, respectively

1 Introduction

Low flows can have severe impacts on ecology and economy. Potential ecological impacts include fish-habitat conditions or water quality (Rolls et al., 2012) whilst economical impacts comprise water supply, river transport, agriculture, and energy production (Van Loon, 2015). The intensity of such potentially harmful low flows is projected to increase in the future due to climate change (Alderlieste et al., 2014; Papadimitriou et al., 2016; Marx et al., 2018). Also high flows, which can cause severe damages and major costs (Aon Benfield, 2016), are expected to change in future. While clear patterns of change have been detected for flood timing (Blöschl et al., 2017), changes in magnitude are less clear than for low flows (Madsen et al., 2014). Together with low and high flows, the whole flow regime, which depicts the magnitude, variability, and seasonality of discharge during the year (Poff et al., 1997), is expected to change (Arnell, 1999; Horton et al., 2006; Laghari et al., 2012; Addor et al., 2014; Milano et al., 2015). Such changes are caused by reduced snow and glacier storage (Beniston et al., 2018), related reductions in melt contributions (Farinotti et al., 2016; Jenicek et al., 2018), and changes in precipitation seasonality and intensity (Brönnimann et al., 2018). It is important to quantify these hydrological changes to adapt water governance and management accordingly (Clarvis et al., 2014).

Previous studies have focused on the detection of changes in mean flow regimes (Horton et al., 2006; Addor et al., 2014; Milano et al., 2015). For planning purposes and river basin management, however, estimates not only for mean conditions but also for extreme conditions are needed (Van Loon, 2015; Ternynck et al., 2016). Extreme regime estimates, which describe the evolution of flow over the year under extreme conditions, provide guidance for water managers, decision makers, and engineers involved in planning and water management. They are essential for the adaptation of hydraulic infrastructure such as reservoirs, and for developing suitable water management and flood protection strategies.

Commonly, extreme flow estimates derived by frequency analysis focus on one characteristic of the hydrological regime, e.g. summer low flows, drought durations, drought deficits (e.g. Tallaksen, 2000; WMO, 2008), flood peaks, or flood volumes (e.g. Mediero et al., 2010; Brunner et al., 2017). The focus on one or several of these individual characteristics, however, neglects the pre-conditions of low- and high-flow events. Yet, for low-flow events, these pre-conditions are crucial for the formation of groundwater storage (Şen, 2015), reservoir filling (Hänggi and Weingartner, 2012; Anghileri et al., 2016), and soil moisture formation (Zampieri et al., 2009). These storages can become very important when it comes to the satisfaction of diverse water needs and to the alleviation of water shortages (Mussá et al., 2015; Brunner et al., 2019b). In the case of high flows, antecedent conditions determine the proportion of rainfall transformed to direct runoff and therefore the severity of the flood event (Berghuijs et al., 2016; Nied et al., 2017). In contrast to the individual low- and high-flow characteristics, the flow regime includes information on both the pre-conditions and the discharge during the low- and high-flow seasons.

Estimating extreme flow regimes with a given exceedance frequency is not straightforward since discharge values at several points in time are correlated. Because of the multivariate nature of the problem, no single solution exists. We here aim at estimating extreme high- and low-flow regimes with a defined return period for current and future climate conditions. We propose two possible approaches for the estimation of such extreme regimes. The first approach is based on flow duration curves (FDCs). FDCs describe the whole distribution of discharge and are particularly suited for planning purposes (Vogel and Fennessey, 1994; Claps and Fiorentino, 1997). It has been shown that frequency analysis performed on annual FDCs allows for the estimation of extreme FDCs with pre-defined return periods (Castellarin et al., 2004; Iacobellis, 2008). While such estimates contain information about the frequency of occurrence and the distribution of flow, they lack information on the seasonality of flow (Vogel and Fennessey, 1994). FDC estimates derived for a certain return period T therefore need to be recombined with a specific seasonality, e.g. the long-term one. This first estimation approach treats distribution and seasonality separately. To overcome this problem, an alternative approach based on stochastically generated time series is proposed. Stochastically generated time series have been used in a number of water resources studies, including hydrologic design and drought planning (Koutsoyiannis, 2000). Stochastic approaches generate large sets of realizations of possible discharge time series, thus sampling hydrologic variability beyond the historical record (Herman et al., 2016; Tsoukalas et al., 2018), potentially including extreme events and regimes. In hydrology, stochastic models have been developed so as to reproduce key statistical features of observed data, including the distribution and the temporal dependence (Sharma et al., 1997; Salas and Lee, 2010; Tsoukalas et al., 2018).

Many different approaches have been proposed for the stochastic simulation of streamflow time series. Often, indirect approaches, which combine the stochastic simulation of rainfall with hydrological models, have been used for the generation of stochastic discharge time series (Pender et al., 2015). These approaches are affected by uncertainties due to hydrological model selection and calibration, which can be avoided by using direct synthetic streamflow generation approaches (Herman et al., 2016). Direct approaches stochastically simulate discharge. The simplest type of models to describe daily streamflow are autoregressive moving average (ARMA) models (Pender et al., 2015; Tsoukalas et al., 2018). However, this type of models only captures short-range dependence (Koutsoyiannis, 2000). Models also capturing long-range dependence include fractional Gaussian noise models (Mandelbrot, 1965), fast fractional Gaussian noise models (Mandelbrot, 1971), broken line models (Mejia et al., 1972), and fractional autoregressive integrated moving average models (Hosking, 1984). An alternative to these time-domain models are frequency domain models (Shumway and Stoffer, 2017). These latter use phase randomization to simulate surrogate data with the same Fourier spectra as the raw data (Theiler et al., 1992; Radziejewski et al., 2000). Despite their favorable characteristics, such methods based on the Fourier transform have been rarely applied in hydrology (Fleming et al., 2002). We apply the approach of phase randomization to simulate stochastic discharge time series using the approach proposed by Brunner et al. (2019a). As opposed to classical phase randomization approaches, this approach does not rely on the empirical distribution but uses the flexible, four-parameter kappa distribution (Hosking, 1994), which allows for the generation of a wide range of realizations of high and low discharge values. Among these simulated series, extreme regimes can be identified. After having identified a suitable approach for the estimation of extreme regimes, we apply this approach to discharge time series representing future climate conditions. A comparison to current estimates allows us to identify future changes in extreme high- and low-flow regimes.

2 Methods

2.1 Study area

The analyses were performed on a set of 19 hydrological regions in Switzerland (Figure 1) with areas between 600 and 5000 km^2, mean elevations between 550 and 2300 m a.s.l., and mean annual precipitation sums between 1000 and 1800 mm. The flow regimes north of the Alps (Plateau and Jura) are dominated by rainfall and characterized by high discharge in winter and spring but low discharge in summer. In contrast, the regimes in the Alps are dominated by snow and ice melt and characterized by high discharge in summer. For illustration purposes, we chose four regions. Two of them (Jura and Thur) have a rainfall-dominated regime and the other two (Valais and Engadin) a melt-dominated regime under the current climate.

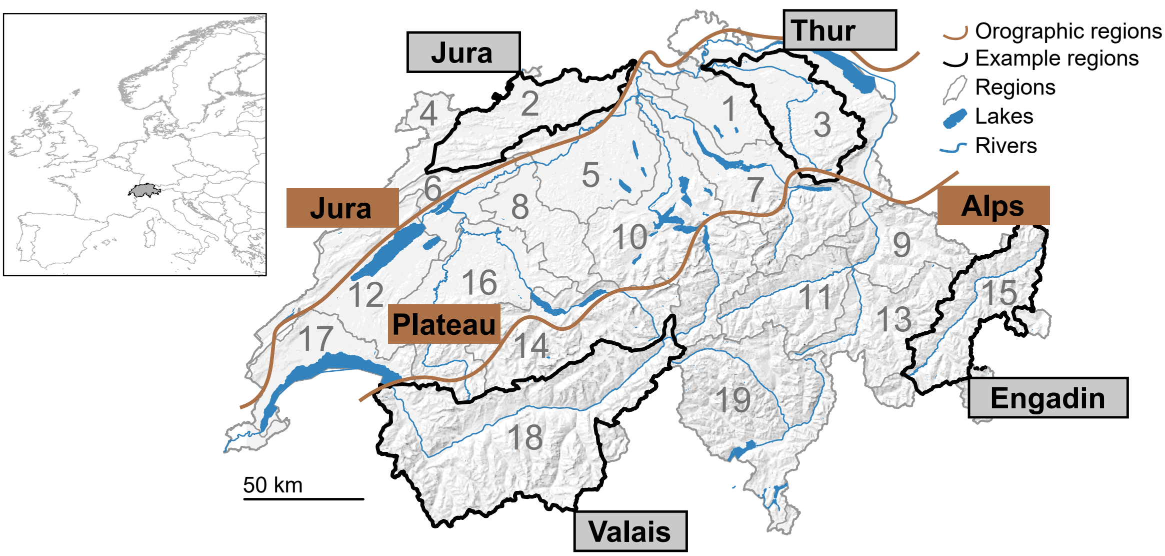

Figure 1. Map of Switzerland with 19 large hydrological regions (grey outline) and the four illustration regions (black border): Thur, Jura, Valais, and Engadin. The main orograpic regions Jura, Plateau, and Alps are outlined by the brown lines.

2.2 Analysis framework

The analysis performed to detect changes in future extreme regimes consisted of three main steps (Figure 2). First, different procedures for estimating extreme flow regimes were tested (first step). Once a suitable procedure was identified, it was applied to estimate extreme high- and low-flow regimes under current and future climate conditions (second step). These extreme regimes were compared to mean regimes. Third, current and future estimates were compared to detect future changes in flow regimes (third step). We used simulated discharge representing both current and future climatology as the basis for the analysis. The current discharge series were derived by feeding a hydrological model with observed meteorological data and with meteorological data simulated by a set of climate models for the reference period. The future discharge series were obtained by driving the model with meteorological data from downscaled and bias-corrected climate model simulations.

The two estimation techniques applied use frequency analysis on different quantities. The first method applies frequency analysis to the individual percentiles of the FDC. The second method uses stochastically simulated discharge time series to identify annual hydrographs with a certain non-exceedance probability. We refer to these methods as *FDC* and *stochastic*, respectively. The two methods are compared to a benchmark method (*univariate*), which performs univariate frequency analysis on the monthly discharge values and neglects the dependence between individual months. We here focus on the estimation of high- and low-flow regimes with a return period of $T = 100$ years since this return period is commonly used for planning purposes. The methods outlined in this study, however, can be generalized to other return periods. In the following paragraphs, we describe the data sets (Figure 2 A, Sect. 2.3), the stochastic discharge generation procedure (Figure 2 B, Sect. 2.4), and the estimation techniques used to derive extreme flow regimes (Figure 2 C, Sect. 2.5).

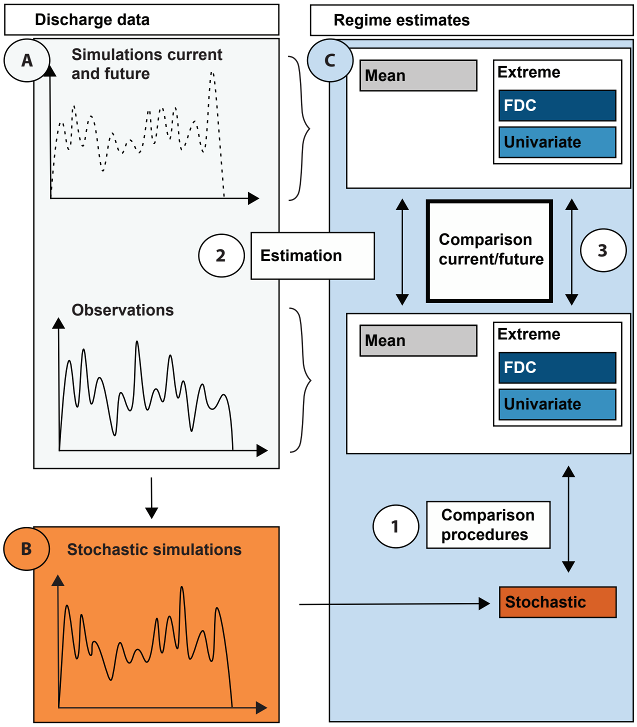

Figure 2. Illustration of study framework: 1) Comparison of different estimation techniques *univariate*, *FDC*, and *stochastic*, 2) estimation of current and future mean and extreme regimes using simulated discharge time series, and 3) comparison of current and future regime estimates. The manuscript A) introduces the simulated data used, B) outlines the stochastic discharge generator, and C) describes the estimation approaches.

2.3 Hydrological simulations

We used discharge time series simulated with the hydrological model PREVAH (Viviroli et al., 2009b) as input for the analysis. To represent current conditions, the model was driven with observed meteorological data for the period 1981-2010. To represent future conditions, it was driven with meteorological data obtained by regional climate model simulations for the period

2071-2100 (see below). PREVAH is a conceptual process-based model. It consists of several sub-models representing different parts of the hydrological cycle: interception storage, soil water storage and depletion by evapotranspiration, groundwater, snow accumulation and snow- and glacier melt, runoff and baseflow generation, plus discharge concentration and flow routing (Viviroli et al., 2009b). A gridded version of the model at a spatial resolution of 200 m was set up for Switzerland (Speich et al., 2015). For the calibration of the model parameters, meteorological and discharge time series from 140 mesoscale catchments covering different runoff regimes were used. The model calibration was conducted over the period 1993–1997. Validation on discharge was performed with the period 1983–2005. More details on the calibration and validation procedures can be found in Köplin et al. (2010). The parameters for each model grid cell were derived by regionalizing the parameters obtained for the 140 catchments with ordinary kriging (Viviroli et al., 2009a; Köplin et al., 2010). The hydrological model has been calibrated using observed meteorological data but will subsequently be fed with meteorological data simulated by a set of GCM-RCM combinations. It is assumed that the parameterset derived in the calibration procedure will still produce reliable results since Krysanova et al. (2018) have confirmed in a review that a good performance of hydrological models in the historical period increases confidence in projected impacts under climate change. Future glacier extents were simulated with two glacier evolution models. We used the global glacier evolution model (GloGEM; Huss and Hock, 2015) for short glaciers (glacier length < 1 km) and GloGEMflow (Zekollari et al., 2019) for long glaciers (length > 1 km). GloGEM simulates glacier changes with a retreat parameterization relying on observed glacier changes (Huss et al., 2010). GloGEMflow is an extended version of GloGEM with a dynamic ice flow component. This new model was extensively validated over the European Alps, through comparisons with various observations (e.g. surface velocities and observed glacier changes) and detailed 3D projections from modelling studies focusing on individual glaciers (e.g. Jouvet et al., 2011; Zekollari et al., 2014). The simulated glacier extents were transformed from the GloGEM(flow) 1D model grid to the 2D PREVAH model grid by ensuring that the area for each elevation band was conserved.

PREVAH is driven by time series of precipitation, temperature, relative humidity, shortwave radiation, and wind speed. The meteorological forcing for current simulations was observed time series provided by the Federal Office of Meteorology and Climatology MeteoSwiss (2018) while the transient meteorological forcing for future simulations was derived from the CH2018 climate scenarios (National Centre for Climate Services, 2018). The meteorological data were interpolated to a 2×2 km grid using detrended inverse distance weighting where the detrending was based on a regression between climate variables and elevation (Viviroli et al., 2009b). The climate scenarios are based on the results from the EURO-CORDEX initiative (Jacob et al., 2014; Kotlarski et al., 2014), which are the most sophisticated and high-resolution coordinated climate simulations over Europe. The scenarios are based on representative concentration pathways (RCP) (Moss et al., 2010; Meinshausen et al., 2011; van Vuuren et al., 2011) and a regional downscaling approach based on quantile mapping (Themeßl et al., 2012; Gudmundsson et al., 2012) The quantile mapping procedure was calibrated on the period 1981-2010 and performed on a grid-by-grid basis for all meteorological variables. The meteorological data were derived from an ensemble of 39 GCM-RCM combinations for different scenarios (Table A1 in Appendix), which provide temperature, precipitation, relative humidity, shortwave radiation, and wind speed, for the locations of various meteorological stations. The selection of scenarios included the three RCPs 2.6, 4.5, and 8.5 for which 8, 13, and 18 GCM-RCM combinations were available respectively. 10 out of the 39 GCM-RCM combinations were available at a high resolution of 12.5 km and the remaining combinations at a resolution of roughly 50 km. Using combinations at both resolutions allows for a larger ensemble, however, it means that those GCM-RCM combinations, which are available for both resolutions obtain more weight. During a model run, PREVAH reads the meteorological grids and further downscales the data to the computational grid of 200 × 200 m using bilinear interpolation. For temperature, a lapse rate of -0.65 °C/100m was additionally used for topographic corrections.

2.4 Stochastic simulation of discharge time series

The discharge simulated with the hydrological model for the current (1981–2010) and future (2071–2100) 30-years periods only represent small sets of possible annual hydrograph realizations. Among these realizations, certain hydrographs including extreme hydrographs such as a 100-year hydrograph were possibly not observed. We used a stochastic discharge simulation procedure to increase the number of possible annual hydrograph realizations. These realizations represent the discharge statistics and temporal correlation structure of the available data, and extend the existing sample to yet unobserved annual hydrographs. To simulate such hydrographs, we used the method of *phase randomization* (Theiler et al., 1992; Schreiber and Schmitz, 2000). We combined this empirical procedure with the flexible four-parameter kappa distribution (Hosking, 1994) to allow for the extrapolation to yet unobserved values. This phase randomization approach preserves the autocorrelation structure of the raw series by conserving its power spectrum (Theiler et al., 1992). The procedure consists of three main steps (Radziejewski et al., 2000). In a first step, the discharge series (here, the simulated discharge for past and future conditions) is converted from the time domain to the spectral domain by the Fourier transform (Morrison, 1994). The Fourier transform of a given time series $x = (x_1, \ldots, x_t, \ldots, x_n)$ of length n is

$$f(\omega) = \frac{1}{\sqrt{2\pi n}} \sum_{t=1}^{n} e^{-i\omega t} x_t, -\pi \leq \omega \leq \pi, \quad (1)$$

where t is the time step, ω are the phases , and $i = \sqrt{-1}$ is the imaginary unit. In this spectral domain, the data are represented by the phase angle and by the amplitudes of the power spectrum as represented by the periodogram. The phase angle of the power spectrum is uniformly distributed over the range $-\pi$ to π. In a second step, the phases in the phase spectrum are randomized while the power spectrum is preserved. In a third step, the inverse Fourier transform is applied to transform the data from the spectral domain back to the temporal domain. A step by step description of the stochastic simulation procedure and more background information on the Fourier transform are provided in Brunner et al. (2019a) and references therein.

An application of the simulation procedure to four example catchments in Switzerland has shown that both seasonal statistics and temporal correlation structures of discharge can be well reproduced (Brunner et al., 2019a). We therefore used this method to stochastically simulate 1500 years of discharge for each of the 19 regions in our data set. Stochastic series representing current conditions were generated by using the hydrological model simulations for 1981–2010 obtained by the 39 GCM-RCM combinations as input. Stochastic series representing future conditions were generated based on each of the hydrological model simulations generated with the 39 GCM-RCM combinations for different scenarios.

2.5 Estimation of T-year hydrographs

We employed two methods for estimating 100-year low- and high-flow regimes: *FDC* and *stochastic*. The extreme regime estimates were compared to the stochastically generated hydrographs to check for plausibility. Furthermore, they were compared to a lower-bound (for low-flow regimes) or upper-bound (for high-flow regimes) benchmark regime derived by combining 100-year monthly discharge estimates obtained from univariate frequency analysis. This frequency analysis was performed on the values of each month independently and the monthly values were fitted with a Generalized Extreme Value (GEV) distribution. This distribution was not rejected according to the Anderson–Darling goodness-of-fit test computed using the procedure proposed by Chen and Balakrishnan (1995) ($\alpha = 0.05$). The disadvantage of the univariate procedure is that the autocorrelation in the data, which is mainly visible for lags of 1 and 2 months, is neglected, which overestimates the extremeness of the 100-year low-flow regime and therefore produces unrealistic estimates. The univariate approach will therefore only be considered as a benchmark for model comparison and not find consideration in the comparison of current and future extreme regime estimates.

2.5.1 FDC

A first extreme regime estimate was derived by performing the frequency analysis on annual FDCs. According to Vogel and Fennessey (1994), an annual FDC with an assigned return period can be obtained from the p^{th} quantile function. To do so, we fitted a GEV distribution to the quantiles corresponding to each percentile. The GEV was not rejected based on the Anderson–Darling goodness-of-fit test ($\alpha = 0.05$). The fitted GEV distributions were used to estimate the 100-year quantile for each percentile. The 100-year FDC was then derived by combining these 100-year quantiles. The 100-year FDC does not contain any information about the seasonality but only about the statistical distribution of flow. To include information about seasonality, we combined the estimated 100-year FDC with a typical seasonal regime. To do so, the individual quantile values of the FDC were assigned to the corresponding ranks of a typical flow regime. This typical regime was defined as the long-term (mean) regime of the daily input time series and varied for current and future conditions. The estimated extreme discharge regimes were aggregated to a monthly resolution to make them comparable to the univariate estimates.

2.5.2 Stochastic

The second method for the estimation of extreme regimes performs the frequency analysis directly on a large set of stochastically simulated annual hydrographs (here 1500 years). The frequency analysis was performed on the annual sums of the stochastically generated hydrographs. We identified the hydrograph corresponding to the empirical 100-year annual discharge sum as the 100-year regime. The application of this procedure is only possible for long time series as given by the stochastic series, since a 100-year annual sum is not necessarily observed in a short record of, say, 30 years. Like the FDC estimates, the regimes derived from the stochastic approach were aggregated to a monthly resolution.

2.6 Comparison of current and future regime estimates

The two methods and the benchmark approach for the estimation of 100-year low- and high-flow regime estimates were applied to discharge time series representing current and future climate conditions. First, 100-year regimes were estimated for current conditions (1981–2010). For generating a *control* regime, we used the discharge simulated with the observed meteorological data. For representing uncertainty due to different GCM-RCM combinations for different scenarios, we derived one *reference* regime for each discharge time series simulated by the 39 climate GCM-RCM combinations for different scenarios. This analysis provided us with a range of current regime estimates due to climate model uncertainty. The regime estimates derived from the 39 GCM-RCM combinations were used to derive a multi-model mean, which served as a reference for determining changes between current and future conditions. In a second step, 100-year estimates were derived for future conditions using the simulated time series for the period 2071–2100 for all GCM-RCM combinations and scenarios. We assessed changes in seasonality and magnitude of flow regimes in terms of their minimum, maximum, and mean discharge by comparing regime estimates derived for future conditions to the multi-model mean representing current conditions. (Figure 3; results were grouped by RCP.).

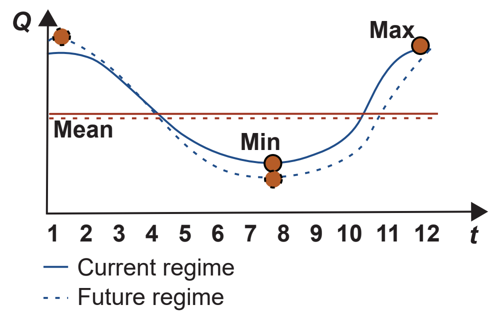

Figure 3. Illustration of the main characteristics of an annual rainfall-dominated flow regime under current and future conditions: maximum, mean, and minimum.

3 Results

3.1 Comparison of estimation methods

The two estimation techniques and the benchmark approach provide distinct estimates for the 100-year low-flow regimes (Figure 4). The univariate technique leads to the most extreme regimes whilst the FDC and stochastic methods lead to similar estimates. The univariate estimate should only be seen as a lower benchmark and not as an estimate for a "true" 100-year regime since the univariate approach neglects the dependence between monthly estimates. In contrast, the FDC and stochastic approaches produce more plausible estimates, i.e., estimates at the lower bound of the observed values. The summer low-flow regimes estimated by the FDC technique are comparable to the regimes of the year 2003, which included a very dry summer (Beniston, 2004; Rebetez et al., 2006; Schär et al., 2004; Zappa and Kan, 2007).

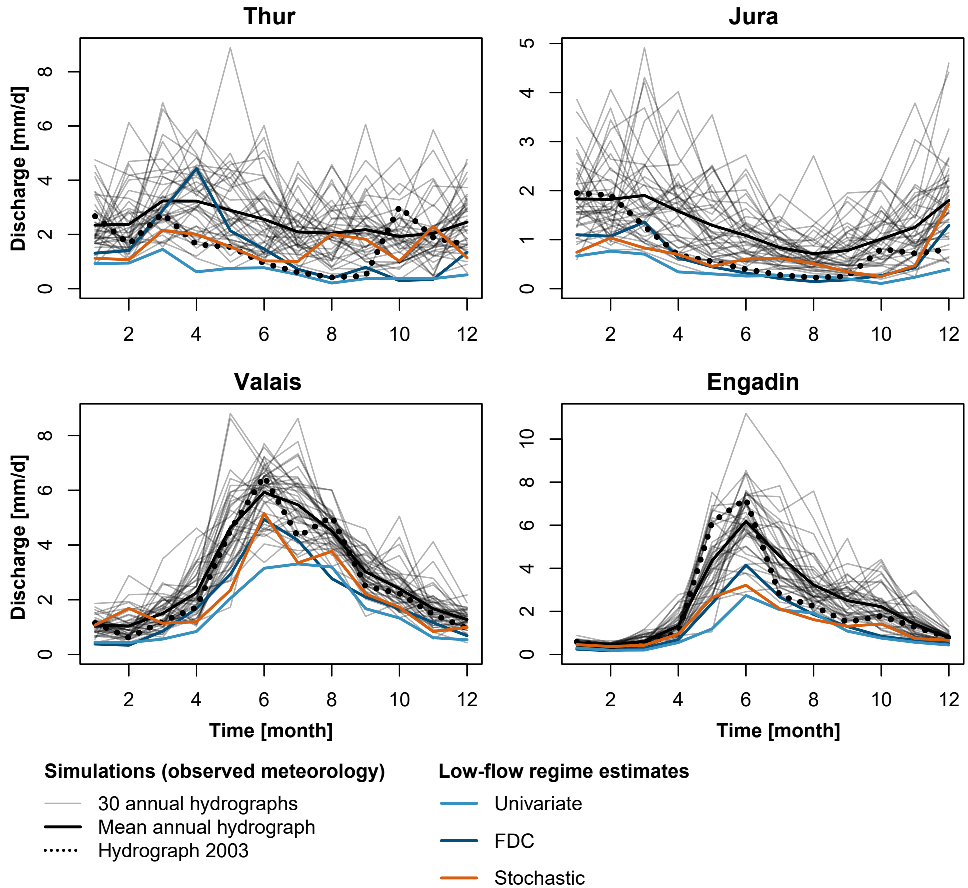

Figure 4. 100-year **low-flow** regime estimates for current climate conditions (control) derived using univariate frequency analysis (light blue), frequency analysis on the FDC (dark blue), and stochastically generated time series (orange). The annual hydrographs simulated using observed meteorological data are given in grey while the mean annual hydrograph and the hydrograph simulated for the year 2003 are given in black. The four panels are shown on different scales.

Similar as for low-flow regimes, the 100-year high-flow regimes derived by the three estimation techniques are distinct (Figure 5). The univariate approach, as mentioned previously, produces unrealistic results in terms of seasonality, since the predictions of the monthly 100-year flows neglects the dependence between the different months. The FDC and stochastic techniques produce more similar seasonalities and more realistic estimates, at the upper bound of the observed annual hydrographs. Contrary to low-flow estimates, high-flow estimates generated with the FDC or stochastic technique can be different. The stochastic approach generally leads to more conservative estimates than the FDC approach in melt-dominated regions. We attribute this to the fact that the stochastic approach performs frequency analysis on annual sums while the FDC approach performs frequency analysis on the percentiles of the FDC.

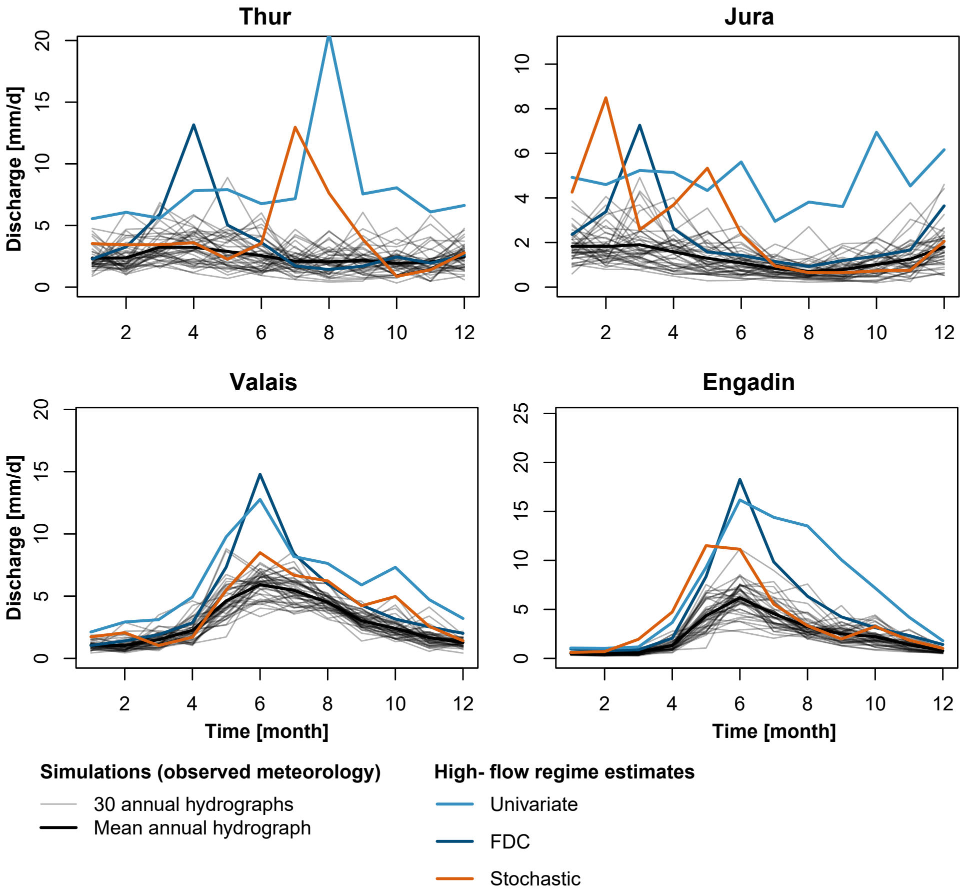

Figure 5. 100-year **high-flow** regime estimates for current conditions (control) derived using univariate frequency analysis (light blue), frequency analysis on the FDC (dark blue), and stochastically generated time series (orange). The annual hydrographs simulated using observed meteorological data are given in grey while the mean annual hydrograph is given in black. The four panels are shown on different scales.

The plausibility of the 100-year estimates derived by using the FDC and stochastic approaches is shown by a comparison with stochastically generated annual hydrographs (Figure A1 in the Appendix for the low-flow estimates). The derived estimates, in fact, are embedded in the lower spectrum of the stochastically generated annual hydrographs. This is hardly the case for the univariate estimates, which lead to "unrealistically low" 100-year hydrographs partly outside of the range of the stochastically generated hydrographs. Similarly, the 100-year high-flow regime estimates derived by the FDC and stochastic methods are embedded in the higher spectrum of the stochastically generated hydrographs while the univariate estimate is "unrealistically high". Since the univariate approach yields unrealistic estimates, it is not considered for further analysis.

3.2 Current and future low-flow regime estimates

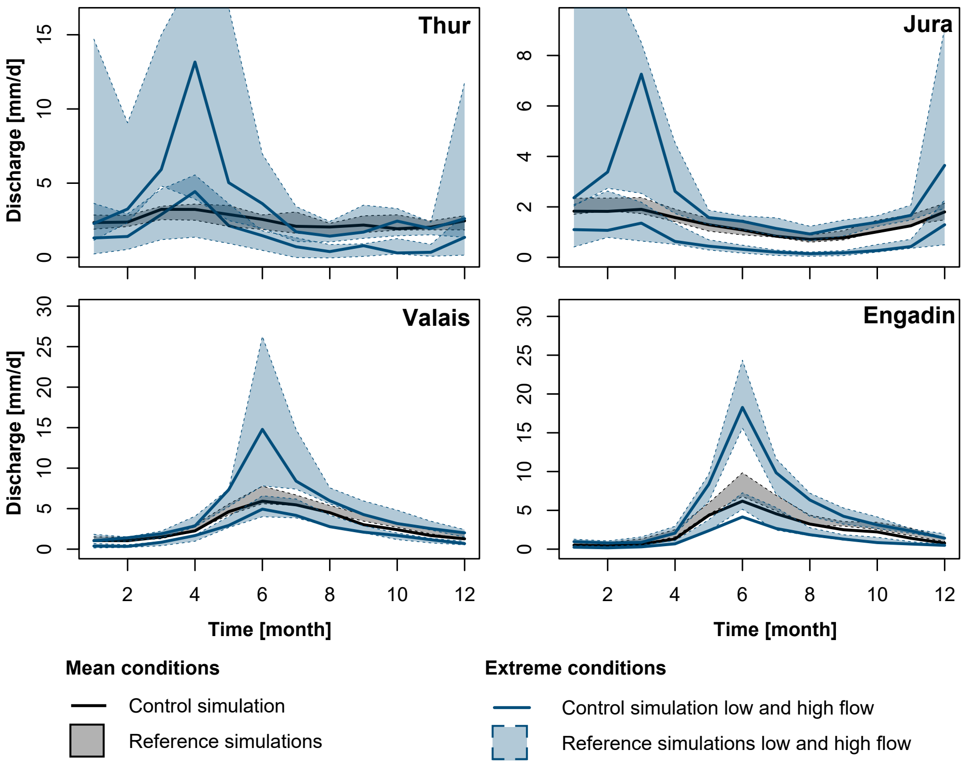

Figure 6. Current 100-year mean regimes (grey), low-flow regimes (blue lower line), and high-flow regimes (blue upper line) estimated by using the FDC method on the control discharge simulations derived by observed meteorological data (bold line) and the reference discharge simulations derived by meteorological data simulated by the 39 GCM-RCM combinations for different scenarios for the reference period (shaded polygons).

Both mean and extreme regimes are subject to uncertainty when derived from simulated discharge. The uncertainty comes from the hydrological model and from the spread between the climate simulations. Figure 6 shows mean and extreme low- and high-flow regime estimates derived for the observed climatology for the four illustration catchments. It also shows the range of regimes obtained by using different GCM-RCM combinations and scenarios. This range of regimes generally encompasses the regime derived from meteorological observations, which suggests that the climate model output realistically reproduces the observed climate. An exception is the Engadin, where the low-flow regimes derived from the GCM-RCM combinations overestimate summer low flows. This overestimation might be related to the univariate bias correction applied, which might not perfectly reflect the interplay between temperature and precipitation and therefore the timing of snowmelt processes (Meyer et al., 2019). The spread in the current regimes is larger for extreme than for mean conditions for the rainfall-dominated catchments Thur and Jura. In addition, the spread is larger for the high- than the low-flow extreme regimes except for the region Engadin. This range should be kept in mind when analyzing future regime estimates.

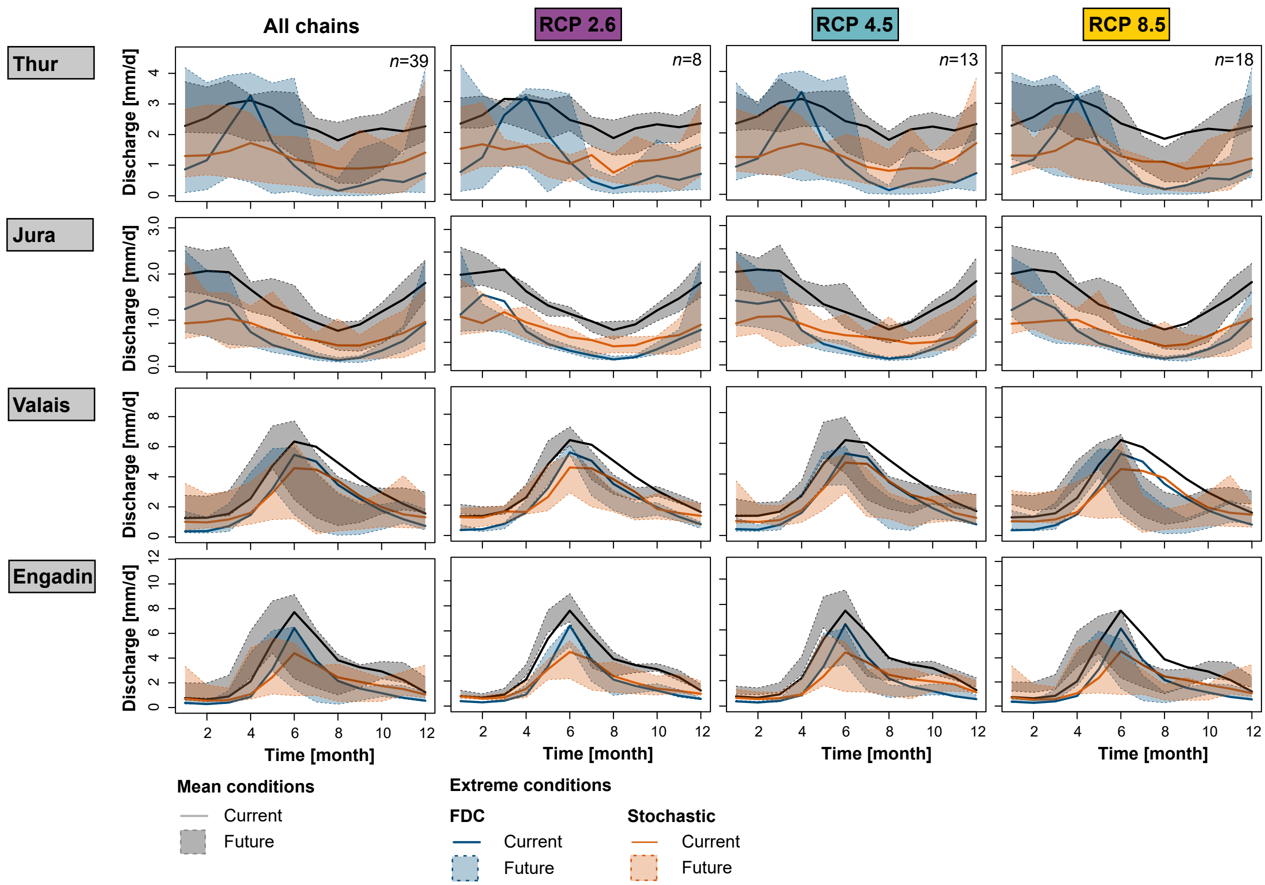

Figure 7. Comparison of current (solid line) and future 100-year **low-flow** regime estimates (shaded polygons) over the 39 GCM-RCM combinations and scenarios derived by the FDC (blue) and stochastic (orange) approaches. The mean regimes are provided as a reference (grey).

Shifts in regimes are expected for both for mean and for extreme low-flow conditions (Figure 7). The shifts are weak for rainfall-dominated regions (e.g. Thur and Jura), while they are strong for melt-dominated regions (e.g. Valais and Engadin). For the rainfall-dominated regions, changes in mean and extreme regimes are most visible for RCP 8.5. Here, the different realizations lead to regimes with more pronounced summer low flows. In addition, there is a reduction in spring discharge under RCP 2.6 for both mean and extreme conditions when looking at the regimes derived from the FDC approach. In the case of melt-dominated regions, most GCM-RCM combinations lead to clear shifts towards regimes with earlier and reduced summer flows. These shifts are more pronounced for RCP 8.5 than RCPs 4.5 and 2.6. Note that the spread of future regimes is smaller for RCP 2.6 than RCPs 4.5 and 8.5 due to the smaller number of chains in the ensemble.

Differences between current and future mean and extreme low-flow regimes are summarized in Figure 8. The detected changes for RCP 2.6 and RCP 8.5 are similar (results for RCP 4.5 are not displayed but lie in between those of RCPs 2.6 and 8.5). Changes are projected for the minimum and maximum discharge of mean and extreme low-flow regimes and for their timing, but less for the mean of these regimes. The changes of the mean flow can reach up to 30%, while the maximum and minimum flows can change up to 100%.

Changes in melt- and rainfall-dominated regions are clearly different. Both the FDC and stochastic approach suggest changes in extreme low-flow regimes. In rainfall-dominated regions, an increase is expected for the discharge maximum independent of the estimation approach chosen. In contrast, a decrease is expected in the discharge minimum according to the stochastic approach while not clear changes are expected using the FDC approach. For melt-dominated regions, the change pattern is different. There, a decrease in maximum discharge is expected. An increase in minimum discharge is expected for mean regimes while changes are less clear for the extreme regimes. Shifts of one or two months are expected in timing for both rainfall- and melt-dominated regions. In most catchments, the timing of future maximum discharge is likely to occur earlier than under current conditions. Shifts towards later in the year are expected in the timing of the minimum flow. The changes in mean and maximum flows are similar for extreme low-flow regimes derived by the two estimation techniques FDC and stochastic. In contrast, the shifts in minimum flow and timing are different if applying the stochastic instead of the FDC approach.

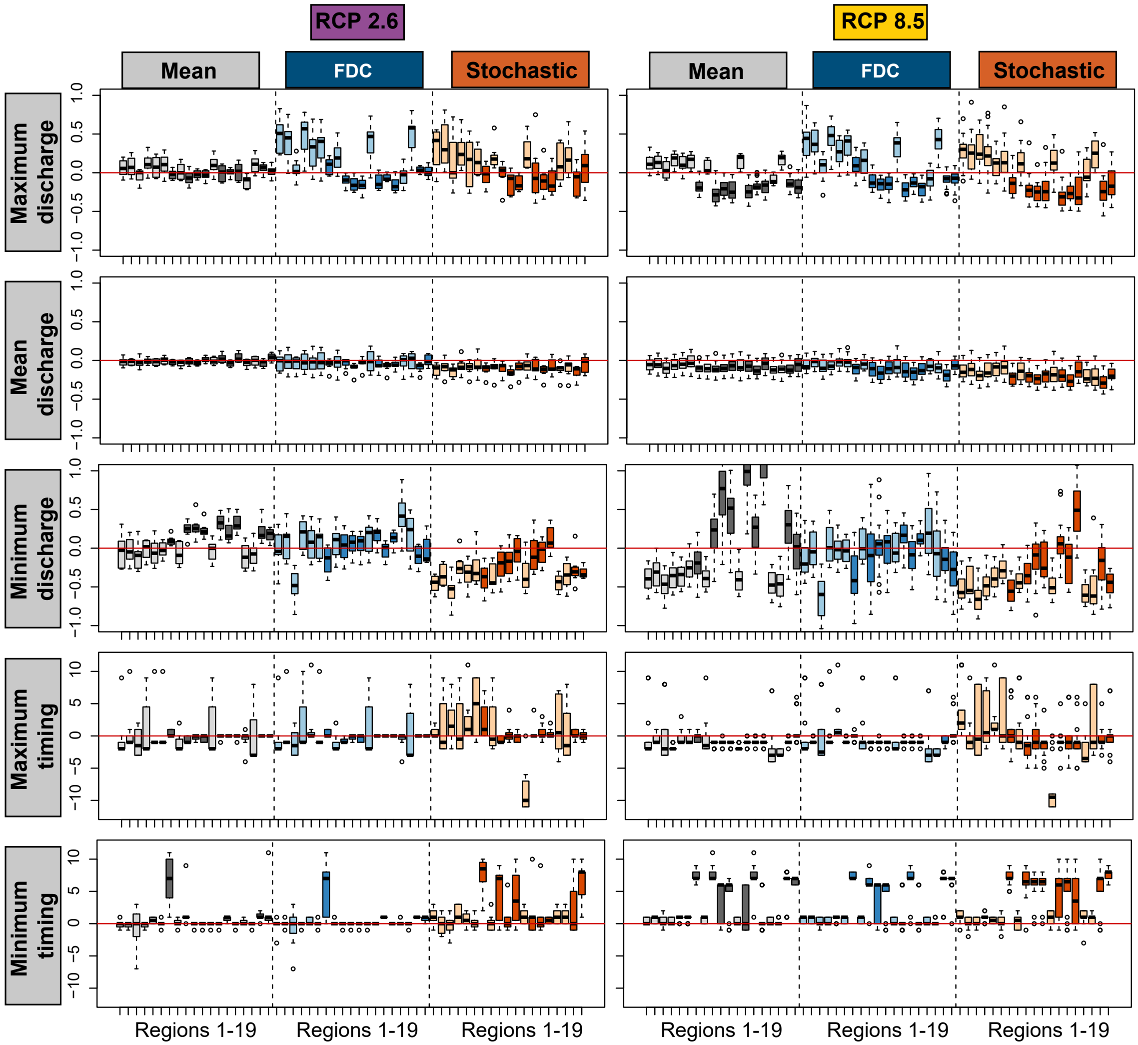

Figure 8. Differences between current and future mean (grey) and extreme **low-flow** regime characteristics for the 19 regions (Figure 1) estimated by the FDC (blue) and stochastic (orange) approaches. Five indicators are shown: maximum discharge, mean discharge, minimum discharge, timing of minimum discharge, timing of maximum discharge. The first three rows show relative changes, the last two rows show changes in months. Melt-dominated (dark colors) and rainfall-dominated regions (light colors) are distinguished. The boxplots indicate the range resulting from using the 39 GCM-RCM combinations for different scenarios.

3.3 Current and future high-flow regime estimates

High-flow regime estimates are also expected to change (Figure 9) with no consistent change pattern visible at the first glance. Changes in high-flow extreme regimes are slightly more pronounced for RCP 8.5 than for RCP 2.6 (Figure 10; RCP 4.5 not shown because it is expected to provide results somewhere in betwen RCP 2.6 and 8.5). They are similar for the estimation techniques used (FDC/stochastic). As for the low-flow regimes, only moderate and mostly positive changes of less than 30%

are expected in the mean discharge of extreme high-flow regimes. The changes in the maximum and minimum discharge of the high-flow regimes are much stronger, i.e up to 100%. In rainfall-dominated regions, changes in maximum discharge are mostly positive while they can be negative for melt-dominated regions. In these melt-dominated regions, an increase is expected in the minimum discharge of high-flow extreme regimes especially when using the FDC approach. In rainfall-dominated regions, changes in minimum discharge are mostly negative, especially for RCP 8.5. Changes in timing are different for the FDC and stochastic approach and there is no consistent pattern across catchments. Minimum and maximum discharge can occur earlier or later in the year than under current conditions.

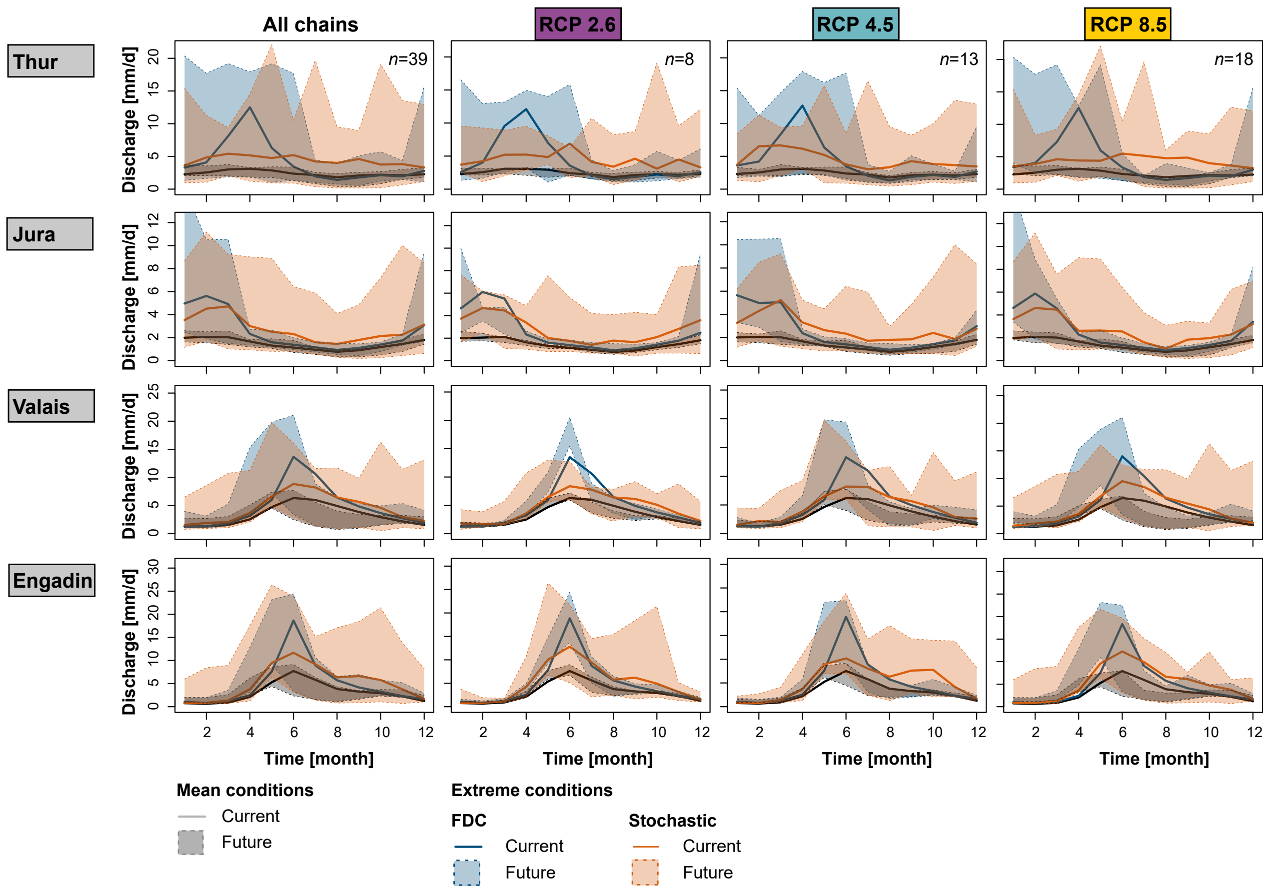

Figure 9. Comparison of current (solid line) and future 100-year **high-flow** regime estimates (shaded polygons) over the 39 GCM-RCM combinations derived by the FDC (blue) and stochastic (orange) approaches. The mean regimes are provided as a reference (grey).

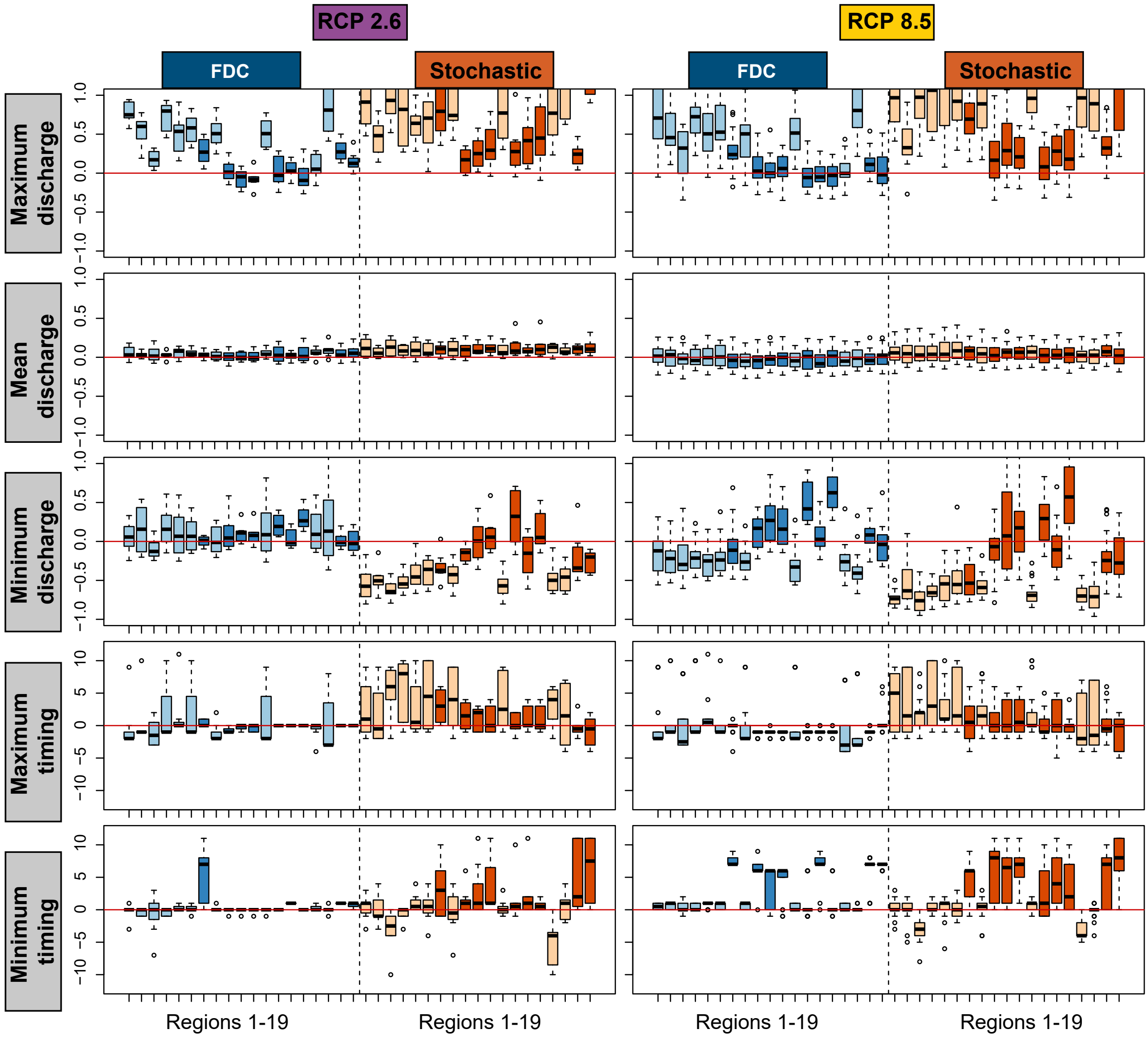

Figure 10. Differences between current and future mean (grey) and extreme **high-flow** regime characteristics for the 19 regions (Figure 1) estimated by the FDC (blue) and stochastic (orange) approaches. Five indicators are shown: maximum discharge, mean discharge, minimum discharge, timing of minimum discharge, timing of maximum discharge. The first three rows show relative changes, the last two rows show changes in months. Melt-dominated (dark colors) and rainfall-dominated regions (light colors) are distinguished. The boxplots indicate the range resulting from using the 39 GCM-RCM combinations for different scenarios.

4 Discussion

4.1 Estimation methods

The low-flow regime estimates derived with the univariate method are implausible because the method neglects the interdependence between flows of adjacent months. In contrast, both other methods, FDC and stochastic, lead to similar results. The differences between the two methods mainly lie in how the seasonality is derived. In the case of the FDC approach, mean seasonality is used. In the case of the stochastic approach, a rather "random" seasonality is used since the regime is chosen according to the annual discharge sum. The use of one potential realization of seasonality in the stochastic approach compared to the use of a mean seasonality in the FDC approach has the disadvantage that it is less representative but the advantage that it is consistent with the corresponding annual discharge sum. The direction of changes derived from the two estimates are similar except for changes of minimum discharge in the low flow regime and minimum discharge in the high flow regimes. Both types of estimates seem to be plausible in the light of the stochastically generated hydrographs, which represent a large set of possible realizations among which extreme hydrographs can be found. While the estimates derived by the two methods do not differ much, both methods have their advantages and disadvantages. The FDC approach is relatively simple to implement, but decouples seasonality from the distribution of daily discharge values. In contrast, the stochastic approach jointly considers magnitude and seasonality, but requires the implementation of a stochastic discharge generator. The main advantage of such a generator is that the individual hydrograph realizations can be used for specific impact studies, which allows for directly performing the frequency analysis on the quantity of interest. There are several possible solutions to the multivariate problem of estimating extreme regimes, and none of these two methods can therefore be said to be the better one.

The estimation of extremes, be it of regimes or individual flow characteristics, is associated with several sources of uncertainty. These comprise the choice of an extreme value distribution used to fit the data (i.e. percentiles of FDCs, annual sums, daily discharge sums) and the estimation of its parameters (Merz and Thieken, 2005; Brunner et al., 2018a). When applied to time series representing future conditions simulated with a hydrological model, additional uncertainty sources are involved. These include the assumptions underlying the applied future global climate scenarios, global climate model structures, initial conditions, downscaling methods, modelled future glacier extents, the uncertainties inherent in the hydrological model results, and the calibration of its parameters (Wilby et al., 2008; Addor et al., 2014; Clark et al., 2016). Despite these uncertainties, the extreme regime estimates can be used to identify future changes and as such these estimates can be further used in climate impact studies. Potential fields of application include water scarcity assessments, where such regime estimates are combined with estimates on water demand (Brunner et al., 2018b), eco-hydrological studies (Wood et al., 2008), or analyses on the future potential of hydropower production (Schaefli et al., 2019).

4.2 Changes in future regime estimates

Changes in all types of regimes (mean/extreme low flow/extreme high flow), were found to be distinct for melt-dominated and rainfall-dominated regions. This refers not only to the entire regime, but also to individual regime characteristics such as minimum, maximum, and mean flow as well as the timing of the minimum flow. The direction of change was different in rainfall- and melt-dominated regions for all regime types. An increase of up to 50% in the maximum discharge of mean and extreme low- and extreme high-flow regimes was found for rainfall-dominated regions. In contrast, a decrease of the minimum discharge by up to 100% is projected to occur for these catchments and all types of regimes. The opposite is true for melt-dominated regimes, where the minimum discharge increases while the maximum and mean discharge decrease. The changes in extreme regimes can be explained by a reduction or an earlier contribution of snow- and glacier melt (Hanzer et al., 2018), and by an increase in winter precipitation (Jenicek et al., 2018), which coincide with the high-flow season in rainfall-dominated regions but with the low-flow season in melt-dominated regions. For mean regimes, changes in melt-dominated regimes were found in previous studies (Barnett et al., 2005; Jenicek et al., 2018; Fatichi et al., 2014; Hanzer et al., 2018). Fatichi et al. (2014) found a projected discharge decrease in melt-dominated regions due to reduced contribution of ice melt in the Po and Rhine river basins. The regime shifts in the rainfall-dominated regions are also influenced by increases in precipitation in the winter season and decreases in the summer season. Precipitation increases in the high-flow winter season lead to increases in the discharge maximum, while precipitation decreases in the low-flow summer season lead to decreases in the discharge minimum. The results of Fatichi et al. (2014) confirm that changes in rainfall-dominated regions are more uncertain since the projected changes in precipitation mostly lie within the range of natural variability of the control scenario. Similar results were found by Jenicek et al. (2018) for several catchments in Switzerland and by Barnett et al. (2005) on a global scale. We have shown here that these previous findings also apply to extreme regimes. The regime shifts detected have implications for various sectors. Regime shifts and more severe low flows were found to lead to more severe water scarcity situations, where water supply is insufficient to meet water demand (Brunner et al., 2019b). In the hydropower sector, future regime shifts are anticipated to lead to a reduction in production (Finger et al., 2012; Schaefli et al., 2019).

5 Conclusions

Extreme regime estimates were derived by frequency analysis performed on 1) annual flow duration curves (FDCs) and 2) on the discharge sums of stochastically generated annual hydrographs. Both were found to provide realistic, similar results. A range of future extreme regime estimates was obtained both for extreme and for mean conditions. In rainfall-dominated regions, the range of these future low- and high-flow estimates comprised the current estimate. On the contrary, in melt dominated regions, future high-flow and especially low-flow regimes were distinct from the current estimate. Changes in mean discharges were moderate for all types of regimes and catchments, and did not exceed 30%. Projected changes in the minimum discharge of mean and extreme high- and low-flow regimes were positive in melt-dominated regions due to increases in winter precipitation and amount to up to a 100%. In contrast, mostly positive changes, of up to 50% in maximum discharge were found in rainfall-dominated regions for all types of regimes. These positive changes in maximum discharge are linked to increases in winter precipitation, which coincide with the high-flow season. High- and low-flow regime estimates derived using the approaches proposed in this study are important for climate impact studies addressing e.g. the future hydropower production potential or the occurrence of water shortage situations. The estimates also provide guidance for hydraulic design, emergency planning and drought and water management.

Data availability. The climate model simulations are available on the webpage of the Swiss National Centre for Climate Services (https://www.nccs.admin.ch/nccs/de/home.html). The hydrological model simulations are available upon request from Massimiliano Zappa (massimiliano.zappa@wsl.ch). The extreme regime estimates are available upon request from Manuela Brunner (manuela.brunner@wsl.ch).

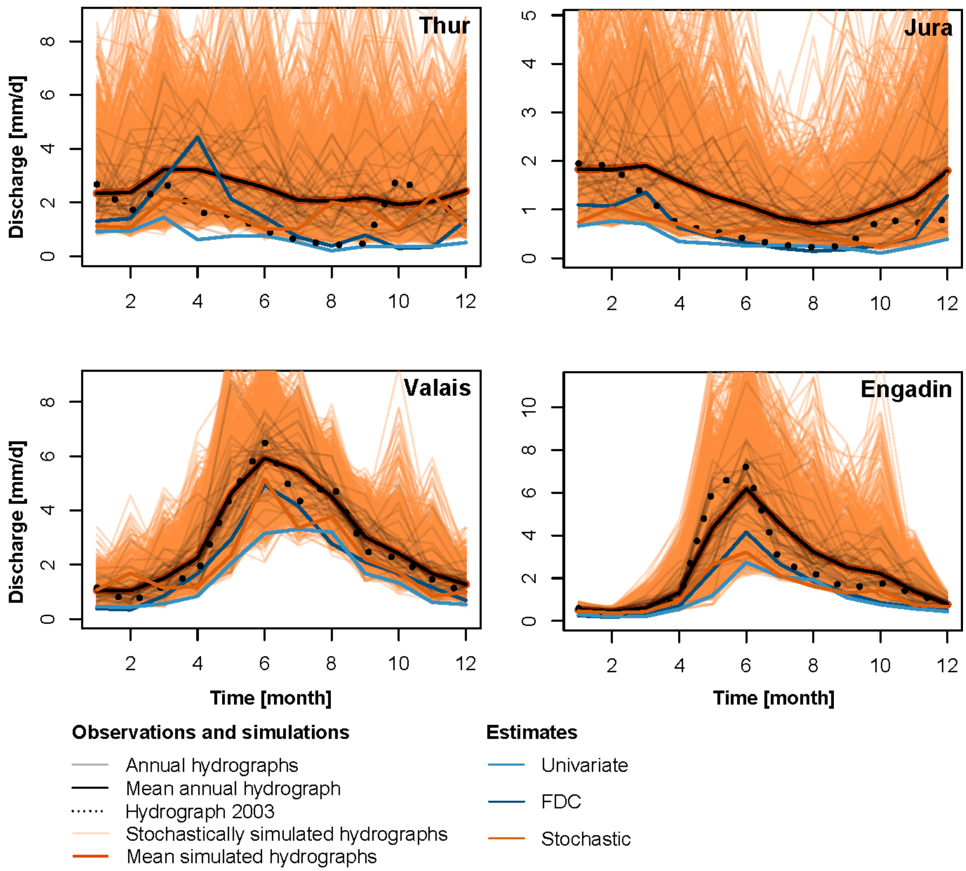

Figure A1. Comparison of the 100-year low-flow regime estimates univariate, FDC, and stochastic with stochastically generated hydrographs (orange lines). The observed mean hydrograph (solid line) and the hydrograph of the year 2003 (dotted line) are given in black.

Author contributions. The idea and setup for the analyses was developed by MB. MZ did the hydrological model simulations. HZ, MH, and DF provided the future glacier extents. The analyses were performed by MB and discussed with MZ and DF. MB wrote the first draft of the manuscript which was revised by all co-authors and edited by MB.

Competing interests. The authors do not have any competing interests

Table A1. Summary of 39 climate chains considered: Global circulation model (GCM), regional climate model (RCM), representative concentration pathway (RCP), and grid cell resolution.

GCM	RCM	RCP	Resolution
ICHEC-EC-EARTH	DMI-HIRHAM5	2.6	EUR-11
ICHEC-EC-EARTH	DMI-HIRHAM5	4.5	EUR-11
ICHEC-EC-EARTH	DMI-HIRHAM5	8.5	EUR-11
ICHEC-EC-EARTH	SMHI-RCA4	2.6	EUR-11
ICHEC-EC-EARTH	SMHI-RCA4	4.5	EUR-11
ICHEC-EC-EARTH	SMHI-RCA4	8.5	EUR-11
MOHC-HadGEM2-ES	SMHI-RCA4	4.5	EUR-11
MOHC-HadGEM2-ES	SMHI-RCA4	8.5	EUR-11
MPI-M-MPI-ESM-LR	SMHI-RCA4	4.5	EUR-11
MPI-M-MPI-ESM-LR	SMHI-RCA4	8.5	EUR-11
ICHEC-EC-EARTH	CLMcom-CCLM5-0-6	8.5	EUR-44
MOHC-HadGEM2-ES	CLMcom-CCLM5-0-6	8.5	EUR-44
MIROC-MIROC5	CLMcom-CCLM5-0-6	8.5	EUR-44
MPI-M-MPI-ESM-LR	CLMcom-CCLM5-0-6	8.5	EUR-44
ICHEC-EC-EARTH	DMI-HIRHAM5	2.6	EUR-44
ICHEC-EC-EARTH	DMI-HIRHAM5	4.5	EUR-44
ICHEC-EC-EARTH	DMI-HIRHAM5	8.5	EUR-44
ICHEC-EC-EARTH	DNMI-RACMO22E	4.5	EUR-44
ICHEC-EC-EARTH	DNMI-RACMO22E	8.5	EUR-44
MOHC-HadGEM2-ES	DNMI-RACMO22E	2.6	EUR-44
MOHC-HadGEM2-ES	DNMI-RACMO22E	4.5	EUR-44
MOHC-HadGEM2-ES	DNMI-RACMO22E	8.5	EUR-44
CCma-CanESM2	SMHI-RCA4	4.5	EUR-44
CCma-CanESM2	SMHI-RCA4	8.5	EUR-44
ICHEC-EC-EARTH	SMHI-RCA4	2.6	EUR-44
ICHEC-EC-EARTH	SMHI-RCA4	4.5	EUR-44
ICHEC-EC-EARTH	SMHI-RCA4	8.5	EUR-44
MOHC-HadGEM2-ES	SMHI-RCA4	2.6	EUR-44
MOHC-HadGEM2-ES	SMHI-RCA4	4.5	EUR-44
MOHC-HadGEM2-ES	SMHI-RCA4	8.5	EUR-44
MIROC-MIROC5	SMHI-RCA4	2.6	EUR-44
MIROC-MIROC5	SMHI-RCA4	4.5	EUR-44
MIROC-MIROC5	SMHI-RCA4	8.5	EUR-44
MPI-M-MPI-ESM-LR	SMHI-RCA4	2.6	EUR-44
MPI-M-MPI-ESM-LR	SMHI-RCA4	4.5	EUR-44
MPI-M-MPI-ESM-LR	SMHI-RCA4	8.5	EUR-44
NCC-NorESM1-M	SMHI-RCA4	2.6	EUR-44
NCC-NorESM1-M	SMHI-RCA4	4.5	EUR-44
NCC-NorESM1-M	SMHI-RCA4	8.5	EUR-44

Acknowledgements. We thank the Federal Office for the Environment (FOEN) for funding the project (contract: 15.0003.PJ/Q292-5096). We also thank MeteoSwiss for providing observed meteorological data and the Swiss National Centre for Climate Services (NCCS) for providing the climate model simulations.

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