Response to Anonymous Referee #2

We thank Referee #2 for reading the manuscript carefully and providing thoughtful and constructive comments. The comments are noted with RC, our responses with AC, and the intended additions or changes in the manuscript are underlined.

RC2.1 The manuscript addresses the important topic of downscaling and bias-correction for hydrological modeling by applying different configurations of a "simulation chain" over an alpine river over the last century. I found the paper interesting and including meaningful results. Nevertheless, the paper lacks both important details on the hydrological modeling and discussion on the uncertainty related to the hydrological modeling within the applied simulation chains.

> **AC2.1** Thank you for this comment. The conceptual hydrological model is mainly used here as a complex and non-linear filter to assess the weather scenarios. Note that the model can be imperfect as we also use it to produce the hydrological reference - against which hydrological scenarios derived from weather scenarios will be compared. The hydrological model is used as a filter to assess the relevance of the downscaling models.
>
> As mentioned in our article, our downscaling models are forced with time series of large-scale atmospheric circulation. Perfect downscaling models would allow to perfectly reproduce the multi-scale spatio-temporal dynamics of weather over the time period used for the simulation. Downscaling models can be assessed, at several scales, for their ability to reproduce observed spatio-temporal dynamics of weather variables. This assessment is rather difficult, especially with regard to the covariability between weather conditions in different sub-basins of the Upper Rhône River basin, or with regard to the covariability between precipitation and temperature.
>
> The hydrological filter is a powerful alternative filter for making this assessment, as the hydrological behavior of sub-basins is highly non-linear, and depends on all the covariability and dependency structures of meteorological conditions, both spatially and between variables. In brief, we need to assess the meteorological variability and covariability features that are important for hydrology and the hydrological model does this job well.

Regarding the hydrological modeling methodology:

RC2.2 L118: please consider adding a diagram of the GSM-SOCONT model in the paper or at least in the Appendix.

> **AC2.2** <u>A scheme of the glacio-hydrological model GSM-SOCONT will be added as an appendix.</u>

RC2.3 L122: are these "ice-covered" and "ice-free" parts of the studied catchments dynamics in time? Indeed, the ice-covered part of the upper catchments may have significantly changed over the last century.

> **AC2.3** No, the hydrological model GSM-SOCONT assumes that glacier extent does not vary over time, and that glacier thickness is infinite. We recognize that this is a strong assumption as the ice-covered part of the upper catchments may have changed significantly over the last century.

This will be mentioned in the text.

RC2.4 L212: what are these additional criteria considering streamflow availability?

AC2.4 We guess you are referring to line 121 and not line 212. The entire catchment was divided into 18 sub-basins. They were selected so that they are roughly the same size, and so that a gauging station is located at the outlet of a sub-basin wherever possible (see Fig. 1).

We will change the formulation in the text and specify that.

RC2.5 L124 to 126: the calculation of the potential evapotranspiration (PE) time series needs to be more deeply presented in the paper: which CRU dataset has been used for this calculation, what is the spatial resolution of this CRU dataset, and how relevant is this database over this region and in this hydroclimatic context? What about this regional temperature-PE relationship in a non-stationary context?

AC2.5 We acknowledge that estimating potential evapotranspiration (PET) in such a mountainous area is a critical issue, and that the CRU data set may give a rough and poor estimate of this variable. However, to the best of our knowledge, PET observations are very scarce in the region, making an evaluation of CRU products almost impossible.

To develop our T-PET model, we use monthly CRU values of PET and temperature T at a resolution of 0.5° x 0.5° for the 1900-2010 period. PET is assumed to be a linear function of temperature T: PET(t) = a x T(t) + b. The coefficient b depends on the calendar month. This model, estimated for the entire Upper Rhône River catchment, is then used at a daily time step to produce daily PET for all its hydrological units. The PET values of the CRU were calculated from a variant of the Penman-Monteith formula (Harris et al., 2014).

We assume that this relationship is the same for the entire period. Variations may have occurred during the period, for instance due to changes in land use and vegetation cover. This will be worth dedicated investigations in future works.

This point will be specified in the text.

RC2.6 L147 to 148: the routing part of the hydrological model needs to be more deeply presented in the paper. What are the hypotheses? How many parameters are devoted to the routing part of the model?

AC2.6 We did not use a routing module. The discharge at a given point in the catchment is simply the sum of the discharges in the upstream sub-basins. In previous work, we used a Muskingum routing model (Hingray et al., 2010), but it was not really necessary here. The size of the catchment is not very large and we use a daily time step for hydrological simulations.

We will change the formulation in the text and specify that.

RC2.7 L149 to 151: please state in the paper the total number of parameters that needs to be calibrated for each sub-catchment and add a list of these parameter in the paper (in the Appendix?).

AC2.7 Please note that the number of parameters (and their names) to be calibrated is already mentioned on lines 149 to 151.

RC2.8 L183 to 184: please give more details on the regionalization procedure applied, and list the ungauged catchment studied here.

AC2.8 Thank you for this comment. All the ungauged sub-basins upstream a given gauging station are calibrated at the same time and are forced to share the same parameters set. The discharge time series used for the calibration is the time series simulated with this multiple sub-basins configuration at the downstream gauging station, where observations are available.

The ungauged sub-basins can be seen in Fig. 1. The sub-basins grouped together for the calibration of their parameters are also listed in Table 2 in Supplementary Materials.

We will clarify this point in the text.

Regarding the discussion about the hydrological modelling uncertainty within the applied chains:

RC2.9 L172 to 174: *"For gauged catchments for which the hydrological behavior is significantly altered over P1 and for which "natural" flow observations are available prior to 1950, parameters were estimated based on hydrological signatures (Sivapalan et al., 2003; Winsemius et al., 2009). In the present case, parameters are calibrated so that simulated signatures reproduce at best observed ones but observed and simulated signatures come from different periods following Hingray et al. (2010) (e.g. 1961-2015 and 1922-1963 respectively for the Viège basin). We thus assume that the weather regimes and the natural hydrological behavior of the catchment have not significantly changed over the last century, which seems a reasonable assumption to make in first approximation."* This strong hypothesis needs to be more deeply investigated in the paper: what about potential significant interannual / decadal hydro-climatic variability in the region? What about potential impacts of such interannual / decadal hydro-climatic variability on the hydrological model parameters? What about using adjustment on long-term climatic information (e.g. Nicolle et al., 2013, doi: 10.1002/2012WR012940)?

AC2.9 The stationarity assumption is indeed a strong one. Unfortunately, there is no other choice for the calibration of some sub-basins of the Upper Rhône River catchment, due to the flow data available here, which have been strongly perturbed by dams since the 1950s. See the figure below from Hingray et al. (2010).

It is difficult to assess the relevance of the stationarity assumption for hydrological regimes. This assumption implies that the following two independent assumptions are valid: the stationarity of precipitation regimes and the stationarity of the natural hydrological behavior of the catchment.

Apart from the impact of dams, the hydrological behavior of sub-basins could have changed over the period, due to changes in land cover (glacier and vegetation). About glacier retreat over the last century, Huss (2011) explains that (i) the contribution of glacier melt is relatively stable over the 20th century, with similar glacier contribution over the periods 1961-1990 and 1908-2008, and (ii) glacier retreat strengthened over the period 1988-2008, with glacier contributions on the Rhône River increasing by 13% for the month of August. Considering a stationary glacier contribution over the whole period is therefore not fully satisfactory for the last two decades, but acceptable over the whole period. On the other hand, the impact of vegetation changes on hydrology is often difficult to highlight. Moreover, in the region, a large part of the sub-basins is free of vegetation (due to elevation). Assuming a stationary natural hydrological behavior seems thus to be reasonable here.

The stationarity of the precipitation regime may be an issue. Significant interannual variability in annual precipitation generally exists for precipitation. It is much lower when the mean interannual precipitation is considered, as it is the case here (we compare the hydrological signatures of two periods of several decades each). To the best of our knowledge, no significant precipitation trends have been observed in the region over the last century (e.g. Masson and Frei, 2016; Scherrer et al., 2016).

We will mention all these points in the manuscript.

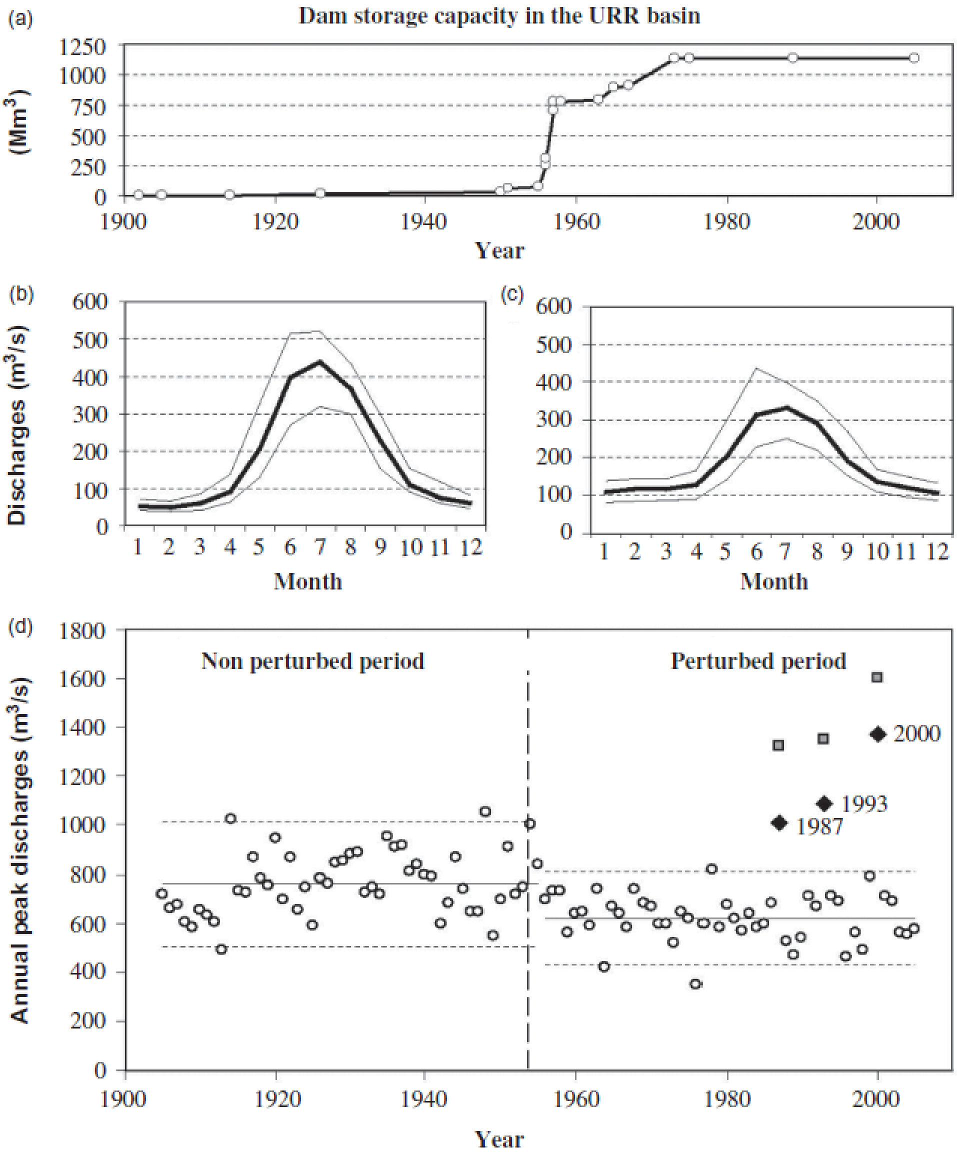


Fig. 1 Effects of water works on the URR basin hydrology: (a) dam storage capacity evolution over the 1905–2005 period; (b) and (c) 10, 50 and 90% percentiles of the mean monthly discharge at Porte du Scex for 1905–1955 and 1955–2005, respectively; and (d) annual maximum peak discharge. For 1987, 1993 and 2000 floods: ◆: observed discharge; □: reconstructed discharge (from Hingray *et al*., 2009).

Using adjustment on long-term climatic information.

Using a blending neighbor approach for the calibration, as in Nicolle et al. (2013), is indeed an attractive alternative. However, this would not be straightforward. In the upstream sub-basins of the Upper Rhône River basin, the hydrological regime is mainly "glacial" (dominated by glacier melt, according to the Swiss classification). It shifts to a "glacio-nival" regime (glacier/snow melt), a "nival" regime (dominated by snow) and a "pluvio-nival" regime (dominated by a mixture of snow and precipitation) as we move downstream. The flow signatures (such as the mean interannual cycle) at different locations along the river present clearly different patterns. It would therefore probably be difficult to find neighboring basins to consider as donors of the signatures used for the signature-based calibration.

RC2.10 L180: Table S1 needs to be presented in the paper and not in the Appendix, and more deeply discussed, since the performance obtained on several subcatchments are poor (e.g. Arve@Genève, BDM). What are the potential reasons for these differences in performance between the studied catchments? Please also consider producing the Figure S2 for every studied catchment in the Appendix.

AC2.10 Thank you for this suggestion. Table S1 could be moved into the article, but it is already quite long. We agree that performance is rather poor for some sub-basins. However, data "quality" varies considerably from one sub-basin to another. For some of them, daily meteorological data and daily non perturbed discharge data are not available. This requires a signature-based approach which, logically leads to lower "performance".

To assess the decrease in performance due to the signature-based approach, we carried out in the meantime the following experiment. For four sub-basins with concomitant meteorological and flow data, we first applied a classical calibration, followed by a signature-based calibration. The signature-based calibration is quite effective, but is still less efficient than the classical calibration.

We will comment this point in the manuscript and include the results of this experiment in Supplementary Materials.

Even when concomitant series are available, the classical calibration is unfortunately not always very effective. This is indeed the case for the gauging station Arve@Genève, Bout-du-Monde. For this basin, the hydrological regime is much less snow-dominated than elsewhere in the Upper Rhône River catchment. The density of the precipitation network is perhaps not dense enough to provide a good estimate of precipitation inputs.

As suggested by the reviewer, the results of the classical and signature-based calibrations will be given for the other sub-basins in Supplementary Materials.

These will be Fig. S3 and S4 below:

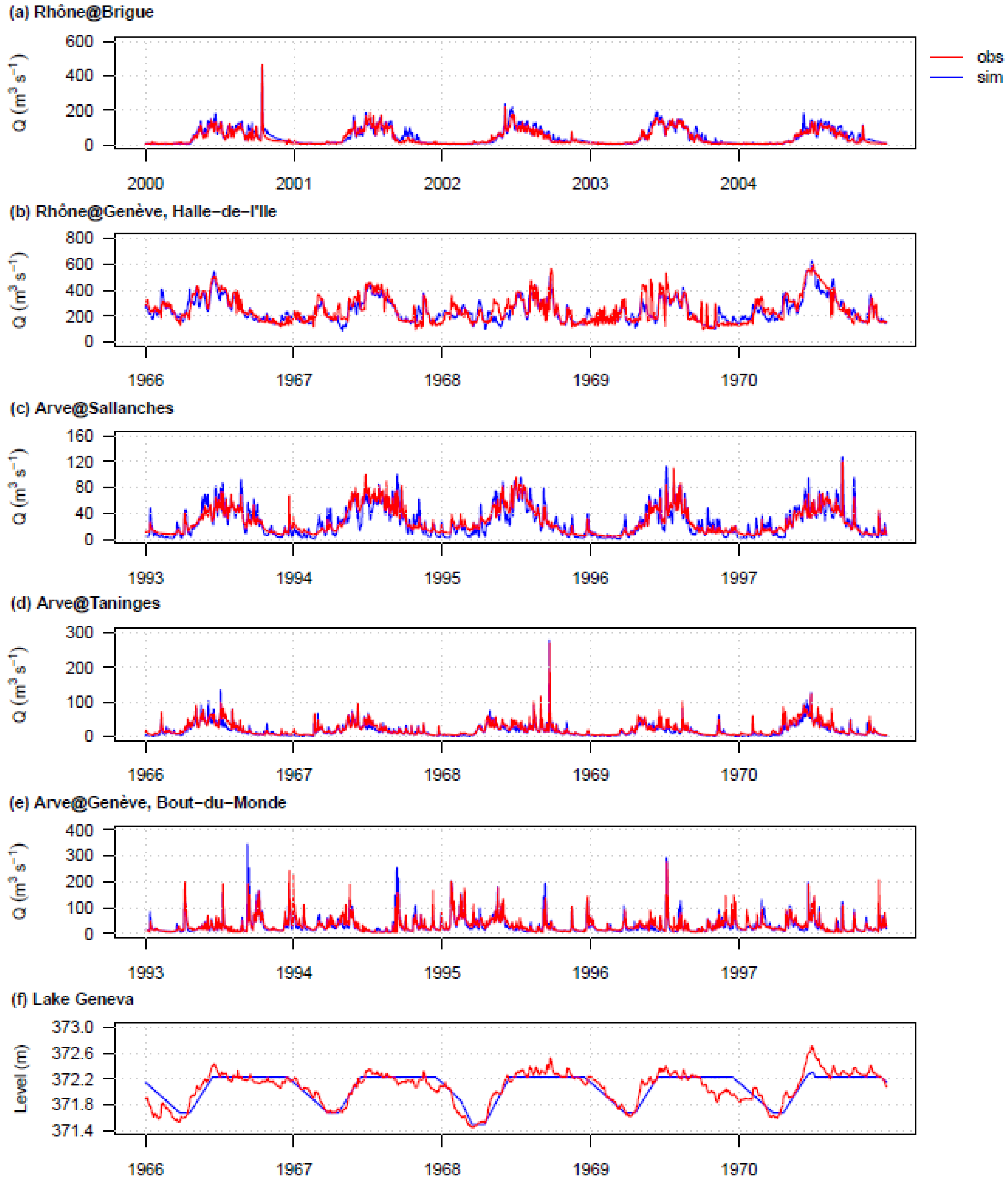


Figure S3. Classical calibration of sub-basins with a natural (or at least not significantly altered) hydrological regime. (a) Rhône@Brigue. (b) Rhône@Genève, Halle-de-l'Ile. (c) Arve@Sallanches. (d) Arve@Taninges. (e) Arve@Genève, Bout-du-Monde. (f) Example of Lake Geneva levels observed and simulated over the same period as discharges in Rhône@Genève, Halle-de-l'Ile. The calibration criterion is the NSE coefficient calculated from the observed and simulated time series of discharge at the sub-basin outlet.

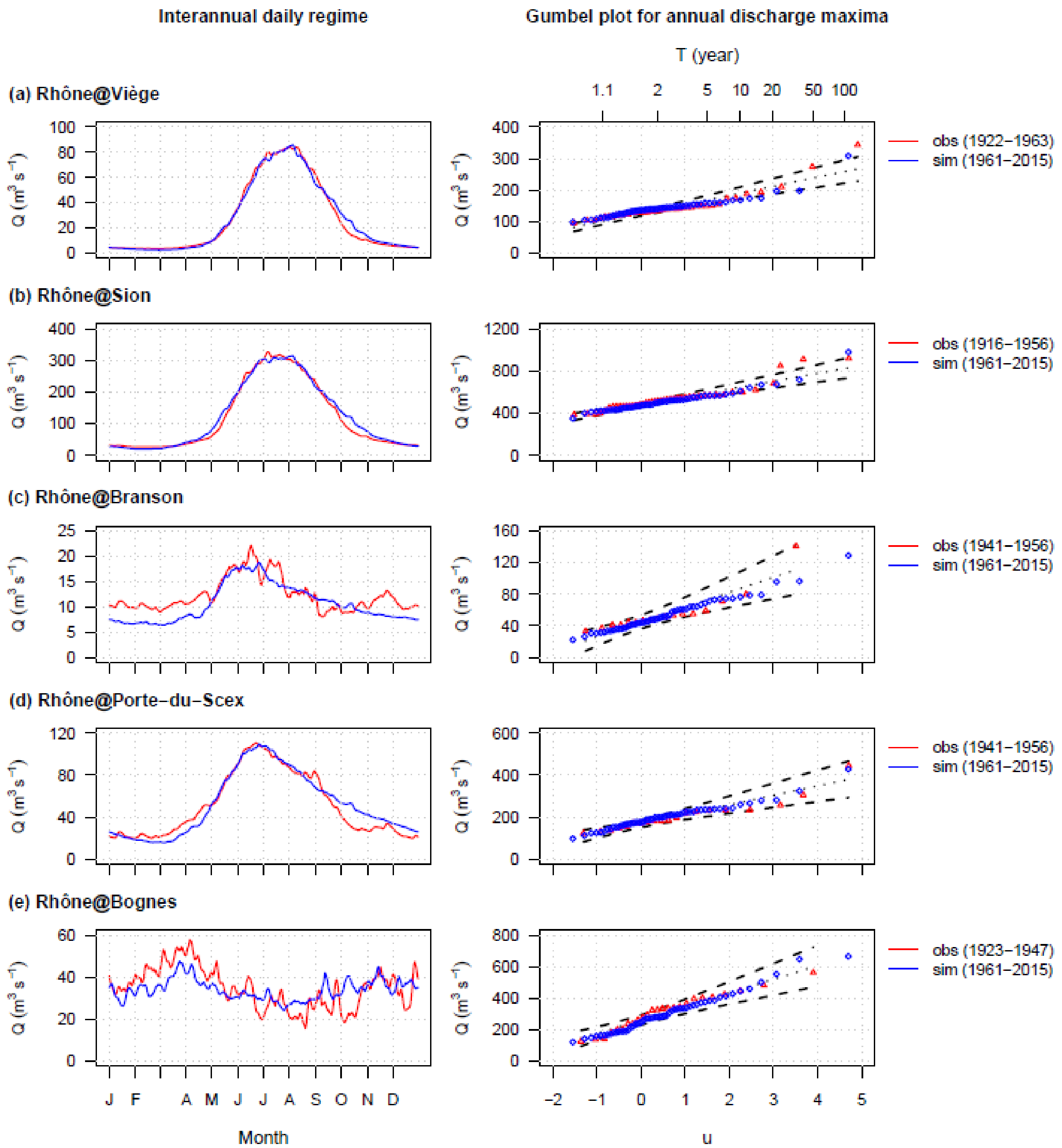


Figure S4. Signature-based calibration of sub-basins with an altered hydrological regime. (a) Rhône@Viège. (b) Rhône@Sion. (c) Rhône@Branson. (d) Rhône@Porte-du-Scex. (e) Rhône@Bognes. (left) Interannual daily regime. (right) Gumbel plot for annual discharge maxima. The x-axis is the reduced variate u for the given return period T, i.e. u = -ln(-ln(1-1/T)). Dashed lines correspond to 90 % confidence bounds of the Gumbel distribution estimated on observed data. The calibration criteria are the NSE coefficient between simulated and observed regimes and the Kolmogorov-Smirnov coefficient between the observed and the simulated distribution of annual discharge maxima.

RC2.11 L279 to 284: *"As many sub-basins have altered hydrological regimes, the "hydrological reference" used for the comparison is the discharge time series obtained via hydrological simulation with the "observed weather" as input. For some upstream sub-basins, which hydrological behavior can be considered as roughly natural, the evaluation could also rely on a comparison with discharge observations. We however choose to use the simulated reference. This first makes the evaluation homogeneous for all URR sub-basins. This additionally allows to only focus on the ability of downscaling chains to simulate hydrologically relevant weather scenarios. In other words, this allows to not distort the evaluation by intrinsic errors introduced by the hydrological model."* This point is critical and needs to be more deeply discussed: what about "simulated reference" that are not hydrologically relevant, i.e., highly different from observed streamflows (e.g. Arve@Genève, BDM catchment, with a NSE after calibration equal to 0.44)? What are "intrinsic errors introduced by the hydrological model" in this context?

> **AC2.11** Please see our response to comment RC2.1. The conceptual hydrological model is mainly used here as a very complex and non-linear filter to assess the weather scenarios. Note that the model can be imperfect as we also use it to produce the hydrological reference - against which hydrological scenarios derived from weather scenarios will be compared.

RC2.12 L424 to 429: this delayed dynamics between air temperature, snow accumulation / melting and thus simulated streamflows might be compensated (for good or bad reasons) by the hydrological model parameters during calibration. This point has to be discussed in the paper.

> **AC2.12** Thank you for this comment. We argue that the temperature lapse rate of the hydrological model has to be relevant first. It would not really be satisfactory and relevant to calibrate a model with known biased weather forcings. In this respect, compensation on certain model parameters would not be very relevant either. Despite this, we could indeed imagine that some kind of compensation exists. However, this compensation is unlikely to be large. The reason is due to the following.
>
> Snowfall at a given location in the model is estimated from precipitation and temperature estimated for that location. The temperature threshold parameters of the snow/rain repartition model (below which precipitation is entirely snow, and above which it is entirely rainfall) are fixed. They are not calibrated. They were estimated from weather stations throughout Switzerland, where observations of the nature of precipitation (rain, snow or mixed precipitation) were estimated each day at 7:30 am, 1:30 pm and 7:30 pm by a MeteoSwiss operator (Hingray et al., 2010; Froidurot et al., 2014). The two temperature thresholds of the snow/rain distribution model are the same everywhere, for high altitudes, low altitudes, etc.
>
> The same applies to snowmelt. The snowmelt threshold is not calibrated (it is set at 0°C). A negatively biased temperature lapse rate will lead to a rather good snow/rain repartition at mid-elevations, but to an overestimation of snowfall (and snowpack size/duration) at high elevations, and an underestimation of snowfall (and snowpack size/duration) at low elevations. A biased temperature lapse rate would therefore lead to an irrelevant simulation of altitudinal dependency of the snowpack dynamics.
>
> This is not expected to be easily compensated in the model. For these reasons, but also for reasons of space limitation, we do not plan to discuss this point in the article.

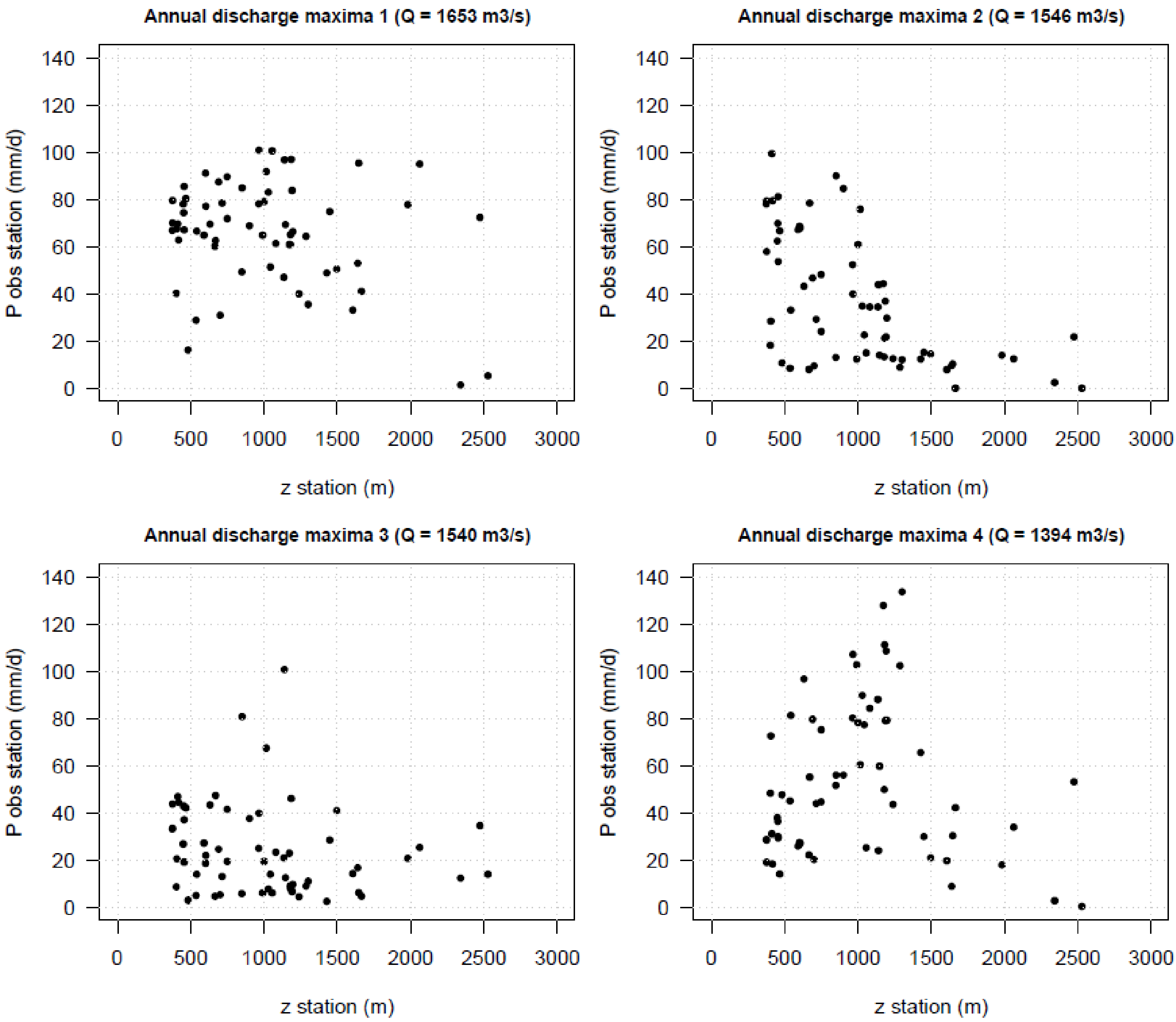
RC2.13 L440 to 450: what are the potential impacts of these changes (on the air temperature lapse rate) on the calibration of the hydrological model parameters? Did you try to do another calibration of the model considering these changes? Please discuss this point in the paper.

AC2.13 Please see our response to comment RC2.12.

RC2.14 L461 to 466: what are the potential impacts of these changes (on the orographic precipitation enhancement) on the calibration of the hydrological model parameters? Did you try to do another calibration of the model considering these changes? Please discuss this point in the paper.

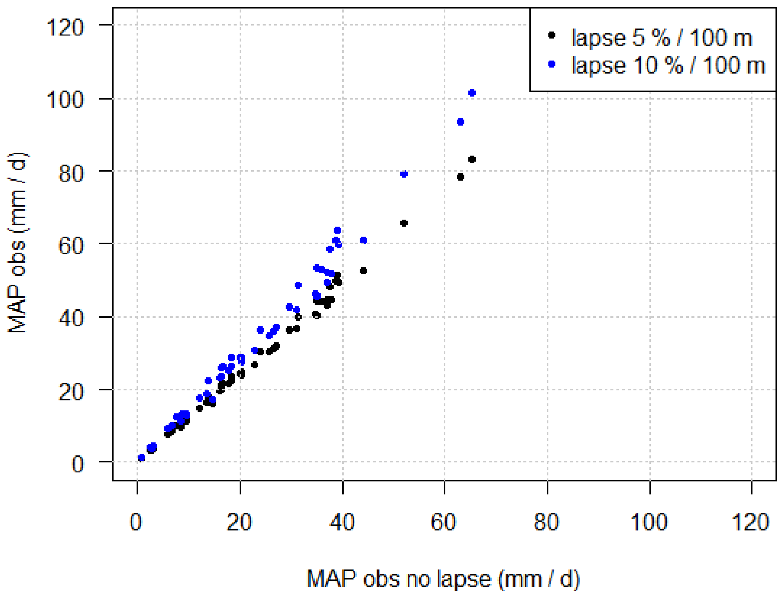
AC2.14 Thank you for this comment. A recalibration would obviously be interesting, but based on previous analyses, we argue that it would not allow to fix this issue in a relevant way.

As mentioned in the article, if an elevation-precipitation relationship can be identified from aggregated (e.g. annual) precipitation data, this is not the case at the scale of individual events. This is illustrated by the daily rainfall amounts observed at the different stations in the catchment area for the 4 largest floods recorded during the period. As shown in the figure below, there is no dependency on elevation. For event 2, precipitations at the highest elevation are even lower than in the lowlands.



As shown in the figure below, a precipitation lapse rate of 10%/100m significantly increases the precipitation amounts, even for the heaviest precipitation events. On average, the annual MAP maxima at the Upper Rhône River basin scale are increased by 20%. Due to the high non-linearity of the production processes, this 20% increase leads to a much higher increase in peak flows. A recalibration of the model would reduce the “productivity” of the catchments, i.e. it would increase the storage capacity of the soil reservoir. The filling rate of this reservoir determines the runoff coefficient of the catchment for that period, and the lower the capacity, the easier it is to fill the reservoir. To avoid huge and unrealistic floods in a +10%/100m lapse rate configuration, a much higher soil capacity is therefore required. Previous analyses show, however, that this can be detrimental for smaller (and more numerous) rainfall-runoff events, leading to a number of minor floods being underestimated.

MAP observed at D for annual discharge maxima



RC2.15 L481 to 488: did you check these hypotheses by comparing simulated streamflows with observed ones (and not “simulated references”)?

AC2.15 No and we acknowledge that this is not an ideal configuration, but unfortunately we did not find a better way to carry out the evaluation. Ideally, the reference should be the observations. However, for the 1961-2009 period, observed discharges are significantly perturbed by dams (most of which were built in the 1950s). See the figure from Hingray et al. (2010) in answer AC2.9. Comparing simulated discharges from meteorological scenarios with observed discharges is therefore meaningless. The observation was thus replaced by a proxy: the discharges simulated from observed weather.

Other specific comments:

RC2.16 L90: what is a “Binn-Simplon” situation?

AC2.16 For the Upper Rhône River catchment, the highest regional precipitation amounts are induced by the “Binn-Simplon” weather situations, where warm and humid air masses from the Mediterranean Sea cross the southern Alps (OFEG, 2002). These situations present a typical spatial pattern, with higher precipitation amounts in the southern and eastern parts of the catchment.

<u>We will add the following reference:</u>
OFEG: Les crues 2000 - Analyse des événements/cas exemplaires. Rapports de l'OFEG. Série Eaux, n°2, Office Fédéral des Eaux et de la Géologie, Berne, Suisse, 2002.

RC2.17 L92: what is a "retour d'Est" situation?

AC2.17 The "retour d'Est" situations are similar to the "Binn-Simplon" ones, but the warm and moist air fluxes from the Mediterranean Sea are finally oriented eastwards, from Italy towards France. They mainly affect the Piémont in Italy and the French Alps behind the border, resulting in heavy to very heavy precipitation amounts one to three times a year in these regions, particularly in the east-facing massifs.

<u>We will add the following reference :</u>
Metzger, A.: Retour d'est - La géochronique du temps qu'il fait, La Géographie, 1588, 64–65, https://doi.org/10.3917/geo.1588.0064, 2023.

Please see also:
http://pluiesextremes.meteo.fr/france-metropole/Retours-d-est-sur-le-Queyras.html

RC2.18 L114 : please consider highlighting the spatial resolution of the ERA-20C dataset on Figure 1 (in the topleft panel?)

AC2.18 In our opinion, the addition of the ERA-20C grid would render the topleft panel of Fig. 1 rather illegible. The spatial resolution of the ERA-20C reanalysis is indicated on line 114. <u>We will add in the text that the Upper Rhône River catchment is covered by 8 ERA-20C grid points.</u>

RC2.19 L213: please consider highlighting the spatial resolution of the MAR model on Figure 1 (in the topleft panel?)

AC2.19 The same issue arises as above. Adding the MAR grid would make the Fig. 1 rather illegible. The spatial resolution of the MAR model and the number of grid points covering the Upper Rhône River catchment are indicated on lines 212 to 215.

RC2.20 L240: how many previous days are considered? Please add details on this point.

AC2.20 One previous day is considered for the pairing. <u>This point will be specified.</u>

RC2.21 L243: please details what is a "non-parametric method of fragment" in this context.

AC2.21 The method of fragment is a non-parametric method. Whatever the context, the observed spatio-temporal structure of the observed variable is used as the structure of the day for which the structure is unknown and required. Here, the structure is defined by the spatial pattern of precipitation observed from precipitation stations. This structure is used to determine how the mean areal precipitation amount of a given day is distributed in space for that day. Mathematically, the observed precipitation of each station is multiplied by a coefficient MAP*/MAPa, where MAP* is the mean areal precipitation at the regional scale for the target day in the scenario and MAPa is the mean areal precipitation at the regional scale for the day used as a reference for the structure. The reference day can be selected on the basis of an analogy criterion (see Mezghani and Hingray, 2009 for an example).

A short clarification will be given in the text.

RC2.22 L336: the comparison of the Figure 8 and 9 is not easy: please consider adding another figure that present flow differences on each catchment and configuration to ease the comparison.

AC2.22 We acknowledge that the comparison is not easy. For reasons of space, however, we cannot add a figure showing the differences.

To show the performance gain associated with bias correction, we will add a Table with the NSE coefficients for the dynamical downscaling model (MAR/MAR-BC) and the statistical index CRPSS (Continuous Ranked Probability Skill Score) for the statistical downscaling model (SCAMP/SCAMP-BC).

RC2.23 Figure 8: please add the observed flows when available. What is the plateau observed for the "reference" streamflow series of the Rhône@Geneve in 07/1982 (and for other dates)?

AC2.23 Unfortunately, the comparison with observed flows is meaningless for this period because (i) the hydrological regime of the Upper Rhône River catchment has been altered by dams since the 1950s, and (ii) the aim of our study is to simulate flows in a natural hydrological regime (see lines 278 to 284).

As mentioned in the article, the regulation rules of the lake are specified in the 1997 settlement. One of the main objectives is that the flow at Genève, Halle-de-l'Ile must not exceed 550 m3 s-1 except during high-water periods in the lake Geneva (see Sect. 4.1.3). The plateau observed for the "reference" streamflow series of the gauging station Rhône@ Genève, Halle-de-l'Ile in 07/1982 corresponds to the 550 m3 s-1 threshold imposed in our simplified modeling of the behavior of Lake Geneva. The other plateaus correspond to the environmental low flow to be satisfied downstream (100 m3 s-1 from May 1st to September 30th and 50 m3 s-1 from October 1st to April 30th). We make the simulated water lake rather far from the observations. However, it is not possible to make a better simulation because the precise operations are not known (they follow daily variations in electricity demand in the region and its price).

RC2.24 L398 to 402: please add some references on the use of ERA-20C for hydrology or other references related to this potential ERA-20c drawback.

AC2.24 As recommended, we will include further references to hydrological studies based on ERA-20C, with the following statement at the end of Sect. 6.1 (where the limitations related to ERA-20C are discussed):

"With our approach, we confirm that ERA-20C can be used for local applications on mountainous catchments after statistical downscaling (e.g. Weber et al., 2021). We highlight that a statistical downscaling of ERA-20C at the regional scale needs to be completed with a bias correction step using local observations to allow realistic hydrological simulations on the Upper Rhône River catchment. This confirms the findings of Bonnet et al. (2017) who had to correct the biases of a downscaled version of ERA-20C to simulate realistic mean river flows in France, avoiding the spurious trend obtained when using the raw ERA-20C data set.”

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