Dear editor, Dear reviewer,

We thank you very much for your constructive and instructive comments. We really appreciate the time taken by the reviewer to provide comments and suggestions on how to improve the presentation of our results. The deeper scientific discussion on the summer water temperature overestimation issue also helped us to reconsider the interpretation of the results and to partly reformulate the confidence related to some of our results.

Please find below a detailed answer to all the points raised in the review. We hope that these answers, together with the corresponding modifications of the manuscript, will clarify and resolve the remaining issues identified by the reviewer.

In the following, reviewer comments are repeated in *blue italic* and, author replies in regular font. Section and figure numbers refer to the revised version of the manuscript if not stated otherwise.

Best regards,

Adrien Michel, on behalf of the authoring team.

General note

As mentioned in a separate email to the editor, we found a minor error in the computation of the seasonal means in the previous version of the paper. The error was that first, monthly averages were computed, and then, seasonal averages were computed from the monthly averages. This has been corrected now by computing seasonal averages from all the days constituting the seasons. Changes in the results are marginal and do not affect any of the paper's outcome and analysis, but explain why some plots and tables in this new version have been updated and slightly differ from the previous version of the manuscript.

Editor comment

Dear Authors,

Thank you for the resubmission of your manuscript. The manuscript has received one re-review, and the reviewer has raised several points they hope you can address through an additional revision. In particular, they recommend rewriting and reorganizing portions of the results and discussion, to ensure limited repetition and improve overall flow of the manuscript. They also raise an important point: the need for a clear statement of objectives in the introduction.

Following the reviewer's suggestion, the manuscript has been substantially reorganized around two clear objectives which are now more prominently stated in the introduction. This resulted in a shorter (word count educed by 18%) and better organized manuscript (the results and discussion have been completely reorganized) that, at the same time, provides more pertinent information than our first version. Again, we thank the reviewer for their insights and useful suggestions which helped to improve the manuscript.

They also raise some strong points regarding future simulation with model results that over-predict during summer periods. I encourage you to be forthright with these limitations in your revised manuscript, and to address some of the questions from the reviewer below regarding this overprediction (recognizing as well that you have made a major effort to reduce the length of this manuscript in your previous revision).

The question of water temperature overestimation in Alpine catchments is discussed below. We provide evidence supporting our hypothesis of a missing cooling mechanism in the paper and in our answers. The presence of the observed issues is now also well discussed as one of the limitations of this work.

Following the concerns of the reviewer, and re-evaluating our results, we lowered the confidence in the results for the Alpine catchments in summer and removed some related part of the analysis. All other results (lower elevation catchments, the metrics used there to assess the impact of CC, and the general pattern of warming in the Alpine regions) are shown to be robust and bring, in our opinion, relevant new insights.

I look forward to seeing an updated version of your manuscript!

Please find the new substantially revised version in the attachment.

Reviewer comment

I reviewed the initial submission of this manuscript. I appreciate the detailed responses to the reviewer comments and actually found many of the responses around model decisions and approaches engaging and insightful. I read the responses prior to reviewing the new version and I was excited to read how the authors had incorporated this material into the revision.

Thank you for acknowledging the work carried out in the previous revision.

Personally I find the model evaluation steps and decisions much more interesting than the climate change simulations. I think we learn more about our systems through testing models and understanding why and where they succeed and fail. In contrast, climate change simulations really amount to a glorified sensitivity analyses that often doesn't provide many new insights into system behaviour or advancing our scientific knowledge. Based on the reply to comments, I was expecting to see more of the 'learning from models' piece in the manuscript. I think some of that discussion is there, but unfortunately, I continue to find the new version of the manuscript difficult to follow and overwhelming, which ultimately reduces the impact of this study. I provide some suggestions on how the presentation could be improved.

We realized and agreed that the paper still had potential for being streamlined, shortened, and sharpened. The “impact studies” versus “model mechanisms” question is discussed below.

I also have a remaining concern about some of the arguments around the model over-estimation for summer temperatures for the Alpine catchments. I detail these comments below, followed by some more specific comments.

1. *Organization and focus of the paper*

I continue to struggle getting through this manuscript and I’ve spent a bit of time reflecting on why that is. There is an immense amount of material presented which partly contributes to the confusion, but in thinking about this more, I suspect some serious efforts in restructuring and adding focus to the manuscript will ultimately make it easier to read and communicate the key points of this study. Here are a few suggestions:

- Some of the result sections contain methodological details, as well as discussion points. This makes it difficult to follow some of the lines of reasoning, as well as getting the key points from the study. In addition, the reader is constantly referred to different sections (‘see Section X’, ‘presented below’, ‘details below’, etc.), as well as being referred to the (extensive) supplemental material and details in other papers – which makes it all challenging to follow, even on the third read through, let alone the first. I think by keeping introduction, methodology, results and discussion material in their own sections would improve the logical flow of the paper. I

also think the authors should spend some time creating a logical narrative throughout the manuscript that is sufficiently supported with standalone evidence and explanations without having the reader search all over for information. However, you don't want to include so much detail that it results in an overly long paper. I recognize this is a difficult balance to strike with the amount of modelling work done here, but the current version remains difficult to follow and digest.

We agree with the reviewer's points, which are well justified. Following these suggestions, the paper has been substantially reorganized:

- In the introduction, we reformulated the objectives of the study (Page 3 Lines 3-9): *"The present study has two main objectives: i) Assess the ability of a physics-based model chain to simulate discharge and water temperature. This is achieved by using performance metrics over calibration and validation periods, and by assessing in how far the models are able to reproduce currently observed trends. ii) Investigate the impact of CC on river temperature. Despite the existence of extensive recent studies on discharge evolution under CC in Switzerland over a larger set of catchments (Brunner et al., 2019a, b; Muelchi et al., 2020, 2021), discharge is included in our analysis given the coupling of water temperature and discharge. For both objectives, the comparison of lowland versus Alpine catchments is one of the focal points of this research."*
- The modified Results Section presents the main findings of this study. First, we present the calibration results and the model performance (this is now a clear result according to objective 1), followed by the presentation of the impact study results.
- A newly added Discussion Section first concentrates on the discussion of the models' performance, in particular the problem in Alpine catchments, and then on the discussion of the impact of climate change.
- We completely reframed and shortened the conclusions to briefly summarize our main findings in view of the two principal objectives of the study.

We provide the manuscript with tracked changes, however, due to the major reorganization it would be endless to mention here all changes appearing in the track-change version. Note that the track-change fails sometimes to attribute deletions to the correct section. We therefore mention in Table 1 below the main modifications in the manuscript.

Overall, the revised version of the manuscript is 18 % shorter than the previous version (and 24% shorter than the first version). It is still a long paper, but this is necessary for reporting and discussing all relevant information. We think that the new organization improves the readability of this paper. By shortening and reorganizing the paper, many cross-references, which were another concern of the reviewer, have been removed.

Table 1 – Summary of the main reorganization and modifications of the manuscript.

Section (previous version)	Section (new version)	Changes
Abstract	Abstract	Some details have been removed, others have been added, e.g. regarding the limitations.
1. Introduction	1. Introduction	Reorganized. Some details have been removed. The part about statistical vs. physics-based model has been shortened substantially.
2. Data	2. Data	Removal of some repetitions and cross-references.
3. Models	3. Models	Removal of some repetitions and cross-references, removal of some minor details.
4. Models calibration and validation	Deleted	Section 4 became the "Results" Section.
5. Climate change simulations – Results and discussion	4. Results 5. Discussion	Section 5 was split in two separate sections (Results and Discussion).
4.1 Calibration and validation setup	3.4 Models calibration and validation	The technical procedure of the calibration is now described in Section 3.4, as part of the main "Model" Section.
4.2 StreamFlow calibration and validation results	4.1 StreamFlow calibration and validation results 5.1 Model chain performance	Former Section 4.2 is now part of the Results Section (4.1). The second subsection, about Alpine catchments, has been shortened to only presenting the results (including the summer problem). All discussion of the performances of the model and the issues has been moved to Section 5.1. The content has been edited to reflect the discussion below on the HSPF scheme and on the uncertainty.
5.1 Swiss Plateau Catchments	5.2 Climate change impact	The discussion of the CC impact, with the two indicators, has been moved to the Discussion Section.
5.2 Alpine catchments	5.2 Climate change impact	The discussion of soil temperature has been moved to the Discussion Section. The discussion on summer warming impacts has been shortened due to related uncertainty.
5.3 Role of discharge variations for summer water temperature	5.2 Climate change impact	The discussion of sensitivity of water temperature to discharge has been moved to the Discussion. Section. Only Plateau catchments are now discussed and, in less

		detail, since this is not directly related to one of the two main objectives.
5.3 Robustness, limitations and open questions.	5.3 Limitations and open questions	Robustness is now discussed in Section 5.1 and Section 5.3 now focuses only on the other aspects.
Conclusion	Conclusion	Part about CC impact discussion has been removed, while part of model mechanism analysis has been enhanced, to better report on the study's two main objectives.

- The introduction could be substantially streamlined. It jumps around and lacks a logical flow. In addition, the study would be better contextualized with clear statements of the study objectives. Currently, the closest I could find to stated research objectives in the last paragraph of the introduction amount to (a) a statement about which models were employed in this study and (b) that these models were used to investigate the impact of climate change. More specific and testable objectives (or even hypotheses) would give the study greater focus and impact.

The introduction has been reorganized profoundly to achieve a better logical flow. Details of lower importance have been removed. The research objectives are clearly stated upfront. We thank the reviewer for this comment which largely helped for the subsequent paper reorganization.

- Some detailed editorial work by the authors is needed. The text throughout can be streamlined - such as removing sentences like Page 1 Line 3-4 and Page 1 Lines 8-9 ('This represents...'). Another example is that the paragraph on page 2 lines 16-21 could be removed or incorporated more succinctly into the opening paragraph. These are just examples and I encourage the authors to critically review the writing throughout to cut unnecessary words and sentences. In addition, the grammar could also be improved throughout.

We removed many clauses or extra-verbosity in the manuscript (see track-changed version). We also checked the grammar of the document which, combined with the excellent language editing service freely available for Copernicus publications, should result in a good general grammar level for a scientific publication.

A simple suggestion, but perhaps add a prefix to the catchment names to designate whether they are plateau or alpine sites (e.g., P-Suze, A-Lonza or something similar). Keeping track of these throughout the manuscript is difficult, particularly since they are not always grouped together in a logical way (especially in the supplemental document).

We tried to follow the suggestion of adding prefixes, but we felt it did not lead to the desired clarity. We now reorganized the plots in Supplementary Material to always distinguish between Plateau and Alpine catchments, in an attempt to facilitate the reading. Also, the catchment type is now always mentioned in the Figure captions. In the main text, we now have distinct sections or paragraphs in the Result and Discussion Sections referring exclusively to one type of catchment.

2. Rationale for the summer over-prediction

I struggle with the logic around continuing with the climate change simulations despite the over-prediction of summer stream temperature at the Alpine catchments. It seems that the authors are arguing that the missing cooling mechanism is conclusively known (cold water advection not captured by the HSPF scheme), hence why the model over-predicts - but that's okay, since that won't be an important process under future climate conditions. This seems like two big assumptions (the cold water advection term is the missing component and that it won't be important in the future)! Despite the multitude of graphs, I don't think there is one that shows future absolute SWE simulations (although there are percent change figures). Is some SWE simulated for future scenarios? If so, I would argue that even if the cold water advection is the missing term, it will remain a key missing process in these models that is potentially important for correctly simulating river temperatures in these systems; therefore, how much can we believe these predictions?

Yes, absolute SWE is modelled in Alpine3D, see Figure 1 below (similar figures for all catchment and for the months of December, January and May have been added to the supplementary, Figures S81 to S86). The computation of change in SWE percent is based on these data. In the manuscript, it is now explicitly stated that this information is simulated in Alpine3D (Page 18 Lines 6-11). The other points raised are addressed below.

I appreciate the systematic evaluation of the potential mechanisms that could be accounting for the over-prediction; however, without a way to check some of the internal processes (e.g., evaluating the estimates of incoming solar radiation reaching the stream surface, above-stream wind speeds and humidity, lateral inflow temperatures and magnitudes, potential influences of groundwater/hyporheic exchange), it seems very difficult to conclusively say that the limitation in the HSPF scheme is the single cause driving the model error. What about evaporative cooling - is the latent heat flux underestimated in summer (I believe the alpine rivers are more open and perhaps characterized by greater ventilation - perhaps this is not properly captured in the model)?

From our detailed analysis (Section 5.1 and S9), we can exclude many potential causes. The reviewer suggests additional reasons. The fact that the model behaves correctly in the lowland Plateau catchments and in Alpine catchments except for some sudden warming in summer suggests that the physical processes shared between both groups of catchments are correctly represented. Errors related to in stream processes or due to input data error or scarcity are not expected to cause such errors, which occur during a (short) well-defined time. The sudden warming peaks erroneously simulated do not always occur at the same period of the year and do not depend on discharge (note that some of the variables mentioned by the reviewer, such as radiation, latent heat fluxes, or lateral energy fluxes are shown in Figures S52 to S58 and discussed in Section S9). Conversely, the warming peaks are strongly correlated to peaks produced by the HSPF parametrization of input water temperature (see Figure S59).

This correlation indicates that it is very likely that the error stems from an overestimated energy input from the HSPF scheme. Considering these sudden energy inputs as correct, while then missing some “in-stream” mechanisms that would dissipate the extra energy only during these short-lived events, seems quite unlikely.

The HSPF approach, while being probably the best simple approach available (see our comparison with other approaches and the study of Leach et al., 2015), still remains relatively basic given its sole dependence on air temperature. In the Plateau catchments, air temperature is a good proxy for soil temperature and thus most likely also for subsurface flow water temperature (very few observations available), and leads to very good results. In the Alpine catchments, as we state on Page 22 Line 32-Page 23 Line2, interaction with a complex water table topology and snow/ice melt-induced effects are not considered by the model.

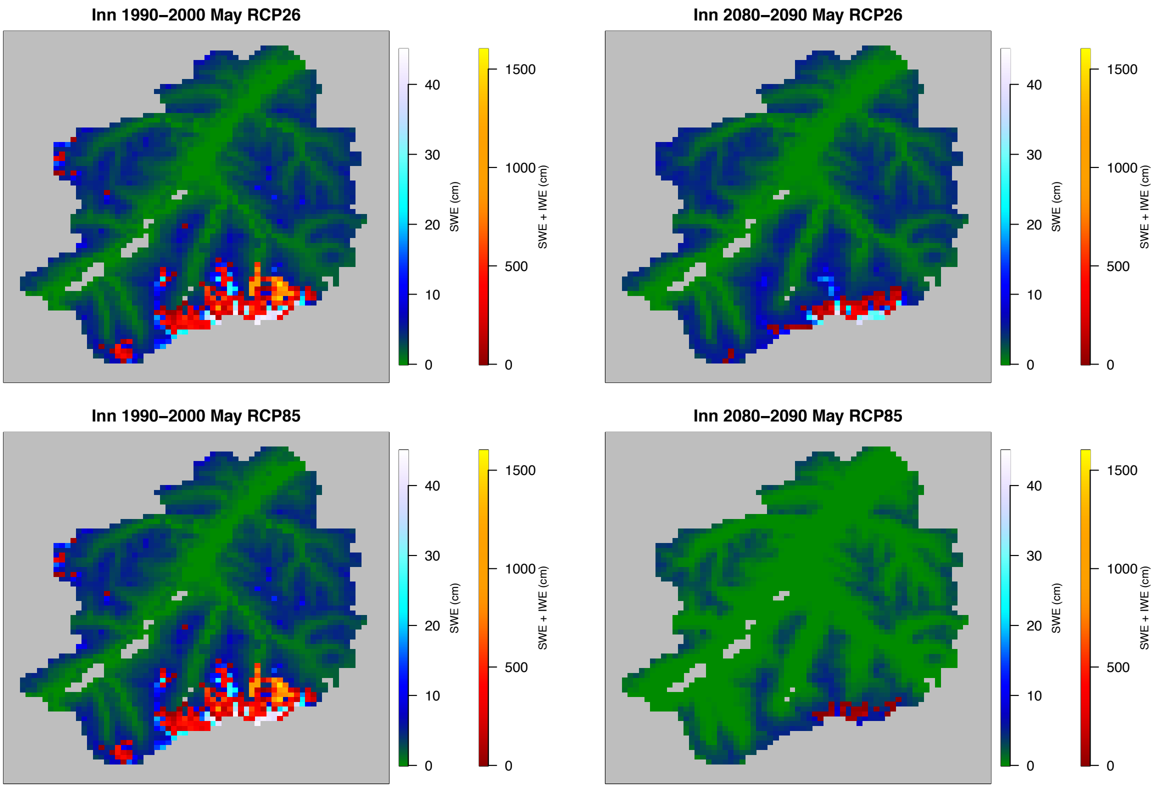

Figure 1 – Average snow water equivalent (SWE) and ice water equivalent (IWE) over the Inn catchment for the month of May. Maps show the average between the 8 model chains used (see Table 2 in the paper). For glaciated pixels, SWE and IWE are summed. Top: RCP2.6. Bottom: RCP8.5. Left: Reference period (1990-2000). Right: End of the century period (2080-2090).

During the early melt season, the air temperature is low (compared to summer) and close to or below subsurface soil temperature; the temperature of water feeding the stream will thus be close to air temperature independent of the actual flow paths (surface, subsurface) and independent of its recent origin from snowmelt or from rain; the HSPF approach is thus leading to correct results despite missing the actual surface/subsurface water exchange mechanisms and in particular by missing fast cold melt water advection at the surface.

The HSPF approach only fails when the air temperature is high, i.e. during periods when the HSPF approach produces large heat input whereas fast surface flow processes could lead to cold water advection from melt. This is another argument to identify the missing subsurface flow paths of meltwater as a potential culprit for the water temperature overestimation during summer. New evidence of the impact of cold advection by ice melt on water temperature has been recently published by Du et la. (2021). This reference has been added in the Discussion Section.

We do not expect the proposed cooling mechanisms (snow and ice melt or local groundwater interaction), if included in the model on top of the HSPF formulation, to directly suppress the large warming peak. We argue here that a completely different approach including these mechanisms should be tested to assess the ability of the model to correctly simulate the water temperature in Alpine catchments (Page 23 Lines 10-11 and Lines 10-20, see also the answer to the next reviewer point for additional elements). However, we also clearly acknowledge that these proposed mechanisms are uncertain and would need further investigation (Page 23 Lines 21-23).

This discussion clearly falls under the first objective of the paper and is extensively treated in Section 5.1 which integrates new elements from the discussion above. We clearly point out the limitation of the HSPF approach and suggest mechanisms that should be accounted for to improve hydrological models. Given the length of the paper, this discussion is not exhaustive and does not cover every aspect in all detail. We consider a systematic solution of the problem of overestimated summer water temperature in Alpine catchments to be beyond the scope of this study.

In the initial version of the manuscript, we stated that snowmelt was the major (and probably only) problem and, as it will be of lesser importance in the future, that it would be a minor issue for the impact assessment. We reconsidered this statement in view of the identification of the mechanisms discussed above, leading to some implications on the presentation and interpretation of the results (see below). However, the reduction of snow and glacier cover, now also shown in the new maps in Figures S81 to S86, and its potential impact on water temperature are still discussed in the revised manuscript (Page 23, Lines 24-32).

What about errors in input data? For example, Figures S36-S46 highlight some interesting differences between the measured and CC scenario precipitation estimates. It seems for many of the streams that exhibit over-predictions in summer stream temperature are also associated with under-estimates of summer precipitation (and discharge), such as Lutschine (Figure S44). Is precipitation under-estimated in these alpine catchments (which is often an issue in high elevation catchments) driving the over-prediction of river temperature?

When forced with CC scenarios during historical periods, discharge simulations show indeed lower performance in Alpine catchments, which is mentioned in the text (Page 15 Lines 10-15). However, the error in temperature does not correlate with the period of maximum discharge underestimation (see e.g. Figures S42 and S45) and the "incorrect" summer warming also appears in catchments where summer discharge is correctly simulated or even overestimated during the summer season when forced with CC scenarios (see e.g. Figures S43 and S44). In addition, the overestimation is also observed when forced with measurements and not only when forced with CC scenarios (Page 22 Lines 15-19):

"These overestimations do not appear during all summers and there is no temporal coincidence between the instances of temperature overestimation and low discharge conditions. Furthermore, only two of the rivers concerned with this overestimation problem (the Inn and the Landwasser) show a correlation between river temperature and discharge errors (Figures S21, S23, S25, S27, and S29), suggesting that the underestimation of summer discharge cannot explain the overestimation of river temperature."

The same conclusion arises from a comparison of the transient discharge and water temperature measurement compared to simulation, e.g., in Figures S20 and S26. Finally, a general bias in discharge prediction in summer would lead to a general bias in water temperature throughout the summer season, but not to sudden warming as simulated here.

Overall, this seems to be a major challenge and undermines the confidence in the climate change scenarios. Similar to my point in the above, I think focusing on this model failure is far more interesting than whether the model simulates X degrees celsius of warming in 50 years, so I don't see this model limitation as barrier to publication. Instead, a repositioning of the manuscript to focus on these model failures and expanding the possible causes of these over-predictions (beyond what is already done), could highlight some important areas of future study to improve our simulations of stream temperature in these types of environments. I realize these types of climate change impact simulations are published all the time, so I'll understand if the authors would like to stick with that focus of the manuscript, but personally I think focusing more on exploring the model failure could make for a more satisfying study.

We understand the opinion of the reviewer about the added values of the "model mechanism" studies with respect to climate impact studies. However, impact studies are of great value as a basis for decisions or further studies (for instance on the impact on the aquatic biota). At the same time, model mechanisms have also been a focal point of this study, cause for the length and earlier structural issues of this paper. These issues have now hopefully been eliminated thanks to the reviewer's suggestions.

We think that simultaneously addressing the model mechanism question and the climate change impact is beneficial. In many recent hydrological impact studies, the model validation part is discussed only very briefly. If we had decided to not go into details, and only show the RMSE results for the Alpine catchments, which are similar to the ones in the Plateau catchments, the summer overestimation would have been unnoticed. This is in no way an argument to downplay the observed issue in this paper, but rather a point to justify a detailed model discussion in impact studies, even if this comes at the price of having a rather lengthy paper.

We think that the revised paper now has a much better balance of the two main objectives and the results about the model mechanism (in our case, the overall good performance, except the issues in Alpine catchments during summer) receive the necessary attention. In particular, the model performance is now discussed as part of the Results Section and the discussion of the model problem is placed in the Discussion Section.

We now address the reviewer's remark concerning the impact study, i.e., the question of treating the summer overestimation and confidence in the values obtained. The main argument given in the initial version was that the identified mechanism will decline and disappear in the future. We acknowledge that our two points are assumptions: (1) correct identification of the mechanisms, and (2) that their impact will actually decrease in the future.

As discussed above, we have strong arguments identifying the HSPF scheme as the culprit but cannot say whether the lacking mechanism in the HSPF scheme is snow/ice melt related (and thus expected to decrease in the future), or some other mechanism such as groundwater interaction (for which it is unclear how it will evolve in the future). This is now stated on Page 23 Lines 16-20, and related statements concerning the (un)certainty we put on these results (Alpine catchments during summer) are adjusted accordingly. Specifically, the manuscript has been modified as follows:

- We shortened the description of the analysis of the summer results in Alpine catchments (Page 19) and clearly mention the related uncertainty and refer to the Discussion Section (Page 20 Lines 1-2),

- When discussing the summer overestimation, we clearly state the related uncertainty and say that our main result regarding the summer temperature in Alpine catchment is rather the identification of the issue and the proposed mechanism to explain it (Page 23, Line 21-23),

- In the Discussion Section, we stress that the actual numbers predicted come with a given uncertainty, and emphasize more on the elements that will impact water temperature in the future in Alpine regions (Page 24 Lines 21-31),

- In the discussion of the sensitivity of water temperature to discharge, we state that the difference observed between Swiss Plateau and Alpine catchments would be worth investigating in more detail, and that for now the uncertainty of summer water temperature in Alpine catchments prevents us from drawing strong conclusions (Page 26 Line 10-15).

Despite this reduced confidence in some specific results presented in the updated study (one season in one of the two types of catchments studied), we have strong confidence in all other results presented. We think that the majority of these results certainly will be of interest to our peers, e.g., for the study of their impact on ecosystems in rivers or for the interaction with lakes downstream of rivers.

Some specific comments:

Page 1 Line 8: This sentence could be removed ('This represents...').

Done.

Page 2 Line 2: I don't think this sentence is needed here.

Indeed, especially in the revised version this is even less relevant. We removed it.

Page 2 Line 9: Do you mean 'along with' instead of 'along to'?

Yes, this has been corrected.

Page 2 Line 22-27: The logical development of this paragraph is confusing. It starts with a statement about river temperatures impacting groundwater temperatures, but then jumps into how precipitation patterns will impact groundwater thermal regimes and then concludes with this being a rationale for studying future changes in stream temperature. Some of these points are important, but how they are developed and linked could improved.

The whole introduction has been reworked to obtain a better logical flow.

Page 3 Lines 1-2: Could you briefly expand on what differences were found in that study instead of just stating there were differences?

This has been added, see Page 2 Lines 23-24: “So far, the warming rate of rivers in Swiss Plateau catchments has been almost twice that of Alpine catchments.”

Page 3 Lines 7-8: This doesn't seem like the most appropriate reference here as the Horton et al preprint hardly talks about river temperature models.

Indeed, the reference has been removed.

Page 4 Line 6: Could you explain to non-Swiss readers why having both Swiss Plateau and Swiss Alps catchments is important?

This has been briefly explained, see Page 3 Lines 10-12: “The focus is on Switzerland, a country presenting a wide topographic heterogeneity leading to different discharge and thermal regimes between the lowland Swiss Plateau regions, where the hydrological cycle is mainly precipitation driven, and the high altitude Alpine regions, where snow and glacier melt play an important role.”

Page 5 Lines 3-4: Do you mean the results of Epting et al 2021 were used in the current study or that the current study results were used in Epting et al 2021?

The results of the current study have been used in the study of Epting et al., this has been clarified (see Page 3 Lines 28-30).

Page 12 Line 15: 'first' instead of 'fist'

Corrected.

Page 13 Figure 3: Spelling mistake in the legend.

Corrected, thank you for catching it.

Page 15 Lines 3-4: Are these sorts of influences (e.g., cement factory effluent) common near the observation points in these catchments? I thought these catchments were selected because they had minimal anthropogenic influences?

This is the only catchment with this kind of disturbances in our selection. Indeed, we tried to select catchments with minimal disturbance. But we also selected catchments suitable for the groundwater study of Epting et al. (2021). The Suze is interesting in terms of groundwater, and has been retained despite some perturbations. It also serves as a good test case for a model setup in a very complex environment, i.e., a karstic region.

Page 27 Lines 13-14: The Du et al study was conducted in Canada, not the USA.

Thank you, corrected.

Page 28 Lines 16-17: But on Page 4, Lines 8-11 it was stated that these study catchments were selected based on criteria (e.g., no large lakes, no anthropogenic disturbances, no dams) that other Swiss catchments didn't meet; therefore, are they actually representative, since it's well established that lakes, dams and anthropogenic disturbance can have profound influence on river thermal regimes?

We changed the sentence to: “The studied catchments can be assumed to be representative of **undisturbed** Swiss catchments in general”; this clarification is indeed needed here.

Figures S52-S58: Are these daily or hourly values presented in the graphs? If hourly, the upper range in incoming solar radiation seems low around the summer solstice.

All values shown in these figures are daily values, this is now clarified in the captions.

References

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