Author response to RC1:

We are grateful for the detailed and critical review by Reviewer #1 and we highly appreciate the generally positive assessment of our manuscript. In the following we address the general and specific comments raised:

Comment: I appreciated the fact that many different runoff signatures are discussed (actually the title could state that not only extremes are considered) and the results are compared to the existing literature.

Response: We appreciate this positive feedback. In the title, we wanted to highlight the analysis of annual extremes as this is mostly lacking in previous studies. However, we acknowledge that the title does not span the variety of analysis addressed in the paper. We suggest to adapt the title: "Future changes in annual, seasonal and monthly runoff signatures in contrasting Alpine catchments in Austria:"

Comment: CMIP5 climate projections are used here, which will be soon become obsolete given the CMIP6 simulations already available (the Authors should also discuss this limitation)

Response: As highlighted in the reply to Reviewer #3, to date CMIP6 simulations are not available as downscaled projections to regional scale using RCMs. The scale of this study is too small to reliably use GCM outputs as climate inputs to our study catchments. However, it is interesting to indicate that as soon as they are available new simulations should be used for similar studies to assess differences in outcomes. We therefore suggest to add to Section 4.7. l. 520: "A new set of GCM simulations is available (CMIP6, Eyring et al., 2016). However, these could not be used in this study as projections downscaled to regional scale are not yet available for CMIP6."

Comment; I also would have expected a more critical questioning on how well this modelling approach can capture runoff changes (e.g. based on the discussions in Duethmann et al., 2020, HESS).

Response: Thanks for this comment. We considered and discussed the modelling approach with regard to transient climate. However, it obviously did not become clear enough in the manuscript. Duethmann et al. (2020) found two main causes for the inability of the HBV model to represent runoff in a changing climate: inhomogeneities in precipitation data due to variable number of stations and variations in vegetation dynamics that were not considered. With respect to the first cause, and with the deliberate intention to avoid this limitation, our modelling approach relies on the same set for stations during calibration and evaluation. For EURO-CORDEX simulations the gridded data set was downscaled to the <u>location</u> of these ground stations. For detecting changes in runoff due to climate change, we compare the EURO-CORDEX simulations of the past and the future. Therefore, inhomogeneities in precipitation data do <u>not</u> affect the results. To further assess and illustrate how well the past EURO-CORDEX simulations represent the past climatic and runoff signatures, they were compared to simulations using observations and to observed data (Section 3.2, Fig. 6; Fig. S13-17). The analysis suggests that, overall, the simulations match the runoff signatures relatively well. We will further clarify this in the revised manuscript.

With respect to vegetation dynamics, we acknowledge that feedback of climate change on vegetation dynamics and thus, possibly increased evapotranspiration was not considered. As mentioned by Duethmann et al. (2020), assessing changes in future vegetation dynamics is difficult due to missing future information. Therefore, changes in growing season and land use change remain very uncertain in future. To prevent introducing additional uncertainty in our modelling approach these effects were omitted. This is acknowledged and discussed in the original manuscript (l.520-525). In the revised version we will extend this discussion to also include the suggested reference as well as perspectives on the effects of increased temperatures and rising CO_2 levels (fertilization effect) on plant transpiration, although the effects are not yet fully understood (e.g., Frank et al., 2015).

Due to the known difficulties of models to reproduce changes in transient climate, we intended to make the representation of hydrological process and the model internal dynamics of and feedbacks between these processes as robust as possible to avoid major misrepresentations of the system. To ensure that, we calibrated and evaluated the model simultaneously to eight individual objective functions describing different signatures of flow (Section 2.2.2). In addition, we performed a long-term calibration of 20 years and a model evaluation of 8 to 10 years and we used 300 parameter sets in an ensemble analysis to account for parameter uncertainty. Furthermore, we considered future changes in glacier extent. With this approach we aim to ensure that our modelling approach can capture runoff changes. However, the uncertainties in model structure remains and was not further assessed, although model structure uncertainty can be significant (e.g. Bouaziz et al., 2021; Knoben et al., 2020). We will clarify this in the Discussion section.

Comment: Regarding the attribution of runoff changes to the causes (precipitation, evapotranspiration and snowmelt), a more quantitative analysis would have made the paper even more interesting

Response: We agree that a more detailed analysis of the causes of runoff changes would be desirable. To attribute changes to specific causes during runoff events, a tracking of the sources of water throughout the hydrological model would be necessary to disentangle the contribution of snowmelt and precipitation. Implementing a correct source tracking remains very difficult (Weiler et al., 2018) and would need detailed tracer data and considerable adaptation of the model structure to allow for mixing effects so that fluxes can then be individually tracked through the system (e.g. Hrachowitz et al., 2013).

Attributing each change in input (precipitation, evapotranspiration and snowmelt) to a change in runoff is very difficult since changes and processes interact. Therefore, a quantitative separation of effects is not warranted here with the available data. The main objective was to examine the combined effect of changes in precipitation and temperature, which was assessed by our simulations. To support the analysis, we will add figures of monthly changes in precipitation, temperature and potential evaporation in the Supplementary Information.

Comment: Line 85: what could be the bias introduced by scaling the runoff data, rather than the precipitation data, for consistency with Budyko? Since the Authors are interested in percental changes, wouldn't this choice exacerbate the changes in magnitude for runoff in those catchments?

Response: First of all, we would like to point out that the scaling of runoff data has no effect on the timing of runoff extremes. A scaling factor for the runoff was derived based on the Budyko framework, so that calibration would be feasible. This scaling factor is not applied to modelled runoff of the past and future generated using the EURO-CORDEX simulations. Thus, the absolute runoff is likely underestimated in simulations. However, the relative change in runoff remains unaffected because it is derived using the past and future modelled runoff from EURO-CORDEX simulations. Absolute changes are likely to be higher than our projections, so that our projections are likely a lower limit of absolute change. We explained this in Section 4.7 line 509-510 in the original manuscript but we will further clarify and elaborate on that in the revised manuscript.

Comment: Line 104: what is the advantage of transferring the precipitation and temperature data from the EUROCODEX pixels to the ground stations and not working with the pixels themselves?

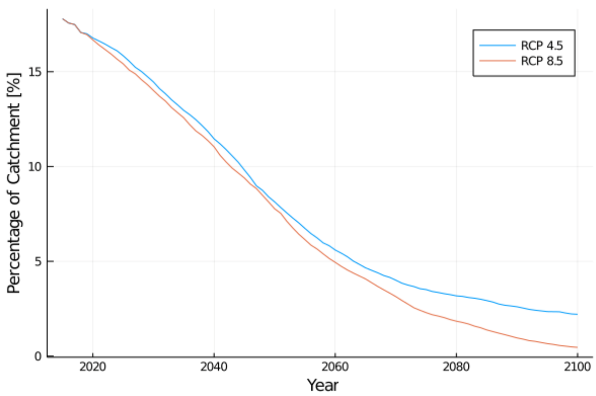
Response: The hydrological model was calibrated using data from ground observation stations for precipitation and temperature by dividing the catchments into different precipitation zones. To ensure as much consistency as possible between the ground data and the EURO-CORDEX data and to avoid a bias introduced by the model parameters that were obtained from calibration to ground data, we decided to transfer the data from the EURO-CORDEX pixels to the ground stations. This was done to keep inhomogeneities in precipitation data (Duethmann et al., 2020) as low as possible, as also discussed above. We will further clarify the approach and the associated limitations of using point-scale data in Section 4.7 line 503-506.

Comment: Line 115: is Table 1 the right table?

Response: No, the reference is wrong. It should be Fig. 2. ("(i) one to four precipitation zones per catchment (Fig. 1), (ii) the four HRUs per precipitation zone (Fig. 2) and (iii) individual 200 m elevation zones per HRU (e.g., Roodari et al., 2021).”

Comment: Line 170: has the glacier extent in the Pitztal a linear decrease till 2100?

Response: No, the glacier extent is adapted according to results by Zekollari et al. (2019). Below is a figure showing the percentage of the Pitztal catchment covered by glacier, from 2015 to 2100 for RCP 4.5. and RCP 8.5. Differences in glacial extent between the two scenarios are largest at the end of the 21st century.



Comment: Page 20: the Gailtal catchment seems special, in terms of annual maxima. Apart from the double peak season, what could explain the largest change in magnitude for RCP8.5?

Response: The Gailtal and Defreggental catchments are located South of the Alpine main ridge and thus under strong influence of moisture circulation from the Mediterranean. However, the Defreggental is located at high elevation so that even under future climate change snow melt will play a role as flood generating process. The Gailtal catchment is mostly dependent on rainfall as flood generating process as most annual maximum flows occur in autumn. As mentioned in the discussion (line 402-403), timing of floods in southern Austria are strongly influenced by Meridional south-east and south weather regimes (Parajka et al, 2010). Therefore, changes in these weather regimes impact the timing but also magnitude of annual maximum flows in the Gailtal catchment. A higher increase in precipitation intensities or maximum daily precipitation as compared to catchments in the

Northern Alps can be assumed to lead to the largest changes in magnitude for the Gailtal under RCP 8.5.

Comment: Line 346: one interesting reference on observed trends in evapotranspiration in Austria and possible causes is Duethmann and Blöschl (2018, HESS).

Response: Thanks for pointing out this interesting study in Austria, which also identified atmospheric demand as main cause for increase in evapotranspiration in the past 40 years. We suggest to add this reference to the statement in line 346: "This slightly lower annual runoff can be attributed to changes in the future partitioning of water fluxes and thus an increased fraction of precipitation to be evaporated due to increased atmospheric demand (cf. Fig. 7a). Increasing atmospheric demand has also been identified as the main driver for increasing evaporation in Austria in the past (Duethmann and Blöschl, 2018)."

Comment: Section 4: the section contains a lot of attribution statements. Are these statements confirmed by simulations, e.g., increase in precipitation keeping temperature unchanged and vice-versa? Or is it just an expert interpretation of the simulations with all variables changing?

Response: Simulations were only performed with all variables changing. However, mean changes in monthly precipitation, snow melt and potential evaporation were analyzed. Based on this analysis, expert interpretations about possible attributions were made. We will clarify this in the revised manuscript.

Comment: Section 4.7: this section could be linked to the hypotheses for potential causes of the divergence between observed and simulated discharge changes in Duethmann et al. (2020, HESS).

Response: We suggest to add a sentence to this section in line 522: "Moreover, the partitioning of precipitation will likely be affected by changes in vegetation dynamics, especially likely extension of the growing season, and can significantly affect changes in runoff (Duethmann et al., 2020), but are not considered here due to lack of knowledge of these changes in future." The lack of considering land use change is already discussed in line 525-529. Inhomogeneities in precipitation should not affect our results as explained in the response to the previous comment.

Regarding the model structure uncertainty, we would add in line 515: "In general, different models with different structures are often not consistent in the results (e.g., Knoben et al., 2020). This uncertainty in model structure was not assessed and it would be worthwhile to repeat a similar study using another hydrological model."

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