**Dear Editor,**

**We hereby resubmit our revised manuscript entitled "Effects of climatic anomalies on low flows in Switzerland". We revised the manuscript according to the recommendations by addressing all comments of the reviewers and the editor, and we hope that our revised version is now suitable for publication.**

**We thank you for the detailed explanation of your decision and addressed the points of concern. Below we list all editor and reviewer comments** *(in italic)* **and our answers (in bold).**

**Thank you for considering our revised manuscript. We appreciate your work and look forward to your response.**

**With best regards**
**Marius Floriancic**

**(on behalf of the co-authors Wouter R. Berghuijs, Tobias Jonas, James W. Kirchner, and Peter Molnar)**

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*Dear Marius et al.,*

*thanks for resubmitting this revised version of the manuscript. In general the two reviewers that assessed this new version found that many of the critical aspects addressed. However, some concerns remain and one reviewer has requested further revisions that require reconsideration before a publication decision is made. Hence I would like to invite you to resubmit a revised version for reconsideration.*

*In summary, both reviewers still raise concerns particularly about*
*a) lacking clarity of the data selection and analysis of sub-samples (streamflow records used and seasonal windows analysed) and*
*b) about choice and terminology of the metrics analysed, questioning in particular the choices made to analyse an impact of SWE.*

*I re-read the Methods Section 2.3 to assess these concerns and also did not find it sufficiently clear. Unless the methodology is properly written out stating for each analysis: the data sampling, the variable used, a hypothesis for the test applied and the assumptions on the data this test requires, and for statistical models ideally also the equation, I see no possibility to accept the manuscript for publication.*

*For illustration perhaps, I try to explain my sources of confusion while reading section 2.3: after the at-site time series correlations are stated as a method, line 156 then suddenly introduces a "sign test for the distribution of the individual rs values". So there is a switch from at-site to a regional test? But what is the (regional/spatial?) hypothesis tested here, which test exactly is used? Then, the text jumps back to at-site correlations, then again to a regional sub-selection, which is suddenly introduced (another one?)... Then the GLM? Is this a regional model again or a number of at-site models (predict Qmin spatially or temporally)? How exactly is this 'fraction of the R2' determined - as far as I know there are many different methods to do this, again making certain assumptions. Finally, I can understand what has been done only by looking at the results and that is not sufficient. Some analysis (like the human influenced catchments) are even not at all introduced in the Methods section. All (!) sampling choices and analyses carried out need to be clearly understandable from reading the methods section alone. I think this revision is easy to implement.*

**We now realize that the methods were not sufficiently presented and therefore we improved the methods section. We now provide a detailed step-by-step description of all analyses and statistical procedures are more carefully described and explained. See the substantial (track) changes in Section 2.3. and Section 2.1 in the revised version of the manuscript.**

*Please also thoroughly consider the concerns of R2 regarding climate anomaly vs absolute low flow. Line 60 of the ms states: " The annual lowest flow is (for a particular year) an exceptional flow condition, so we expect low flows to occur after weather conditions that are atypical (for that same year)." This sentence is very hard to read, but as I understand it, the assumption is that any annual minmum flow must be caused by seasonal climate anomaly. For very stable glacial and nival regimes, the Qmin of which is almost in the same week-month, I doubt this is correct. Please check if the statement is generally applicable like this and make it more clear.*

**We reformulated the sentence to make the sentence easier to understand. In addition, we state that (most) catchments tend to have year-to-year variations in low-flow timing (e.g., Fig 1 revised paper). Many catchments with relatively stable low-flow timings (e.g., some high alpine sites) still tend to have substantial year-to-year variability in their low-flow timing (e.g., Fig 1 revised paper). We therefore believe it is logical to expect that annual low flows occur after weather conditions that deviate from their seasonal norm. We now reformulate and extended the sentence:**

**"Because the annual lowest flow is an atypical flow condition, we expect it to follow atypical weather conditions, rather than reflecting climate seasonality alone. Therefore, we hypothesize that annual lowest flows will typically occur after anomalous weather conditions, that is, weather conditions that deviate from the seasonal average."**

*I think we don't doubt the result of the SWE impact, but it will only be credible if the assumptions are well justified. I agree with the R's concerns that the reduction to using 1 March snowpack as an indicator may be a lost chance and certainly will require better argument for this choice. The rest of the mountain-world uses April 1st snowpack for water resources planning! I strongly suggest that you add some proof (could be literature) that for Switzerland March 1st is the 'consensus' peak-of-snow-accumulation and really reflects the 'end-of-winter' storage of snowpack+groundwater well in CH.*

**We understand that 1$^{st}$ of April is in many cases used as the standard reference for (northern hemisphere) studies that consider SWE. However, in Switzerland many lower elevations locations have no substantial snow left by this date, whereas 1$^{st}$ of April snowpack depths are likely strongly correlated with snowpack depths a month prior. Therefore March 1$^{st}$ snowpack better serves the particular purpose of our study, focused on warm-season low flows, but April 1$^{st}$ snowpack would yield comparable conclusions. We now also state this in section 2.1 in line 144 – 146, and added references to three papers presenting data evidence for this across Switzerland (Steger et al., 2013 – Figure 3; (Lüthi et al., 2019 – Figure 4 and Winstral et al., 2019 – Figure 3).**

*A concern not yet sufficiently well responded to is the one-sided outlier removal. The 'three-sigma rule' intends to detect statistical outliers: on both ends of the distribution. Removing them from analysis is another step that needs argument. The underlying assumption of the statistical view is that such values are unlikely/physically impossible and must be wrong due to the measuring technique. Eliminating* *subjectively the outlies in (only) one tail of the distribution because (?) they are inconvenient (?) represents a non-acceptable data selection. The lowest flows will likely also be not well-gauged! I cannot accept the simple addition of a reference to the general three sigma rule paper as a response to this concern. I also don't understand why the removal would be useful. Having higher flow values and hence more variability in the sample that is correlated with preceding climate anomaly (which will for sure be not a deficit when there is high flow - unless it's caused by snowmelt and then that is relevant!) should only be beneficial to finding a higher correlation. If for some reason high flow values are not wanted, another sampling strategy up front is necessary (like annual series vs partial duration series in flood stats - "peak over threshold", for low flows there is a reason why normally events under threshold are commonly used in low flow statistics).*

**To eliminate the problems of the three-sigma rule we decided to now – instead of removing the high annual low flows by the 3-sigma rule – remove all annual lowest flows that are higher than the $25^{th}$ percentile of all flows, so above 2.5 mm/d. This choice is made because we still believe that setting an upper threshold is important to ensure we characterize actual low-flow conditions (similar to how flood studies use peaks over threshold in frequency analysis). We now state this in section 2.1 of the revised version.**

*Additional editorial comments:*

*I am afraid the abstract could better reflect the work - maybe a result of the revisions?. It has redundancy and contradictory statements in several sentences. The repeated focus on the comparison to larger scale Europe does not match title nor the real contribution that this study now makes. I suggest to revise it to bring out the contribution better and attract the right attention.*

**We edited the abstract to better reflect the results presented in our manuscript. We did this by rewording several sentences, by removing any reference to wider patterns across Europe, and we do not mention spatial patterns anymore. Together this should attract the attention to the right places, as all results mentioned in the abstract are at the heart of our manuscript.**

*Yes, I will insist in changing PET to the likewise common Ep for example if it is used as a variable name. If it's only used in text and as acronym, please do as you like. In any case, just because others have done it wrong is not a reason to do it wrong also.*

**Thank you for the clarification. We now changed PET to $E_p$ throughout all text and figures.**

*Regarding figure legends and captions: HESS house style asks for "concise figure captions". There are different styles for figure captions, yes, and that can be accommodated. However, in the current version of the manuscript the same information on figures is sometimes repeated 3-4 times: in a header over the figure (really unnecessary!) and exact same text in the caption text under a) and b) for example, then in the following explanatory sentence again, and in the text of the manuscript. Please revise this for conciseness - in particular do not repeat colors if there are legends. Repetition does not make anything more clear but is instead confusing for readers.*

**We reviewed all captions and adjusted them accordingly:**

- **Fig 1: No changes made because it was already concise.**
- **Fig 2: This caption is shortened by removing some repetitive statements.**
- **Fig 3 & 5: The captions might still look long, but they describe multiple subfigures. The only part we could reduce is removing the statement on the main finding from this figure. However, we really believe that we do the reader a service by including this statement as it provides guidance and only marginally extends the caption.**
- **Fig 4: This caption is shortened and concise.**
- **Figs 6-9: We reduced the number of words used in the caption and the figures (i.e. headers).**

## Anonymous Referee #2

*Review of "Effects of climate anomalies on low flows in Switzerland" by Floriancic et al.*

*Many of my previous comments were acknowledged and I find the focus shift towards the assessment of the shaping of the low flows worthwhile.*

*I went through the revised version and found still some points that the authors might consider before publishing:*

*Main comments:*

*• Now the shaping of low flows focuses on summer low flows, which excludes all the catchments that have winter low flows. While I find it important to explicitly distinguish between summer and winter low flow due to the processes driving, I would suggest looking also at the development and drivers of the low flows in the cold season. Here as well there might be a pattern occurring from simply lack of precipitation and the built up of snowpack or a combination of the two. This analysis could be done in a similar manner as the one for summer low flows using PET and lack of precipitation, for instance using low air temperature (or since available estimates of SWE).*

**We changed the title (and various other parts) of the paper to better emphasize our work is about warm-season low flows. We agree that analyses of cold season low flows can also be interesting. However, from the start the focus of this study was on warm-season low flows only, because these are the low flows that are driven by summer climate anomalies and are a source of severe river droughts in lowland catchments in recent years. Cold-season low flows may also be related to climate anomalies, but less strongly than summer low flows. Including winter low flows would therefore go beyond the original scope of the paper. However to reach out to the reviewer, we show results for the 30-day climate anomaly analysis (Figure 2c&d) also for cold-season low flows (occurring in December through April) in the supplementary materials (Figure S2). This emphasizes that climate anomalies are important for summer low flows, but maybe less so for winter low flows.**

*• While the authors made efforts in the revision to make the terminology used less ambiguous and more consistent, I am not convinced of every choice made here. To me anomaly for the cumulated sum of differences between actual an average value the preceding period is not a good idea. It suggests already that the variable (PET or PRECIP) was anomalous before even looking at it, at the start of the analysis only the streamflow is low, but it might not be at all. I disagree also on the definition of anomaly for low flows with the authors arguing that within the year the streamflow deviates from the "norm". In my opinion on the contrary it most of the times is not anomalous since it occurs very reliable in the same season of the year.*

**We improved the textual description and introduction to "climate anomalies". Using deviations from the seasonal norm comes with the advantage that can reveal how short-term weather anomalies affect low flows, rather than seasonal climatological patterns. These short-term weather anomalies obviously do not fully explain all low-flow characteristics, but clearly explain a significant part of it. We also emphasize that this definition has been used from the first time this paper was send out to review.**

*• The authors have with their data set the chance to show which of the preceding periods for which driver or combinations of drivers was anomalous but the study at state does not take that chance. It would require rewording and calling only anomalous conditions anomalies and then second it would make the study much stronger if there was a quantification of the drivers and clear communication of what a combination causes in terms of low flow or not.*

**Our paper characterizes which anomalies lead to annual low flows highlighting several aspects of low flows, and the anomalies that drive them. The provided suggestion is an interesting alternative suggestion to look at the data, but we do not see any chance of including this without changing the entirety of the paper or by extending the paper with more data methods and results, without a clearly defined connection to the current version.**

*• Rather than only arguing with correlation coefficients it would be very interesting to see a quantification f the effects. To keep it comparable between the catchments that could be expresses in percentage. But*

*precipitation deficit in the preceding period as well as PET compared to mean PET in the season could be compared to Qmin. This would make a stronger argument for the study.*

**Perhaps we do not understand what the referee is pointing to, but Figure 6 shows an objective measure of the bivariate non-parametric correlation between P and PET deviations from their means and annual $Q_{min}$. All catchments and years are put together for this analysis so that we get a regional robust signal. Figure 7 instead shows the fraction of the best R2 in a multivariate linear model obtained by each variable P and PET. We do not follow which stronger arguments can be made.**

*• Snow in the preceding winter was found to be only weakly related to summer low flow, this was based on the SWE of the 1st of March. I am not convinced of taking the SWE of a specific date, that might be already in the melting season for many lower elevated catchments and may not be the maximum amount for the highest elevations. I would suggest testing another metric maybe the maximum SWE in the winter period or something else that can be considered representative for the snowpack that could (or not) contribute to summer low flow for each catchment.*

**See comment to the editor earlier. We considered and discussed a suite of snow-related variables, including $SWE_{max}$. Finally we chose a SWE at a fixed time in spring as the best measure because this in our opinion captures the lasting snow still available for melt into the summer and feeding baseflow. $SWE_{max}$, which will occur much earlier in the winter season, may be depleted rapidly during warm periods and not contribute to summer low-flows directly.**

*Minor comments*

*• Most results show only % of the low flow of the catchments show correlation with anomaly xy. I suggest to add more comparison between the catchments (where is the correlation stronger, weaker? can this be attributed to a region, geology, elevation range?) for more than only the map of low flow occurrence, such material could help follow up studies and they could be for instance be placed in a supplemental material.*

**We now provide maps of the spatial distribution of the rank correlations between the 30-day anomalies and low flows in the supplementary material (Figure S3).**

*• Statistical tests and quantification of process importance: Why the original data set was reduced first to selected warm season flow? Why not first select this period and then determine Qmin for all years and all catchments in this period? Were there really some that have only 5 years available? Are these then only the drought years?*

**As now more clearly stated (and explained above) our study aims to report the climate drivers of warm-season low flows only. In addition, we only select events that can be considered low flows (i.e. by setting an upper threshold). Just over 15% of the sites had less than 10 years of data available after setting these criteria, which typically occurred in the drought years. The nature of our analysis is that we do not emphasize the results of individual catchments, but rather infer behaviors from patterns and behaviors that are revealed across many sites.**

*• The expression "annual late summer and autumn low flow period" could be simply introduced as warm season/period, as is also used already sometimes by the authors (why would May be late summer?).*

**We now consistently use the term "warm-season low flows" throughout the whole manuscript and fully avoid the term "summer and autumn low flow period".**

*• The colors of the figures are not readable in black and white print. While I am aware these are also electronically available at least the figures with blue and red lines should be distinguishable in b&w, that could be by choosing a different line type or a different color choice. Best would be if also the colors of the maps could be distinguishable then e.g. Jun and Oct would not look the same. There are palettes that have 12 colors that can be also distinguished in b&w e.g. viridis.*

**We changed the blue colors throughout the manuscript to make the figures readable in black and white in Figures 2, 4, 6, 7 & 9.**

*Detailed comments line by line*

*L18 In the abstract 2011 is still mentioned as summer low flow despite occurring in spring*

**We changed this to "years".**

*L21 what is meant by characteristics and where is that picked up in the study?*

**By characteristics we refer to duration and magnitude of the anomalies. We slightly reworded the abstract, explain it better in the introduction, and remind the reviewer that these analyses can be found in Section 3.2., 3.3., 3.4 (and figures 2, 3, 4, 5).**

*L35 I am not convinced that event is the right term for low flow; for an event I would expect that there is a threshold involved defining he start and end of it. The reference discussed droughts and I guess the authors intend to write also here "drought" as suggested by the follow-up sentence*

**We changed it to "droughts".**

*L37 One key reference here is Price (2011)*

**We included a reference to Price et al, 2011.**

*L41 I guess here drought is intended again (at least the references point there)*

**We changed it to "droughts and their effect on low flows".**

*L53 add Staudinger et al. (2017) for storage in Swiss catchments*

**We included a reference to Staudinger et al, 2017.**

*L55-62 see general comment above: I am not convinced of the terminology and would not call every low flow preceding period "climate anomaly", I would rather call the deviating periods among the preceding periods anomalies.*

**We refer to our earlier response above.**

*L65 "likely" sounds like it could be also not true? Why would that be?*

**We changed the wording to "expected to be" as there are several scenarios possible where this may not be true (although such scenarios are unlikely to happen consistently, except in for example completely human controlled flow environments).**

*L70 add something on that the lag time is dependent on the storage behavior that is different for each catchment; limited-substantially they express the opposite please clarify*

**In the revised version, the sentence before makes the connection with storage.**

*L73 But there is also snow involved in these changes which could cause a less seasonal than we are used to effect anyhow?*

**We now added "In addition, anticipated changes in snowfall and snow packs may also alter river flows (CH2018, 2018)."**

*L75-76 please revise and be more precise: Temperature is not depleting soil moisture storage. PET is also influenced by wind and not solely by temperature. T is a good indicator for PET, but AET will be very much dependent on how much a storage (soil) is wet or dry. E.g. with high PET but zero water in the soil, the soil will not be depleted and AET accordingly will be low, same PET on a wet soil will cause the depletion described and AET is high.*

**We have revised this to be more precise. The passage now says, "High temperatures can be an indicator of high Ep, and thus high potential for depletion of soil moisture storage, reducing aquifer recharge and streamflow (e.g., Jaeger & Seneviratne, 2011; Vidal et al., 2010). Temperature extremes can be amplified when low soil moisture limits evapotranspiration, leading to lower relative humidity and higher air temperatures, which further increase Ep (Granger, 1989)."**

*L103 which are the few studies? Please add.*

**To our knowledge there are no studies that look at low flows the way we do in our manuscript. We changed it to "To our knowledge there are no studies…"**

*L194 What is "tend" intended to express? The majority? And after which climate anomalies this is not the case? Please, clarify or reformulate.*

**We reformulated this sentence.**

*L196 remove "tend"*

**We removed it.**

*L197 affect -> affects*

**"affect" relates to "…magnitudes of both precipitation and PET anomalies…"**

*L203 at the same time? or in the same period in series or in parallel -> rephrase*

**We changed it to "in the same time period".**

*L213 remove Particularly*

**We removed "particularly".**

*L245 “below-threshold precipitation … above-threshold PET” which threshold is that? From the methods I got that it is about the entire cumulated variable (difference actual value and average) preceding the low flow period. Please, clarify*

**We now explicitly explain this in the methods section (line 174-177).**

*L243-248 I would argue that it is not only because of the duration but when the “anomaly” starts, because together they form somehow an intensity of the anomaly. The authors argue that duration of high PET is stronger correlated than duration of low precipitation. This might be because of the seasonal character rather than the duration implicitly considered. This is for precipitation much lower than for PET. And this might change again whether the anomaly starts say in May and lasts for a month or whether it starts in September and lasts for a month.*

**We mention that different dimensions of climate anomalies (i.e., magnitudes, timings, and durations) are important in low-flow formation in the discussion section in lines 481 – 486. Indeed the reviewer is right, the “intensity” of the anomaly is precisely a combined effect of the departures from mean and the duration. This is exactly what we try to capture. It is also true that seasonality plays a role in this intensity, and this is especially true for Ep due to temperature seasonality.**

*L249/250 If a single precipitation event can exceed the “threshold” maybe the definition of anomaly is ill-posed?*

**This specific analysis is using above threshold P and Ep rather than climate anomalies. We updated the text accordingly to make this distinction clearer.**

*L286/287 exhibit clear growth -> clearly increase*

**We changed this.**

*L317 “explains most of the predictability” should that be variability? Please clarify*

**This was a typo: explains most of the variability in $Q_{min}$ correct.**

*L362 What does "relatively comparable" mean?*

**We changed it to "similar".**

*L412 Virtually?*

**We changed it to "Almost".**

*Figures*

*Generally, all figures have long captions including partly interpretation that is already in the text. Please, remove the redundant parts and only leave the necessary elements in the captions. E.g. Figure 1 drop the last sentence, that is literally repeated in the main text.*

**We removed the last part of Figure caption 1 and shortened the other Figure captions as well. See comments to the editor above.**

*Figure6 in black and white the lines cannot be distinguished either use different line type or colors with different hue. Some methodological questions: 1) are the anomalies in fact cumulated sums over the preceding period for PET and precipitation differences, respectively 2) if these are anomalies shown, does each point consider a different number of data pairs 3) are here all catchments included, i.e. also the high elevation catchments?*

**We changed the colors throughout the manuscript (i.e., in Figs. 2, 4, 6, 7, 9 of the revised manuscript) to make the lines (and bars) distinguishable in black and white. Anomalies are cumulated departures of P and PET from the mean for periods preceding the annual low flow. Non-parametric correlations (markers) shown in Fig 6 are computed from a combined dataset of all stations and years together. Each marker has exactly the same number of station-years in the correlation. We did not analyze station-wise correlations because for most sites the record would not be long enough. With the combined record and using variables that are depths over the catchment area (mm) we believe we obtain a robust regional estimate of the strength and direction of the relationship between P/PET departures and $Q_{min}$. High-elevation catchments are included in our dataset only if they have warm-season annual low flows.**

*Figure 7 b) it would be good to see next to an average how different that is for the dry years, please add the lines for each single year*

**The data in Figure 7b are not an average, it is the fraction of the R2 obtained by a multivariate GLM model by P and PET for all catchments in the 4 dry years. The data are insufficient to get robust estimates of the bivariate P or PET correlations for each year individually, so this fraction cannot be computed for every drought year.**

*References:*


*Price, K. (2011). Effects of watershed topography, soils, land use, and climate on baseflow hydrology in humid regions: A review. Progress in physical geography, 35(4), 465-492.*

*Staudinger, M., Stoelzle, M., Seeger, S., Seibert, J., Weiler, M., & Stahl, K. (2017). Catchment water storage variation with elevation. Hydrological Processes, 31(11), 2000-2015*

*11), 2000-2015*

## Anonymous Referee #3

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*A review of "Effects of climate anomalies on low flows in Switzerland" by Floriancic et al. (2nd round of reviews)*

*In my opinion, authors have considerably improved the manuscript. New methods and results have been added to support the study results (e.g. the GLM model or assessment of human impacts). The clarity of the text has been improved by several text modifications and by splitting results and discussion sections. Additionally, further information has been added to the text to better explain methods and results. Nevertheless, some of the previous comments were not fully addressed and thus I would like to ask for further clarification. Although, my comments below are relatively large in extent, I think that it should not be time demanding to implement suggested changes.*

**Thank you for acknowledging the changes we made in the revised manuscript.**

*General comments*

*I am still not convinced about the fact that authors used only catchments where summer low flows are also annual low flows. This way, they excluded most of high elevation catchments from the analysis. Therefore, it is not much surprising that SWE (or winter precipitation) are not important indicators for summer low flows since snow dominated catchments were (probably) not analysed. Nevertheless, I am accepting authors decision to present the results in this way.*

**Thank you for accepting our choice to focus on warm-season low flows.**

*However, the fact that only a subset of 380 study catchments was used for most of the analyses is (in my opinion) not fully clear from the methods and results sections. I think that most of readers might be confused about how exactly you proceeded. For example, in Section 3.1 one would conclude that you analysed all 380 catchments and showed the results in Fig. 1 (a-d). However, this would be not fully true* *since all catchments are shown only in Fig. 1a and 1b, while Fig. 1c a 1d show only those catchments for which the annual low flow occurred in summer (as I understood from your response). I think that most of readers cannot infer this important limitation from the text, despite the fact that you mentioned that Fig. 1c and 1d show May-November low flows (which is mentioned only in the Figure caption, but not in the main text). For the reader this would not be clear since two possible interpretation exists (at least to me); 1) you considered all catchments, but only warm period low flows, or, 2) you considered only those catchments where annual low flows occurred in the warm period. Without knowing your response, I would (wrongly) assume that (1) is how you proceeded. Similar notice, which might be a bit confusing is given in Fig. 2 caption ("winter low flows were excluded"). A clear statement that two different subsets of catchments were used for presented analyses is also missing in methods. I partly found it in Section 2.3 (L 161-163), but, again, I think that the formulation here is not fully clear and do not explicitly mention that this procedure caused exclusion of several snow dominated catchments from analysis.*

*A clear statement, how you proceeded is given only in discussion Section 4.2 (L 401-406). I would recommend to provide the reader with a clear information already in methods (and results) about the catchment reduction since it widely affects your interpretation and conclusions regarding the role of SWE and winter precipitation. Also maybe add the information how many catchments were excluded in the end. Besides, consider to reformulate the abstract as well which (wrongly) implies that your results regarding winter precipitation and SWE can be related to all selected 380 catchments across Switzerland.*

**We now fully revised the methodology section to provide a step-by-step explanation of when and where we used subsets of the data (see chapter 2.3. – lines 164 - 204). We also better emphasize that the main motivation of the manuscript is to better explore warm-season low flows, by adapting the title and also the wording throughout the revised version of the manuscript. We'd like to point out, that the main focus of the paper was on warm-season low flows in lowland catchments that are sensitive to climate anomalies and have the greatest adverse economic impacts (agriculture, shipping, etc.).**

*Additional to the above, I think that some interpretation regarding the role of snow or winter precipitation is oversimplified. The reaction of individual catchments to climatic anomalies and thus low flows is also a matter of catchment storage, which is usually longer than one season. Therefore, the winter conditions most likely influence the summer streamflow (and low flows), although the importance of such influence* *may be minor (as shown by your results for lower elevation catchments) and it certainly differs from catchment to catchment. I am aware that this goes much beyond the scope of the paper, but I would suggest reflecting the issue of catchment storage in discussion (beyond the sentence on L 370-371).*

**As correctly observed, by looking at warm-season low flows only, we exclude most of the high-elevation catchments. In the lower elevation catchments, snow only represents a small fraction of total annual precipitation, thus snow has almost no importance for (long term) storage in low elevation catchments, where the annual lowest flows occur in the warm season.**

*Specific comments and technical corrections*

*Authors did not consider a comment to describe (in methods section) the procedure how they analysed the role of winter precipitation (although they declared in the response that they added the description to methods section). Similarly, the newly used predictor (SWE) is not mentioned in methods (there is only the information about source of SWE data).*

**We now updated the methods section accordingly and describe how we calculate the winter precipitation sums and also SWE. See section 2.3 at lines 191-195.**

*Regarding the comment of the Reviewer 3 on L237 (original manuscript). All specific terminology ("below-threshold" and "above-threshold" in this case), should be defined at the place, where it is firstly used. This is not the case in the revised version. Additionally, the explanation needs to be in the main text, not only in the Figure caption.*

**We now included this in the methods section 2.3 at lines 174-177.**

*L 169: Perhaps, you wanted to rename Section 3 to "3. Results" since the discussion is newly included as Section 4.*

**Thank you, we changed this in the revised version.**

*Please use term "elevation" instead of "altitude" consistently in the paper.*

**We now consistently use "elevation" throughout the manuscript.**

*Technical note: For the future, it would be great if you would be more specific in the response, specifically, to indicate where one could find the changes you made (e.g. by referring to line numbers in the response). Additionally, to submit a "tracked changes" version of the revised manuscript (as requested by HESS and which was missing here) really helps the reviewers with orientation.*

**We apologize for this inconvenience and now (try to) provide more specific response including section number and line numbers, and also provide a track-changes manuscript.**

**References:**

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**Lüthi, S., Ban, N., Kotlarski, S., Steger, C. R., Jonas, T. and Schär, C.: Projections of Alpine Snow-Cover in a High-Resolution Climate Simulation, Atmosphere, 10(8), 463, doi:10.3390/atmos10080463, 2019.**

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# Effects of climate anomalies on warm-season low flows in Switzerland

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**Short summary**: Low river flows affect societies and ecosystems. Here we study how precipitation and potential evapotranspiration shape annual warm~~-~~-season low flows across a network of 380 Swiss catchments. Low flows in these rivers typically result from below-average precipitation and above-average potential evapotranspiration. The lowest low flows result from long periods of the combined effects of both drivers.

**Abstract.** ~~Large parts of Europe have~~Switzerland has faced extended periods of low river flows in recent ~~summers~~years (2003, 2011, 2015, and 2018), with major economic and environmental consequences. Understanding the origins of events like these is important for water resources management. ~~While precipitation~~In this work we provide data illustrating the individual and ~~potential evapotranspiration obviously impact summer low flows, it remains largely unquantified which characteristics~~joint contributions of precipitation and ~~potential~~ evapotranspiration ~~are related~~ to low~~-flow magnitude,~~ flows in both typical and ~~how these relationships may vary regionally.~~dry years. To ~~reveal~~quantify how weather drives low flows, we explore how deviations from mean seasonal climate conditions (i.e., climate anomalies) of precipitation and potential evapotranspiration ~~shaped~~correlate with the occurrence and magnitude of ~~the~~ annual 7-day lowest flows ($Q_{min}$) during the warm season (May through November) across 380 Swiss catchments from 2000 through 2018. Most ~~annual~~warm-season low flows followed periods of below-average precipitation and above-average potential evapotranspiration, and the lowest low flows resulted from both of these drivers acting together. ~~In the driest years, low-flow conditions occurred simultaneously across large parts of Europe, but low~~Low-flow timing ~~during these years~~ was ~~still~~ spatially variable across Switzerland~~. Low flows~~ in ~~the~~all years, including the driest (2003, 2011, 2015, and 2018~~-~~). Low flows in these driest years were associated with much longer-lasting climate anomalies ~~compared to~~than the ~~maximum two~~≤2-month anomalies which ~~caused~~preceded typical warm-season low flows in other years. ~~Across Switzerland, we~~We found that ~~precipitation totals in winter and~~ snow water equivalent and winter precipitation totals only slightly influenced the magnitude and timing of ~~summer and autumn~~warm-season low flows~~. –~~ in low-elevation catchments across Switzerland. Our results provide insight into how precipitation and potential evapotranspiration jointly shape warm-season low flows across Switzerland, and potentially aid in assessing low-flow risks in similar mountain regions using seasonal weather forecasts.

## 1. Introduction

In recent decades, Europe has experienced several severe ~~low-flow events~~droughts (Van Lanen et al., 2016). Their impacts, such as dry river reaches and high water temperatures, have a range of adverse effects on society and river ecology (e.g., Poff et al., 1997; Bradford & Heinonen, 2008; ~~Rolls et al., 2012~~Price et al., 2011; Rolls et al., 2012; van Vliet et al., 2012). Severe low flows in the years 2003, 2011, 2015 and 2018 led to substantial economic losses by limiting water availability for households, industry, irrigation and hydropower, as well as impacting river transportation (Stahl et al., 2016; Munich Re, 2019). Such effects are expected to become more severe and frequent as water demand rises, and as droughts are anticipated to increase in frequency and intensity in the future (e.g., De Stefano et al., 2012; Wada et al., 2013), leading to calls for improved understanding and management of droughts and their effects on low flows across Europe (e.g., Seneviratne et al., 2012a; Van Lanen et al., 2016; WMO, 2008).

In temperate climates, annual low flows typically occur in two distinct seasons, i.e~~., in~~. during late summer and autumn in warmer regions and during winter in colder regions~~ during winter~~ (Fiala et al., 2010; Smakhtin, 2001). This typical low-flow seasonality has been reported for many regions of the world, including, for example, Austria (Laaha & Blöschl, 2006; Van Loon & Laaha, 2015), the Rhine river basin (Demirel et al., 2013; Tongal et al., 2013), and North America (Cooper et al., 2018; Dierauer et al., 2018; Wang, 2019). Switzerland also has two~~ distinct~~ low-flow seasons, where the distinction between warm-season low flows and winter low flows is strongly connected to elevation (Wehren et al., 2010; Weingartner & Aschwanden, 1992). Low flows ~~in low-elevation Swiss catchments~~ tend to occur in late summer and early autumn (August through October~~), whereas~~) in ~~high~~low-elevation Swiss catchments~~ most low flows occur~~, and during the winter (January through March~~).~~) in high-elevation catchments.

Catchment properties shape low flows by controlling the storage and release of water ~~(~~(e.g., Stoelzle et al., 2014; Van Lanen et al., 2013; Van Loon & Laaha, 2015~~), but the landscape itself does not cause low flows.~~; Staudinger et al., 2017), but the landscape itself does not cause low flows. Instead, the drivers of low flows are meteorological conditions that dry out catchments (e.g., Fleig et al., 2006; Haslinger et al., 2014 ; Smakhtin, 2001). ~~Two distinct low-flow seasons exist throughout Switzerland (and many other regions), suggesting that different weather conditions drive low flows during these two seasons: warm~~Warm-season low flows are typically caused by sustained periods of high evapotranspiration and low precipitation, whereas winter low flows often follow sustained periods of sub-freezing temperatures (e.g.; Laaha et al., 2013~~),~~; Van Loon, 2015). ~~Thus, low flows are not created instantaneously, but result from~~ The duration of these anomalous weather conditions ~~acting over longer periods. The~~ is critical in shaping the annual lowest ~~flow is (for a particular year) an exceptional flow condition, so we expect low flows to occur after~~ flows. Their timing varies between years and is largely driven by climate seasonality. In this paper we refer to weather conditions that ~~are atypical (for that same year). From now on, we refer to atypical weather conditions~~deviate from the seasonal norm as 'climate anomalies'~~.~~ regardless of the magnitude of this departure.

The two main climatic factors controlling water storage and release in a catchment are precipitation and temperature (through ~~controlling~~its influence on snow processes and evapotranspiration). ~~It is therefore likely that~~Therefore precipitation (P) and potential evapotranspiration (~~PET~~$E_p$) anomalies are expected to be important drivers of warm-season low flows across Switzerland. ~~For example, precipitation~~Precipitation controls the amount of water that is ~~made~~ available ~~to~~ for runoff in a catchment~~. Sustained~~, and sustained periods with little precipitation will inevitably reduce storage and thereby limit streamflow. Because there is a time lag between low precipitation and low streamflow, meteorological droughts (i.e., precipitation deficits) result in hydrological droughts and/or low flows if they persist for long enough ~~(~~(e.g., Peters et al., 2006;

Tallaksen & Van Lanen, 2004; Van Loon, 2015). In Switzerland, there is limited precipitation seasonality, but precipitation can still vary substantially within seasons or from year to year. However~~, in coming decades~~, precipitation is expected to become increasingly seasonal with changing climatic conditions in the future, with less precipitation during summer and more precipitation in winter. In addition, anticipated changes in snowfall and snow packs may also alter river flows (CH2018, 2018).

High temperatures ~~(or~~can be an indicator of high ~~PET) can deplete~~$E_p$, and thus high potential for depletion of soil moisture storage, ~~thereby~~ reducing aquifer recharge and streamflow ~~(~~(e.g., Jaeger & Seneviratne, 2011; Vidal et al., 2010). ~~This effect is~~Temperature extremes can be amplified when low soil moisture limits evapotranspiration, leading to lower relative humidity and higher air temperatures, which further increase ~~PET.~~$E_p$ (Granger, 1989). Furthermore, vegetation decreases the amount of water available for streamflow by increasing ~~evaporative water use~~transpiration during periods of high ~~water~~ vapor pressure deficits. Although these mechanisms are known, the effects of evapotranspiration on ~~low-flow occurrences and magnitudes~~river low flows have received relatively little attention compared to precipitation effects. Seneviratne et al. (2012) reported that low flows ~~of 2003~~ across Switzerland ~~were most~~in 2003 more likely ~~more the result of~~ resulted from excess evapotranspiration ~~excess rather~~ than from spring precipitation deficits, and Teuling et al. (2013) have documented the depletion of soil water storage by high evapotranspiration during past European low flows. Woodhouse et al. (2016) reported that temperatures rather than precipitation explained the interannual streamflow variations of the Colorado river. More recently Cooper et al. (2018) reported that summer low flows in the maritime Western US are largely driven by summer ~~PET~~$E_p$, rather than by winter precipitation or snow water equivalent. Mastrotheodoros et al. (2020) modeled how increasing evapotranspiration strongly reduced streamflow across the European Alps during the summer of 2003. Future ~~PET~~$E_p$ is projected to increase along with increases in incoming longwave radiation (Roderick et al., 2014), with uncertain consequences for future low flows. In Switzerland, ~~in the next decades,~~ temperatures are expected to rise even quicker than the global average in the next decades (CH2018, 2018), potentially influencing low-flow dynamics.

Future climate changes will also affect low flows in mountain regions by altering ~~snowpack~~snow accumulation and ~~meltwater release~~melt. Multiple studies have examined how winter precipitation and snow water equivalent affect summer low flows~~.~~ in high-elevation catchments. For example, Godsey et al. (2014) found that ~~decreasing~~shrinking snowpacks in the Sierra Nevada of California led to smaller low flows in the following summers. Jenicek et al. (2016) reported that maximum snow accumulation strongly affected summer low flows across several Swiss mountainous catchments. Dierauer et al. (2018) found that warmer winters with less snow accumulation led to lower summer low flows in mountainous catchments of the Western United States. Recently, Wang (2019) reported that climate warming might increase aquifer conductivity and thereby streamflow in cold region watersheds. Future climate warming in both warm and cold seasons will most likely impact summer low flows through different mechanisms. In summer, higher temperatures increase potential evapotranspiration, whereas in winter they reduce snowpacks (e.g., Déry et al., 2009; Diffenbaugh et al., 2015; Musselman et al., 2017).

The effects of precipitation, temperature and evapotranspiration on low flows have been investigated for individual events or individual catchments and regions~~.~~ in the literature. Previous studies have largely focused on how signatures of low flows (averaged across many events) relate to catchment and climate characteristics (e.g., Fangmann & Haberlandt, 2019; Hannaford, 2015; Laaha & Blöschl, 2006; Van Loon & Laaha, 2015). ~~So far, few~~To our knowledge, however, no studies have systematically assessed the direct impact of temperature and precipitation during periods immediately preceding individual annual low-flow events across many catchments in a topographically diverse region.

Here we explore how precipitation and ~~PET~~$E_p$ deviations from their seasonal norms (here termed “climate anomalies”) jointly shape the occurrence and magnitude of annual warm-season low flows across a network of 380 Swiss catchments. Because ~~low flows are normally~~the annual lowest flow is an atypical flow ~~conditions~~condition, we expect ~~them~~it to follow atypical weather conditions, rather than reflecting climate seasonality alone. Therefore, we hypothesize that ~~low~~annual lowest flows will typically occur after anomalous weather conditions, that is, weather conditions that deviate ~~substantially~~ from the seasonal ~~norm~~average. Understanding how anomalous weather drives low flows may help to reveal the processes at work, and also ~~may~~ support low-flow forecasting. Switzerland is an interesting study region because gauging and climate data are available from a dense station network spanning a wide range of elevations, climates, and topographies. We investigate (a) how precipitation and ~~PET~~$E_p$ anomalies separately and jointly shape the occurrence and magnitude of warm-season low flows across Switzerland, (b) which durations of these anomalies have the strongest impact on low-flow occurrence and magnitude, both in typical and in exceptionally dry years, and (c) how winter precipitation and snow packs influence the magnitude and timing of ~~summer~~warm-season low flows. Understanding these connections is important for anticipating how streamflows are likely to respond as the exceptionally dry years of today are expected to become more typical in a future warmer climate.

## 2. Data and methodology

### 2.1. Streamflow and climate data

We compiled daily streamflows for 380 gauging stations across Switzerland for a 19-year period (2000-2018), using data collected by the Swiss Federal Office of the Environment (FOEN) and the Swiss Cantonal authorities. ~~Low flows were defined as the lowest 7-day average streamflow for each year ($Q_{min}$). We determined the catchment area and the~~This data set excludes catchments with obvious anthropogenic influences on the hydrograph, e.g., from major dams or hydropeaking operations. Low flows were defined as the lowest 7-day average streamflow for each year ($Q_{min}$). We calculated the magnitude and timing of $Q_{min}$ in each catchment for each year from 2000 to 2018. Not all catchments had continuous data for all 19 years; in total we could calculate low-flow magnitude and timing for 6237 station-years. This data set included years when the lowest annual flows were much higher than typical low flows (e.g., in especially wet years and years without distinct dry periods). We removed all annual low flows above the threshold of 2.5 mm $d^{-1}$, which is the 25th percentile of daily discharges across all catchments, because flows above this threshold cannot be considered truly low flows. This resulted in the removal of approximately 2% of all low flows, leaving a total of 6124 station-years for our analysis. We split the dataset of annual low flows into cold-season low flows occurring between December and April and warm-season low flows occurring between May and November. In total, we observed 2122 cold-season low flows and 4002 warm-season low flows across the 380 catchments within the 19-year time period.

We determined catchment area and mean catchment elevation for each gauging station based on a 2-m DEM (SwissAlti3D 2016, Swisstopo), using functions provided in the ArcGIS “Spatial Analyst” toolbox. The catchments range in size from 1 to 519 km$^2$, vary in mean elevation from 309 to 2930 m, and ~~are distributed across different regions with~~have diverse landcovers and climates. Daily gridded precipitation and temperature data (~2x2 km cells; Meteoswiss products “RhiresD” and “TabsD”) were used to derive catchment-averaged weather and climate conditions. Daily potential evapotranspiration (~~PET~~$E_p$) was estimated following the method of Hargreaves & Samani (1985). A gridded dataset of snow water equivalent (SWE) on March 1st of each year was used to estimate catchment-average SWE. The SWE product was based on data from 320 Swiss snow monitoring stations that were assimilated into a distributed snow cover model (Magnusson et al., 2014; Griessinger et al., 2016). We use SWE on March 1st instead of April 1st because our focus is on warm-season low flows in lower-elevation catchments, most of which have no substantial snow left by April $1^{st}$ (Steger et al., 2013; Winstral et al., 2019; Lüthi et al., 2019).

### 2.2. Anomalies of climate variables

To infer ~~which~~ climate conditions ~~cause~~preceding annual low flows, we selected the annual 7-day minimum streamflow events ($Q_{min}$) in each catchment for each year from 2000 to 2018. ~~There were years when the lowest annual flows were much higher than typical low flows. We removed outliers by the 3-sigma rule, a standard procedure in statistics to remove extreme tails of a distribution (Pukelsheim, 1994). The removal of unusually high annual low flows that exceeded three standard deviations above the catchment mean of all annual low flows resulted in the removal of 2% of all low flows.~~ We then calculated precipitation and potential evapotranspiration for time windows of different lengths prior to each annual low flow. We hypothesize that severe low flows will usually follow periods in which precipitation and potential evapotranspiration significantly deviate from their seasonal ~~norms (i.e., the average conditions during that time of the year).~~averages. Thus, we define climate anomalies as deviations of precipitation and potential evapotranspiration from their climatic norms, defined as their long-term averages on the same day of the year. For example, we quantify precipitation anomalies (in mm) by:

$$\cancel{\sum_{t=d_l-d_t}^{d_t} P(t)-\bar{P}(t)} \qquad \cancel{Eq.(1)}$$

where $P(t)$ is daily precipitation (mm) at day $t$, $\bar{P}(t)$ is the climatic mean precipitation on day $t$ averaged across all of the years of record, $d_t$ is the time period over which anomalies are calculated for each annual low flow, and $d_l$ is the day of the low flow. We vary the time period $d_t$ from one week to half a year (7, 14, 30, 60, 90, 120, 182 days), with the endpoint always being the date of the low flow. For example, the 30-day precipitation anomaly for a low flow that happened on 30 September 2018 is calculated using the sum of precipitation from $1^{st}$ to ~~$30^{st}$~~$30^{th}$ September 2018 minus the mean of precipitation for all $1^{st}$ to ~~$30^{st}$~~$30^{th}$ September periods from 2000 to 2018. We calculate ~~PET~~$E_p$ anomalies in ~~an equivalent manner.~~ the same way.

### 2.3. Statistical tests and quantification of process importance

~~Because relations between the climate anomalies and annual low-flow characteristics can be non-linear, we use Spearman rank correlation coefficients ($r_S$) to quantify their dependence~~We first report the spatial distribution of the timing of the annual lowest flows across Switzerland for 2000 until 2018. We then show the magnitude of 30-day climate anomalies before each annual low flow as a function of elevation. The mechanisms involved in generating annual cold-season low flows and warm-season low flows are different, thus we split our dataset into cold-season and warm-season low flows. From this point on, we report results only for warm-season low flows. To quantify the relationship between the magnitudes of climate anomalies and the magnitudes of warm-season annual low flows, we use Spearman rank correlation coefficients ($r_S$) as a robust estimator (Legates & McCabe, 1999). ~~The statistical~~We report these rank correlations across all catchments in a histogram. To test the regional significance of the ~~distributions~~$r_S$ coefficients we use the sign test.

We assess the impact of ~~$r_S$ across the study catchments is assessed~~the length of climate anomalies preceding the annual warm-season low flows by comparing the magnitude of P and $E_p$ anomalies for the different time windows (7, 14, 30, 60, 90, 120, 182 days) between the four driest years and the more typical years. We also correlate the magnitude of warm-season $Q_{min}$ with the ~~sign test, indicating if a~~ number of days that P and $E_p$ exceed certain thresholds. The threshold that defines low precipitation is the 20th percentile of 10-day running averages of precipitation over the entire period of record. Similarly, the threshold that defines high $E_p$ is the 80th percentile of 10-day running averages of $E_p$ over the entire period of record. We report the distribution ~~is significantly positive or negative.~~ of rank correlations calculated for each catchment based on the 19 years of data in histograms. The magnitudes of the annual low flows are shown as boxplots for each individual year. The horizontal line in the boxplots indicates the median, the box represents the interquartile range, and the whiskers extend to 1.5 times the interquartile range above and below the box; the dots are outliers.

To quantify the individual and joint importance of ~~precipitation~~the magnitude of P and ~~PET~~$E_p$ anomalies, we first calculated the bivariate Spearman rank correlation between the individual anomalies and $Q_{min}$ for the different time windows (30, 60, 90, 120, 182 days) for all years (2000-2018) and for the years with the lowest low flows (2003, 2011, 2015 and 2018). For this analysis we reduced the original dataset to only ~~selected warm-season low flows in May through November and those catchments where at least 5 years of $Q_{min}$ data were available, and calculated correlations for all years and the years with the lowest low flows (2003, 2011, 2015 and 2018). In a next step we used the joint anomalies of precipitation and PET for the~~those catchments where at least 5 years of $Q_{min}$ data were available, as suggested in WMO (2008). In a next step we used the joint anomalies of P and $E_p$ for all durations 30, 60, 90, 120, 182 days to predict $Q_{min}$ with a multivariate stepwise generalized linear model (GLM~~).~~) fitted by minimizing RMSE. We then computed the fraction of the ~~maximum~~GLM's $R^2$ ~~achievable by the joint GLM by~~ attributable to the individual precipitation and ~~PET~~$E_p$ anomalies for each duration, to assess ~~which~~the relative contribution of each anomaly to the ~~anomalies is a better predictor.~~prediction of $Q_{min}$. We ~~compare~~compared the results for all years to those for the lowest-flow years (2003, 2011, 2015 & 2018) to assess ~~if different mechanisms are at play~~whether the relations between climate anomalies and $Q_{min}$ differed during the driest years.

~~**3. Results and Discussion**~~

~~**3.1.**~~

To test how warm-season low flows are influenced by precipitation and snow processes in the preceding winter, we calculated the Spearman rank correlations between the total December-March precipitation sum and the following warm-season $Q_{min}$, and between SWE on 1st March and the following warm-season $Q_{min}$. We again report these rank correlations across multiple catchments in histograms, and test the significance of these distributions of correlations by the sign test.

Finally, we assess whether the correlations we obtained between P and $E_p$ anomalies and warm-season $Q_{min}$ are influenced by the extent of human impact in each catchment. We quantify human impact by the fraction of human affected land cover in each catchment. As a proxy for human activity we use the Corine landcover dataset (CLC, 2018) and calculate the fraction of catchment area with “Artificial surfaces”. We then show histograms of the rank correlations between P, $E_p$, and $Q_{min}$ in the 20% of catchments with the most human-influenced land use, and the 20% of catchments with the least human-influenced land use, compared to the distribution across all catchments. We assessed the significance of the differences between the obtained distributions by the Student t-Test.

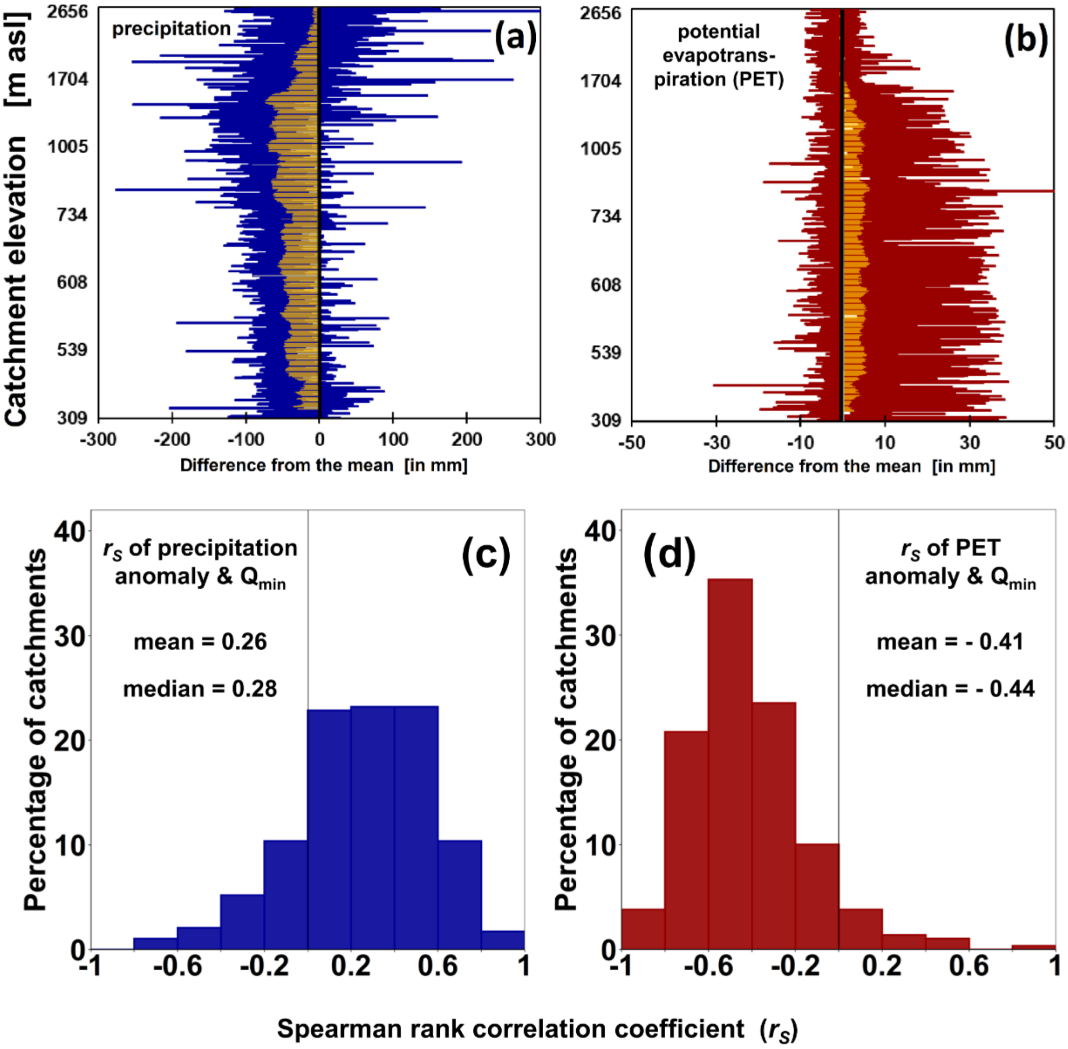
## 3. Results

### 3.1. Spatial patterns of low-flow timing

~~**Climate anomalies control low-flow timing and magnitude**~~

~~The occurrence of low flows is linked to periods of below-average precipitation and above-average PET (Fig. 1a&b). However, distinct site-to-site differences exist: at elevations below approximately 1500 m asl, almost all annual low flows occur after periods of anomalously high potential evapotranspiration and anomalously low precipitation (Fig. 1a&b). At higher elevations, by contrast, PET anomalies have no systematic effect and precipitation anomalies become less important with increasing~~

~~elevation. This reduced importance of anomalies at these higher elevations is probably because low flows here result primarily from freezing temperatures (or periods of snow accumulation), rather than precipitation or PET patterns. Low flows at higher elevations occur during the winter months when there is a lack of liquid water inputs to catchments, due to precipitation mostly accumulating as snow, with little snowmelt. These processes are mainly driven by sustained below-zero temperatures. Thus, the main determining factor in winter low flows at high elevations (or in cold environments) will likely be the length of the snow accumulation period, rather than what the exact temperatures were, or how much precipitation occurred.~~




~~**Figure 1: Altitudinal variation in 30-day anomalies of precipitation (a) and potential evapotranspiration (b) preceding annual low flows from 2000 through 2018. Blue and red horizontal bars indicate the range between the minima and maxima of these anomalies at each catchment across the 19 years of this study. Yellow bars show moving averages of these climate anomalies for bins of 10 catchments ordered by elevation. Note that the elevation scale is not linear. Low flows are associated with below-average precipitation (a) and above-average potential evapotranspiration (b); however, above roughly 1500 m asl, PET anomalies have no systematic effect and precipitation anomalies become less important with increasing altitude. Histograms of rank correlations between anomalies of precipitation (c) and potential evapotranspiration (d) and low-flow magnitudes for late summer and autumn (May through November) low flows across Swiss catchments. Low-flow magnitudes tend to be positively correlated with precipitation anomalies and negatively correlated with PET anomalies, but with considerable site-to-site variability.**~~

More severe climate anomalies tend to lead to lower low flows (Fig. 1c&d). Spearman rank correlations of magnitudes of the climate anomalies to magnitudes of $Q_{min}$ (shown for the months May through November) indicate that lower precipitation in the 30 days prior to $Q_{min}$ usually results in smaller $Q_{min}$ (median $r_S$=0.28). Similarly, higher potential evapotranspiration usually results in smaller $Q_{min}$ (median $r_S$=-0.44). This indicates that the magnitudes of both precipitation and PET anomalies tend to affect low-flow magnitudes ($p$-values < 0.001 according to the sign test), but with substantial site-to-site variability.

### 3.2. Combined effects of climate anomalies on low flows

Our previous results (Fig. 1) indicate that both precipitation and PET can affect low flows. However, most low flows are not caused by only one driver, but instead result from the combined effects of below-average precipitation and above-average PET both acting at the same time. Warm-season low flows, occurring from May through November, usually follow periods of below-average precipitation and above-average potential evapotranspiration (72.2% of low flows fall in the top left quadrant of Fig. 2a). Less than a quarter of the annual low flows occur after periods of below-average precipitation and below-average potential evapotranspiration (20.5% lower left quadrant – Fig. 2a). Only very few annual low flows (7.3%) occur after periods of above-average precipitation. Thus, precipitation anomalies appear to be the most important driver for warm-season low flows in Switzerland, and potentially also in other regions with distinct warm-season low flows. While potential evapotranspiration appears to be less important than precipitation, more than 70% of low flows are caused by a combination of both drivers. The combined effect of above-average PET thus more than triples the chance of an annual low flow (compared to when precipitation is below average, but there is below-average PET).

Particularly severe low flows occur through the combined effects of low precipitation and high potential evapotranspiration. For example, 96% of low flows during the most severe low-flow year (2003, shown by green markers in Fig. 2a) follow periods of both below-average precipitation and above-average potential evapotranspiration. This behavior is not unique to the 2003 event, but was also observed for other years with severe annual low flows such as 2011, 2015 and 2018 (Fig. 2b&c).

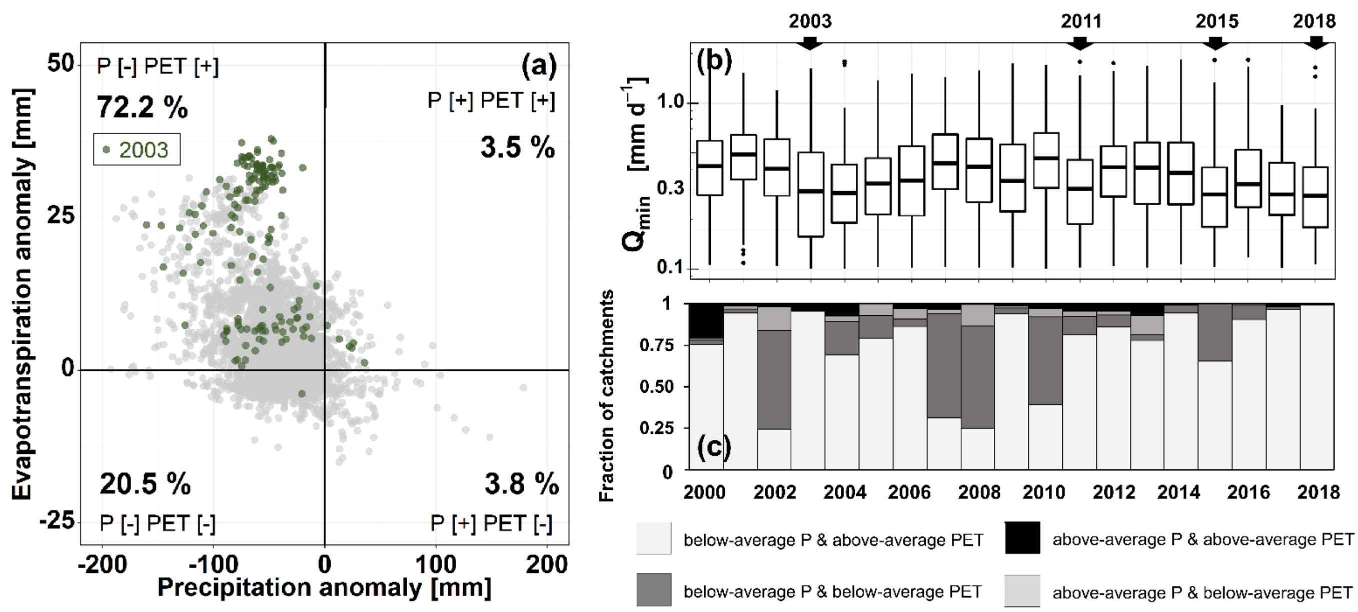



**Figure 2: Anomalies in precipitation and potential evapotranspiration 30 days prior to each annual late-summer and autumn (May through November) low-flow period in each catchment (grey dots); winter low flows were excluded (a). The most severe low-flow year during the study (2003) is highlighted in green. Almost all (92.7%) annual low flows occurred following below-average precipitation (the left half of the figure), and 72.2% of all low flows occurred**

~~**following a combination of below-average precipitation and above-average potential evapotranspiration (the upper left quadrant of the figure).**~~ ~~**Boxplots of annual 7-day minimum flows in May through November for the Swiss study catchments (b) and the catchment distribution of the signs of precipitation and evapotranspiration anomalies that preceded these low flows (c). The most severe low-flow years (2003, 2011, 2015, and 2018) were characterized by negative precipitation anomalies and positive *PET* anomalies for the large majority of catchments, as indicated by the light grey bars in (c). The horizontal line of the boxplots indicates the median, the box represents the interquartile range and the whiskers extend to 1.5 times the interquartile range above and below the box; the dots are outliers.**~~

During the dry years of 2003, 2011, 2015, and 2018, low-flow conditions occurred across large parts of Europe (Laaha et al., 2017; Van Lanen et al., 2016). Annual low flows did not occur simultaneously across Switzerland, but instead occurred primarily during winter in the Alpine regions and summer and autumn in the Swiss Plateau (Fig. ~~3~~1). In addition, within these two sub-regions, the timing of low flows was still spatially variable, indicating that annual low flows may be surprisingly asynchronous across Switzerland, even in ~~extremely~~unusually dry years~~, when the climate drivers are similar (Fig.2c).~~. Within the Swiss Plateau, low-flow timing is more spatially consistent during some years without severe low flows (e.g., 2009, 2013, 2016), than during others (e.g., 2000, 2002, 2004, 2010, 2017).

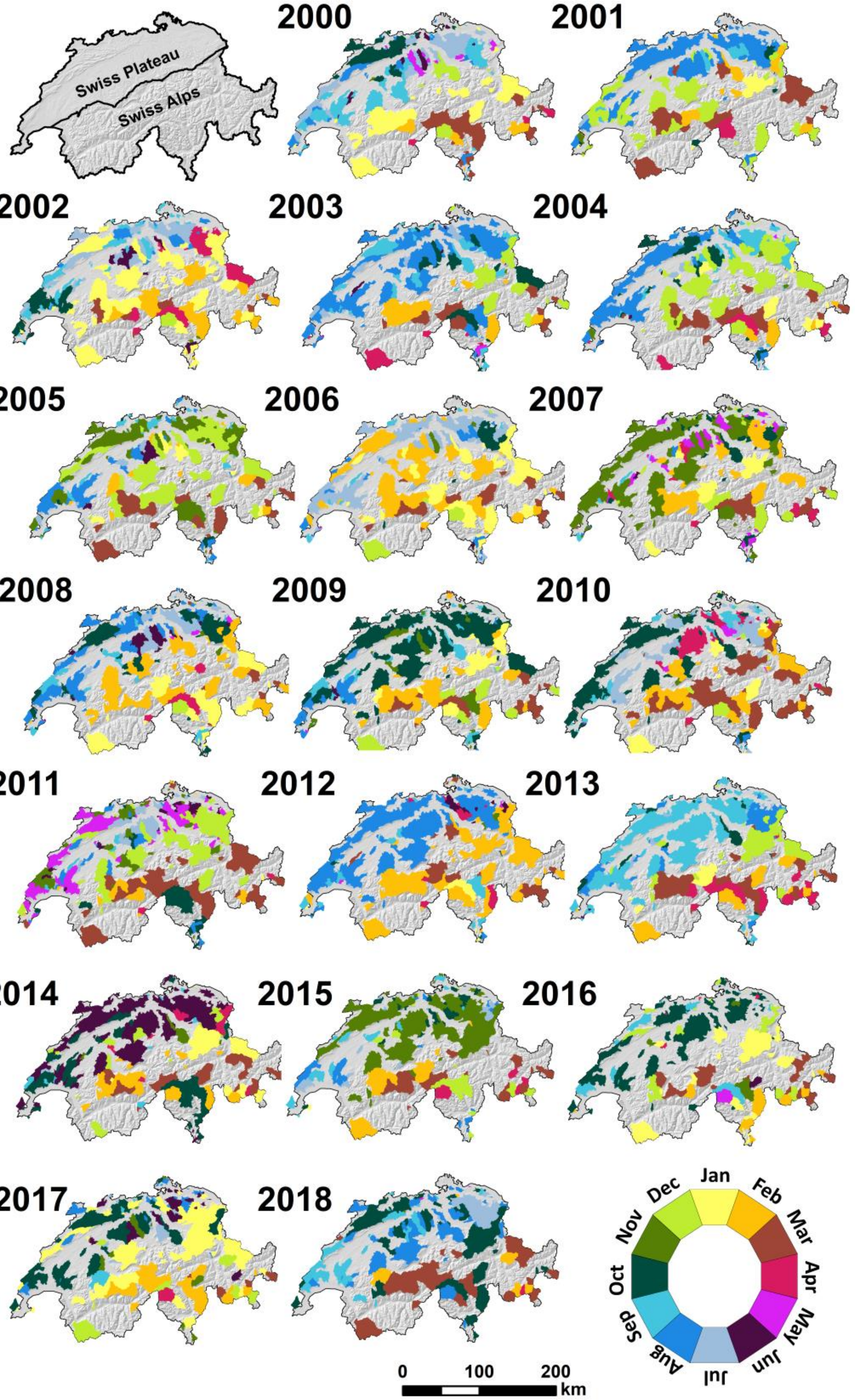



**Figure ~~3~~1: The timing of occurrence of annual low flows across Switzerland for the years 2000 to 2018 in the two main regions: the Swiss Plateau and Swiss Alps (roughly the northern and southern halves of the country, respectively). Low-flow timing tended to be spatially heterogeneous, even in years when large parts of Europe simultaneously experienced severe low flows (2003, 2011, 2015, 2018).**

### 3.~~3.~~2. Climate anomalies control low-flow timing and magnitude

The occurrence of low flows is linked to periods of below-average P and above-average $E_p$ (Fig. 2a&b). However, distinct site-to-site differences exist: at elevations below approximately 1500 m asl, almost all annual low flows occur after periods of anomalously high potential evapotranspiration and anomalously low precipitation (Fig. 2a&b). At higher elevations, by contrast, $E_p$ anomalies have no systematic effect and precipitation anomalies become less important with increasing elevation. This reduced importance of anomalies at these higher elevations is probably because low flows here result primarily from freezing temperatures (or periods of snow accumulation), rather than precipitation or $E_p$ patterns. Low flows at higher elevations occur during the winter months when there is a lack of liquid water inputs to catchments, due to precipitation mostly accumulating as snow, and little snowmelt. These processes are mainly driven by sustained below-zero temperatures. Thus, the main determining factor in winter low flows at high elevations (or in cold environments) will likely be the length of the snow accumulation period, rather than what the exact temperatures were, or how much precipitation occurred.

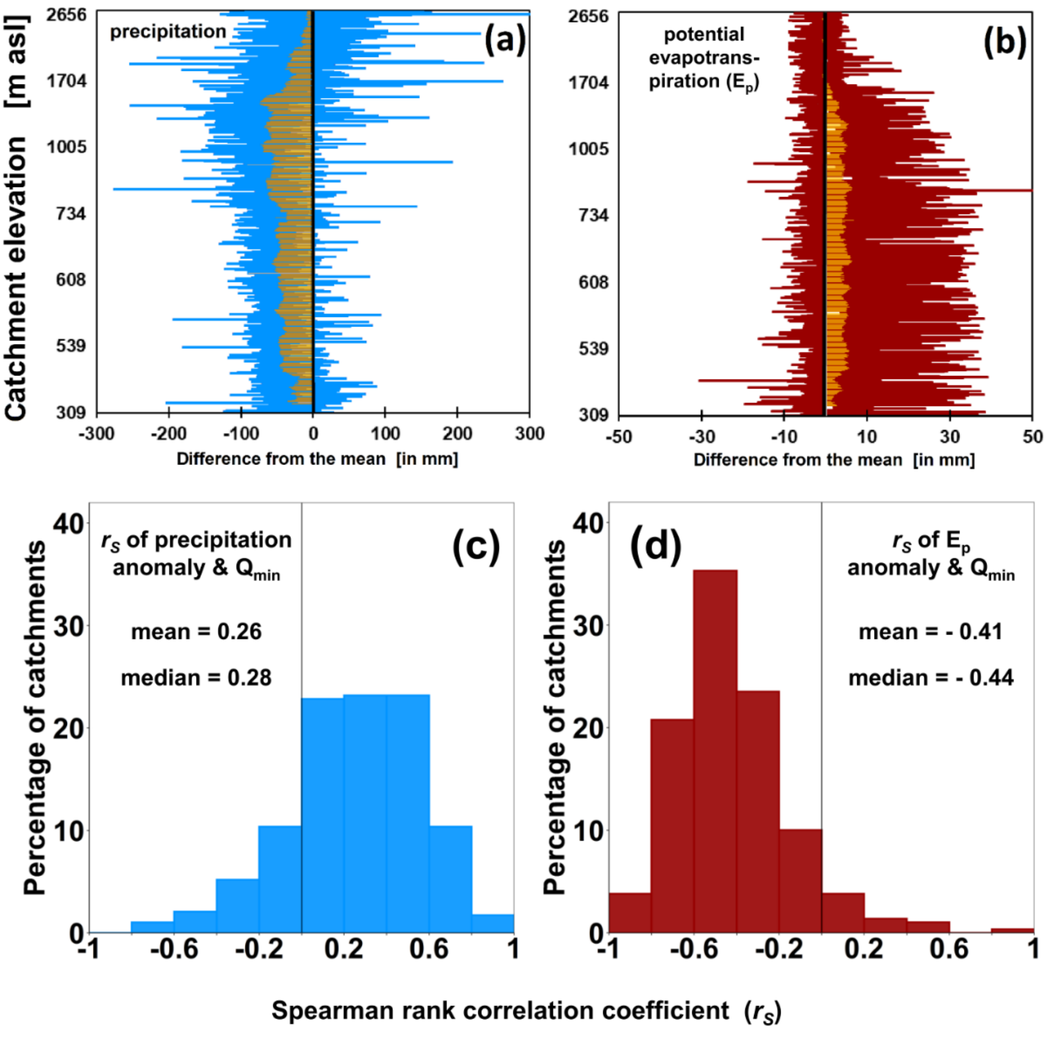



**Figure 2: Altitudinal variation in 30-day anomalies of precipitation (a) and potential evapotranspiration (b) preceding (warm and cold season) annual low flows from 2000 through 2018. Blue and red horizontal bars indicate the range between the minima and maxima of these anomalies at each catchment across the 19 years of this study. Yellow bars show moving averages of these climate anomalies for bins of 10 catchments ordered by elevation. Note that the elevation**

**scale is not linear. Low flows are associated with below-average precipitation (a) and above-average potential evapotranspiration (b). Histograms of rank correlations between anomalies of precipitation (c) and potential evapotranspiration (d) and low-flow magnitudes for warm-season (May through November) low flows across Swiss catchments. Results for cold-season low flows can be found in the supplementary Fig. S2.**

More severe climate anomalies lead to lower low flows (Fig. 2c&d). Spearman rank correlations of magnitudes of the climate anomalies to magnitudes of $Q_{min}$ (shown for the months May through November) indicate that lower precipitation in the 30 days prior to $Q_{min}$ usually results in smaller $Q_{min}$ (median $r_S$=0.28). Similarly, higher potential evapotranspiration usually results in smaller $Q_{min}$ (median $r_S$=-0.44). This indicates that the magnitudes of both precipitation and $E_p$ anomalies affect low-flow magnitudes (p-values < 0.001 according to the sign test), but with substantial site-to-site variability. The $r_S$ between 30-day climate anomalies and $Q_{min}$ does not show distinct spatial patterns across Switzerland (see supplementary Fig.S3). The $r_S$ between the 30-day precipitation anomaly and $Q_{min}$ is not correlated with mean catchment elevation ($R^2$ = 0.08), and the $r_S$ between the 30-day $E_p$ anomaly and $Q_{min}$ is weakly correlated with mean catchment elevation ($R^2$ = 0.33).

### 3.3. Combined effects of climate anomalies on warm-season low flows

The results shown in Fig. 2 indicate that both P and $E_p$ can affect low flows. However, most low flows are not caused by only one driver, but instead result from the combined effects of below-average P and above-average $E_p$ during the same time period. Warm-season low flows usually follow periods of below-average precipitation and above-average potential evapotranspiration (72.2% of low flows fall in the top left quadrant of Fig. 3a). Less than a quarter of the annual low flows occur after periods of below-average precipitation and below-average potential evapotranspiration (20.5% lower left quadrant – Fig. 3a). Only very few annual low flows (7.3%) occur after periods of above-average precipitation. Thus, precipitation anomalies appear to be the most important driver for warm-season low flows in Switzerland, and potentially also in other regions with distinct warm-season low flows. While potential evapotranspiration appears to be less important than precipitation, more than 70% of low flows are caused by a combination of both drivers. The combined effect of above-average $E_p$ thus more than triples the chance of an annual low flow (compared to when precipitation is below average, but there is below-average $E_p$).

In particular, the most severe low flows occur through the combined effects of low precipitation and high potential evapotranspiration. For example, 96% of low flows during the most severe low-flow year (2003, shown by green markers in Fig. 3a) follow periods of both below-average precipitation and above-average potential evapotranspiration. This behavior is not unique to the 2003 event, but was also observed for other years with severe annual low flows such as 2011, 2015 and 2018 (Fig. 3b&c).

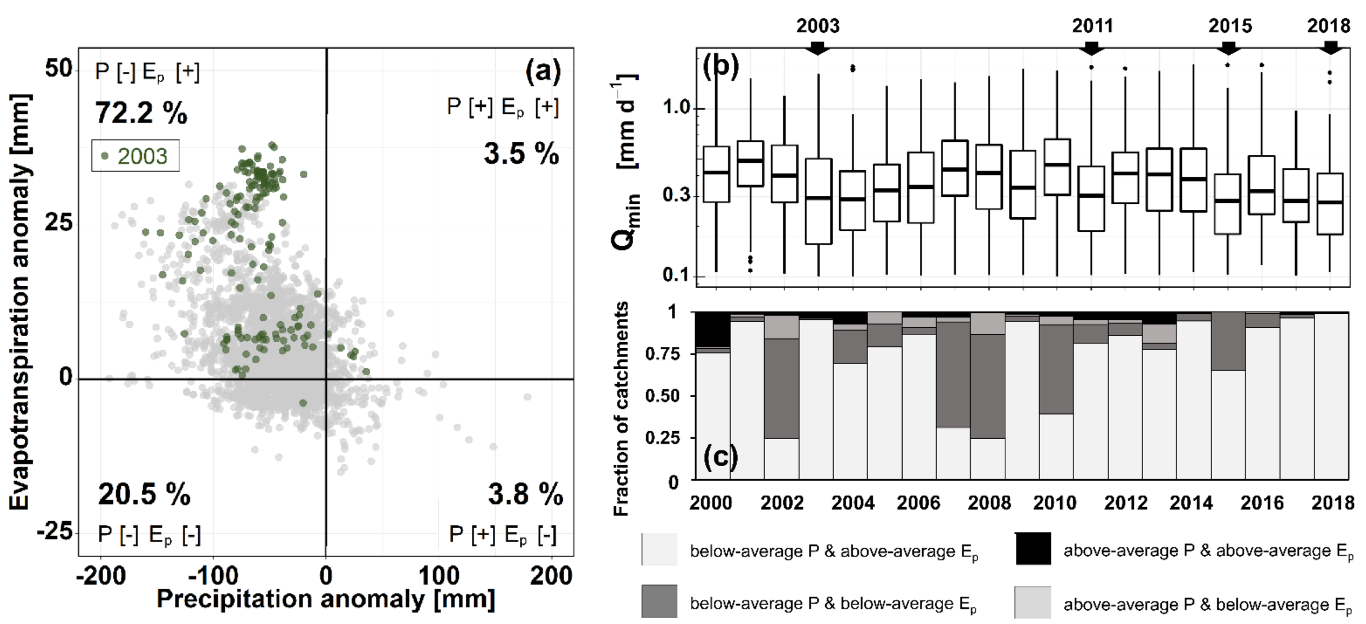
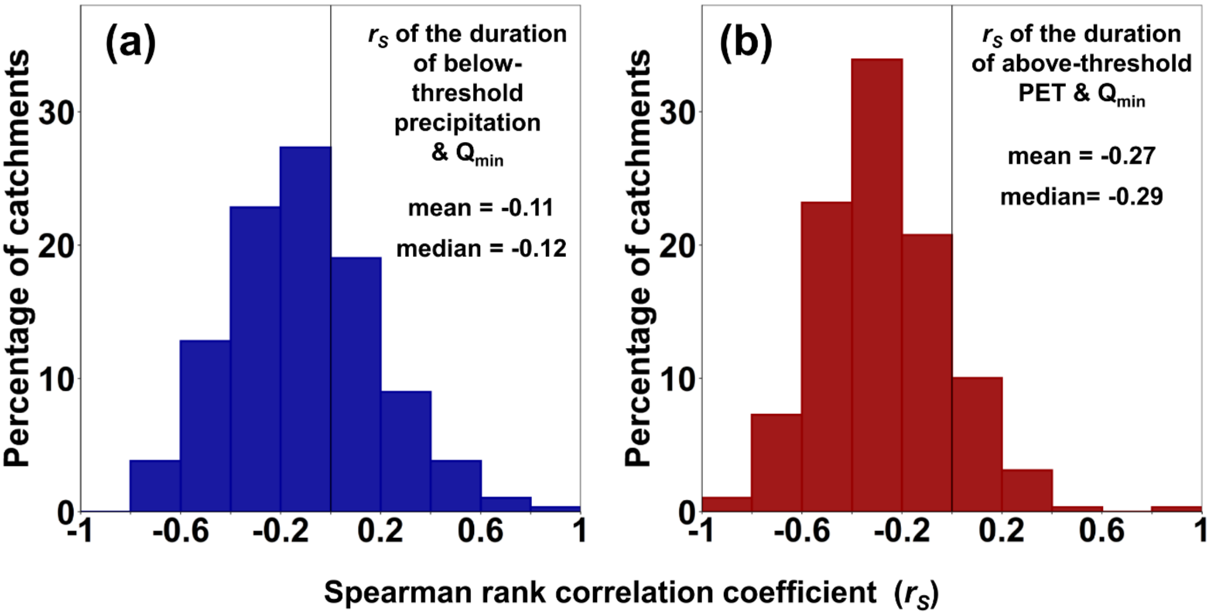



**Figure 3: Anomalies in precipitation and potential evapotranspiration 30 days prior to each annual warm-season (May through November) low-flow period in each catchment (grey dots); annual cold-season low flows were excluded (a). The most severe low-flow year during the study (2003) is highlighted in green. Almost all (92.7%) annual low flows occurred following below-average precipitation (the left half of the figure), and 72.2% of all low flows occurred following a combination of below-average precipitation and above-average potential evapotranspiration (the upper left quadrant of the figure). Boxplots of warm-season 7-day minimum flows for the Swiss study catchments (b) and the catchment distribution of the signs of precipitation and evapotranspiration anomalies that preceded these low flows (c). The most severe low-flow years (2003, 2011, 2015, and 2018) were characterized by negative precipitation anomalies and positive $E_p$ anomalies for the large majority of catchments, as indicated by the light grey bars in (c).**

### 3.4. Duration of climate anomalies

The magnitudes of low flows are also related to the durations of the preceding precipitation and evapotranspiration anomalies. Longer periods of below-threshold ~~precipitation~~P and above-threshold ~~PET~~$E_p$ tend to lead to lower low flows in most of our catchments (Fig. 4). The duration of high ~~PET~~$E_p$ is more strongly correlated with low-flow magnitudes than the duration of low precipitation is (mean Spearman correlations $r_S$ of -0.27 and -0.11 respectively; ~~medians~~median $r_S$ values differ from 0 at $p<0.001$ by sign test; Fig. 4). The weaker correlation with the duration of below-threshold precipitation probably arises because precipitation is more erratic through the years than ~~PET~~$E_p$. A single precipitation event may exceed the precipitation threshold (according to the ~~criteria~~criterion outlined in ~~the caption to Fig. 4~~Sect. 2.3), but ~~not nearly enough~~be insufficient to end the low flow in the stream. Low-flow magnitudes are less strongly correlated with the duration of below-threshold precipitation than with the intensity of 30-day precipitation anomalies (compare Fig. 4 with Fig. 1; mean $r_S$ of -0.11 and 0.26, respectively). Similarly, low-flow magnitudes are less strongly correlated with the duration of above-threshold ~~PET~~$E_p$ than with the intensity of 30-day ~~PET~~$E_p$ anomalies (compare Fig. 4 with Fig. 1; mean $r_S$ of -0.27 and -0.41, respectively).



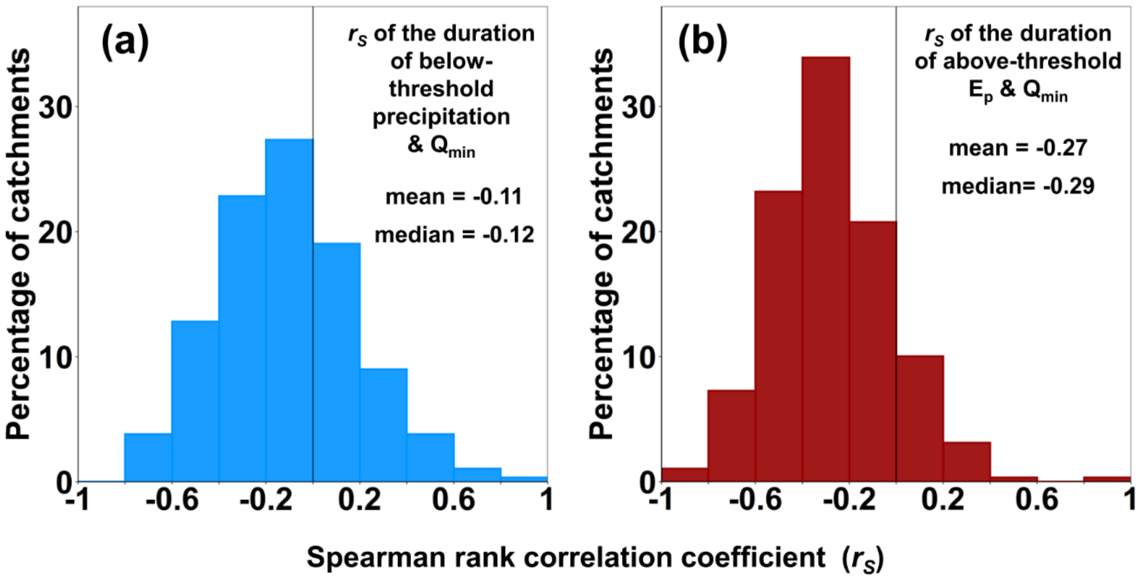




**Figure 4: Histograms of rank correlations between the magnitudes of ~~late summer and autumn (May through November)~~warm-season low flows and the lengths of the preceding intervals with ~~low~~ below-threshold precipitation (a) or ~~high PET (b). The threshold that defines low precipitation is the 20th percentile of the 10-day running averages of precipitation over the entire period of record. Similarly, the~~ above-threshold ~~that defines high PET is the 80th percentile of the 10-day running averages of PET over the entire period of record. Histograms show distributions of rank correlations calculated for each catchment based on the 19 years of data.~~ $E_p$ (b). Longer periods of high ~~PET~~$E_p$ are associated with lower low flows, whereas a weaker association is seen between lower low flows and longer periods with low precipitation.**

Summing ~~precipitation~~P and ~~PET~~$E_p$ anomalies over time windows ranging from one week to half a year indicates that most low flows can be well explained by anomalies of up to 60 days (Fig. ~~5~~5h). This is because in the typical Swiss climate, precipitation and ~~PET~~$E_p$ anomalies usually last for 60 days or less. This is depicted by the grey cloud of points in Fig. 5, as well as the mean anomalies (indicated by the dotted lines in Figs. 5a-g) which remain approximately stable for periods exceeding 60 days. Thus, while longer precipitation and ~~PET~~$E_p$ anomalies would lead to lower flows, most low flows result from anomalies of up to 60 days. This is because most anomalies peak at around that 60-day time scale, which is also indicated by the ~~mean~~means of the precipitation and ~~PET~~$E_p$ anomalies as ~~a function~~functions of timescale (dashed ~~line~~lines in Figs. 5h and 5i).

The severe low flows in 2003, 2011, 2015 and 2018, however, are associated with ~~precipitation~~P and ~~PET~~$E_p$ anomalies that grow for much longer, and thus become much larger, than the roughly 60-day anomalies that are typical in this climate (colored symbols in Fig. 5). Long periods of above-average ~~PET~~$E_p$ appear to be an important factor for these severe low flows; the colored points in Figs. 5e-g expand more on the y-axis than the x-axis for timescales >60 days. Thus, severe low flows result from longer-lasting (and thus larger) ~~precipitation~~P and ~~PET~~$E_p$ anomalies, whereas more typical low flows result from climate anomalies that end after roughly 60 days, as illustrated by Figs. 5h&i.

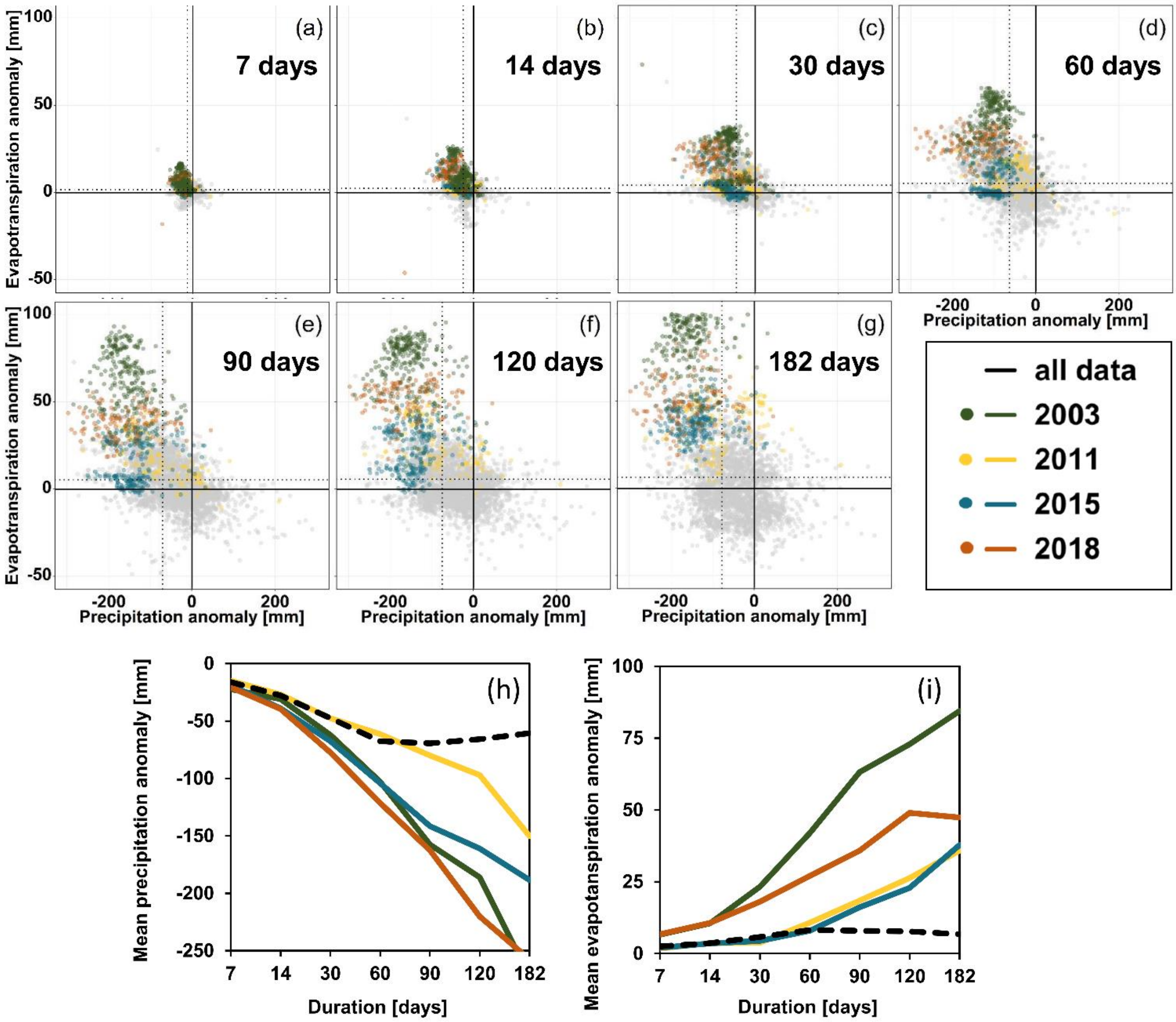



**Figure 5: Cumulative anomalies of precipitation and potential evapotranspiration over 7, 14, 30, 60, 90, 120 and 182 days prior to every annual ~~late summer and autumn (May through November)~~warm-season low flow in each catchment (a-g), and the evolution of the mean anomalies over the different time windows (h & i). Each grey dot represents the combination of precipitation and ~~PET~~$E_p$ anomalies before one low-flow event at one site. Low-flow anomalies in the**

**most severe low-flow years are indicated by different colors (2003 in green, 2011 in yellow, 2015 in cyan and 2018 in orange). The dotted lines indicate the mean precipitation and ~~PET~~$E_p$ anomalies. The mean anomalies (dotted lines in all panels) ~~exhibit clear growth~~clearly increase within the first 60 days prior to low flows, but show no clear trend over longer time windows. During the most severe low-flow years, however, the mean anomalies continue to increase across all of the time windows examined here. In particular, the ~~PET~~$E_p$ anomalies during the severe low-flow years grow well beyond the range that is observed during more typical years.**

### 3.~~4.~~5. The relative importance of P and ~~PET~~$E_p$ anomalies ~~on~~for warm-season low-flow magnitudes

We further assessed the relative importance of each of the climate drivers and their duration in predicting the magnitude of annual low flows by calculating the bivariate Spearman rank correlation between each climate driver and $Q_{min}$ as one value for all stations and years together (Fig. 6). The results also include the site-to-site variability in $Q_{min}$~~,~~; thus the overall $r_S$ correlations are weaker than those shown in Fig. 1c&d. Typical low flows across all years of the observation period (2000-2018) are more strongly correlated to precipitation anomalies than to ~~PET~~$E_p$ anomalies (see also Fig. 1), and this correlation becomes slightly stronger at longer durations. However, during the driest years of our dataset (2003, 2011, 2015 and 2018), the correlation between precipitation anomalies and $Q_{min}$ drops to roughly zero, suggesting that under these extreme conditions low precipitation alone cannot explain the variation in annual low-flow magnitudes. Instead, in these dry years~~ PET~~, $E_p$ anomalies retain their predictive power for $Q_{min}$, suggesting a relatively more important role of ~~PET~~$E_p$ in ~~these~~dry years.

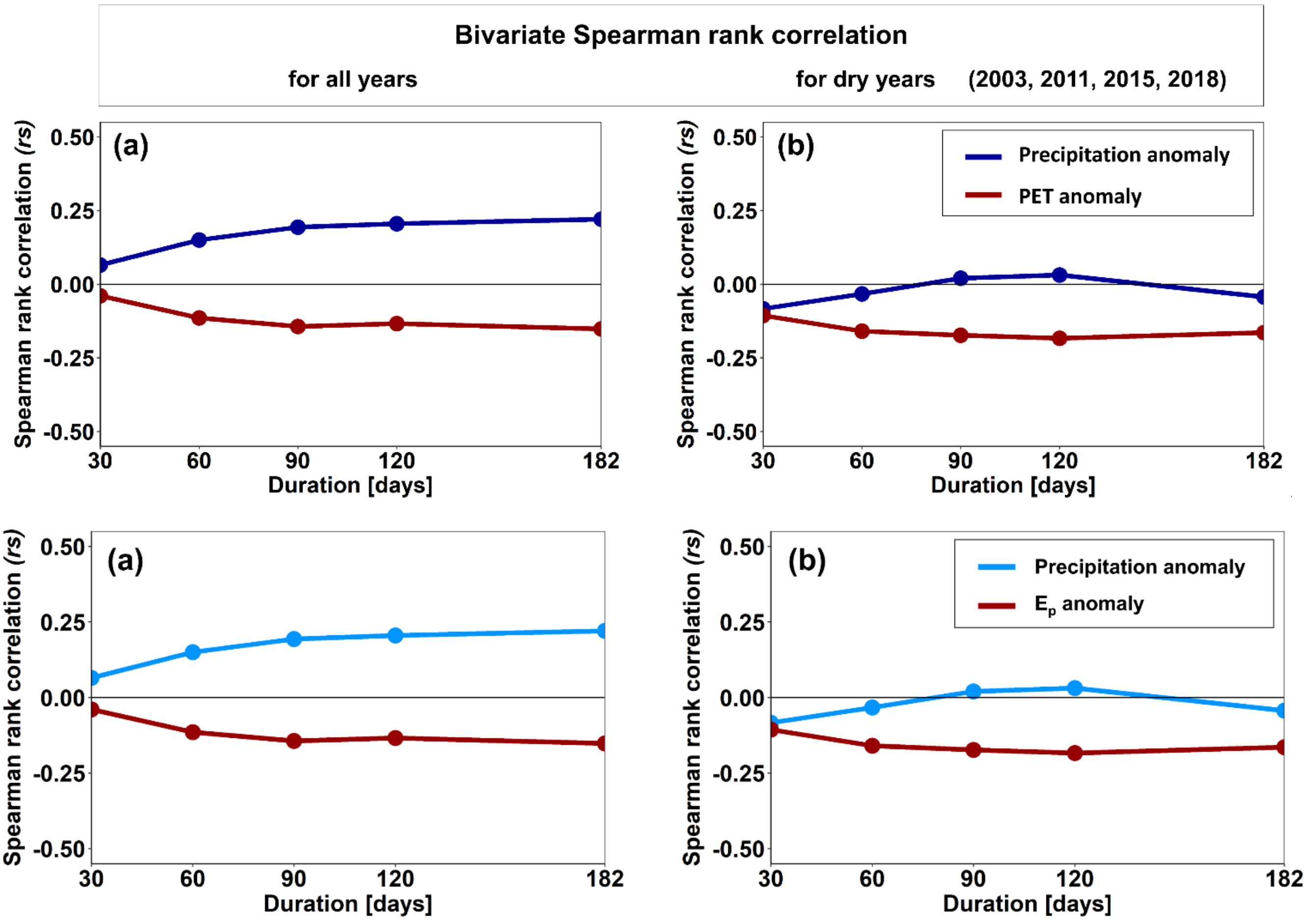



**Figure 6: Bivariate Spearman rank correlation coefficients between precipitation (blue) and ~~PET~~$E_p$ anomalies (red) and $Q_{min}$ of warm~~-~~-season (May to November) low flows for durations of 30~~, 60, 90, 120 and~~ to 182 days, across all**

**stations and years. The overall explanatory power of the climate anomalies in a bivariate regression framework is low, although precipitation anomalies are slightly better correlated to $Q_{min}$ than ~~PET~~$E_p$ anomalies in the whole dataset (a). In the four driest years (b) the overall explanatory power of precipitation anomalies is much smaller, ~~whereas~~and the explanatory power of ~~PET~~$E_p$ anomalies is slightly greater, than ~~for~~in all years combined.**

To quantify how much of the maximum predictive power lies in individual anomalies, we first used a multivariate stepwise generalized linear model (GLM) to predict $Q_{min}$ as a function of all precipitation and ~~PET~~$E_p$ anomalies for all durations of 30, 60, 90, 120 and 182 days. In Fig. 7 we show the fraction of the model $R^2$ explained by ~~this model with~~ individual P and ~~PET~~$E_p$ anomalies for the different durations. Across all stations and years of the observation period (2000-2018), warm season $Q_{min}$ is best predicted by precipitation anomalies with increasing duration (Fig.~~-~~ 7a), which shows the cumulative effect of low precipitation. However, in the years with the lowest annual warm season low flows (2003, 2011, 2015 and 2018) the picture reverses, and instead ~~PET~~$E_p$ explains most of the ~~predictability~~variability in $Q_{min}$ ~~up to about 50% of the best predictive GLM model~~. This is true across a wider range of durations, starting even at 30 days. Thus, although precipitation anomalies are a good predictor for typical low flows, low~~-~~-flow magnitudes in the driest years are more strongly related to ~~PET~~$E_p$ anomalies when precipitation ~~anyway~~ is also very low.

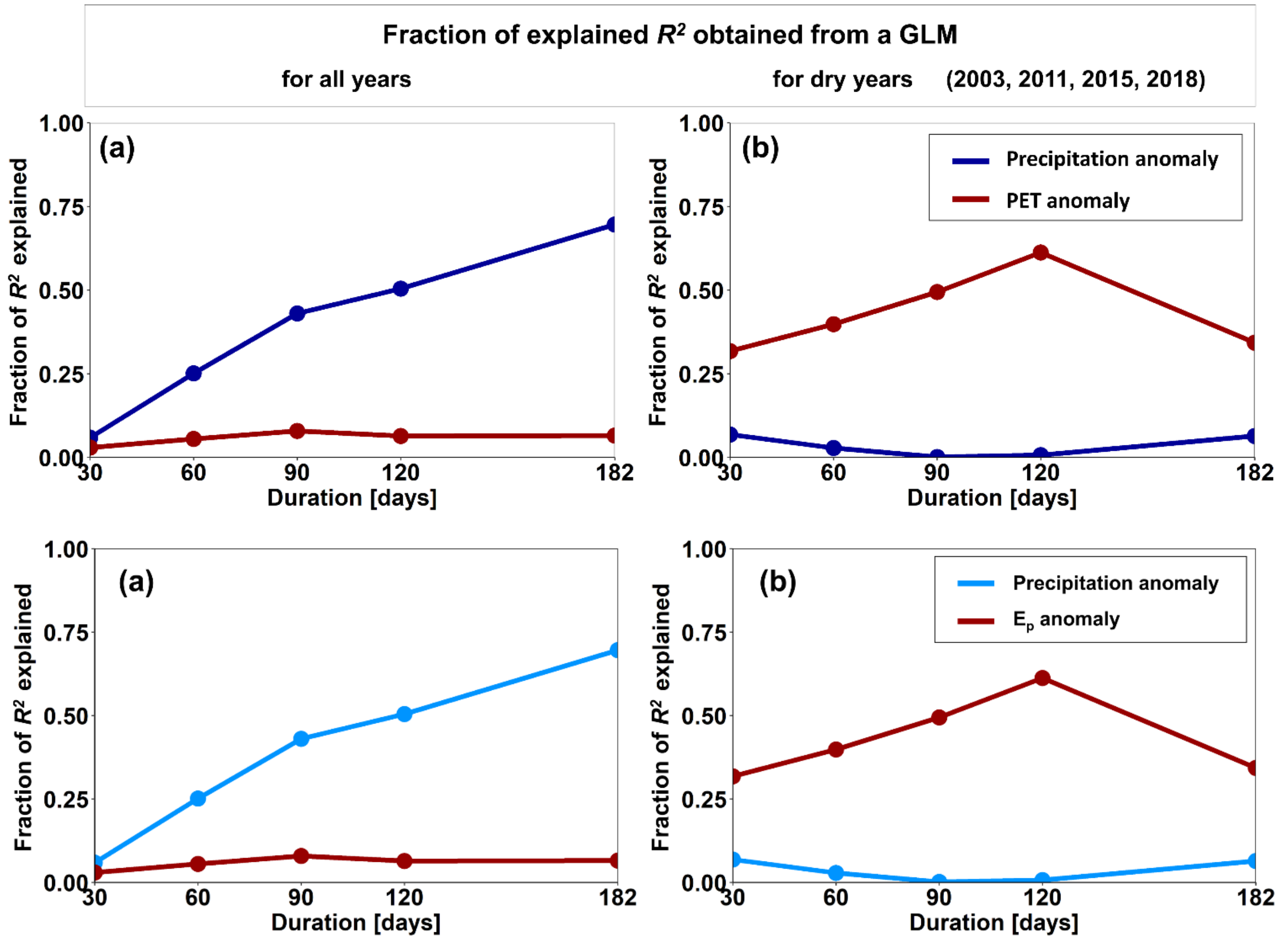
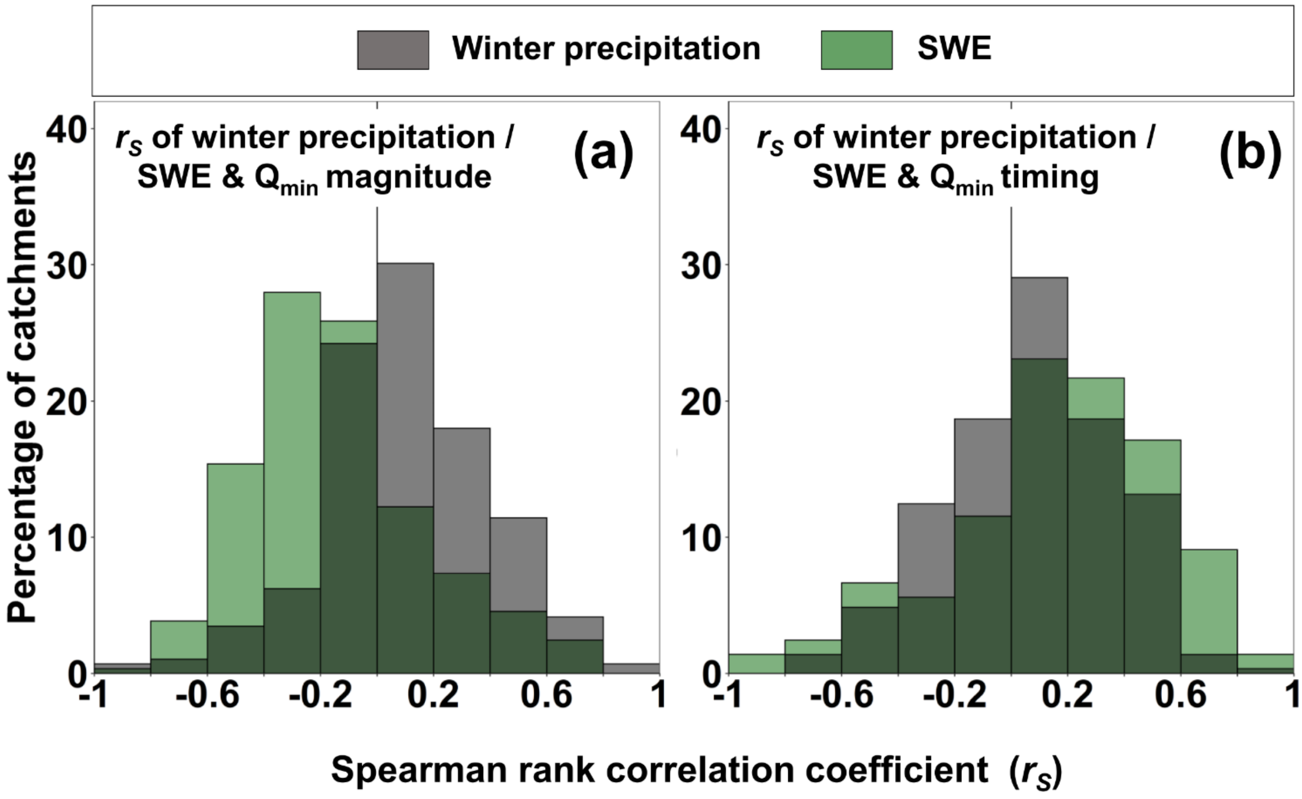



**Figure 7: The fraction of multivariate $R^2$ ~~–~~(calculated by a stepwise generalized linear regression model ~~(GLM) with~~that explains warm-season low-flow magnitudes using all climate variables and ~~warm season (May to November) low flows~~ -durations) that can be explained by a precipitation (blue) or ~~PET~~$E_p$ (red) anomaly of ~~a certain~~the specified**

**duration. Precipitation anomalies explain most of the variation in $Q_{min}$ when looking at all stations and all years (a). However, precipitation anomalies are not good predictors for low flows that occurred in the driest years (2003, 2011, 2015, 2018~~) and instead PET~~), when $E_p$ anomalies are instead much better predictors of $Q_{min}$ variability (b).**

### 3.~~5~~6. The ~~influence~~impact of winter precipitation and snow on ~~summer~~warm-season low flows

Previous studies indicate that winter snowpack and snowfall can influence the timing and magnitude of summer low flows in some regions (e.g., Dierauer et al., 2018; Jenicek et al., 2016; Godsey et al., 2014). If this holds true for our study catchments, more winter precipitation (December through March), or higher SWE on March 1st, should lead to larger and later ~~summer/autumn~~warm-season low flows. To test for this effect, we calculated Spearman rank correlations between winter precipitation totals and subsequent warm-season low-flow magnitudes and timing~~ (May through November).~~. The correlations between winter precipitation and the magnitude and timing of $Q_{min}$ (mean absolute $r_S < 0.11$ for both; grey bars in Fig. 8) are weaker than those between low-flow magnitudes and climate anomalies ~~in the period~~ directly ~~before the~~preceding low ~~flow~~flows (Figs. 1c&d), and they do not vary systematically with ~~altitude~~elevation. We also calculated the Spearman rank correlations between ~~SWE on~~ March 1st ~~of every year~~SWE and subsequent low-flow magnitudes and timing, and ~~also~~ found no strong relationship (Fig. 8, green bars; mean absolute $r_S < 0.17$ for both).



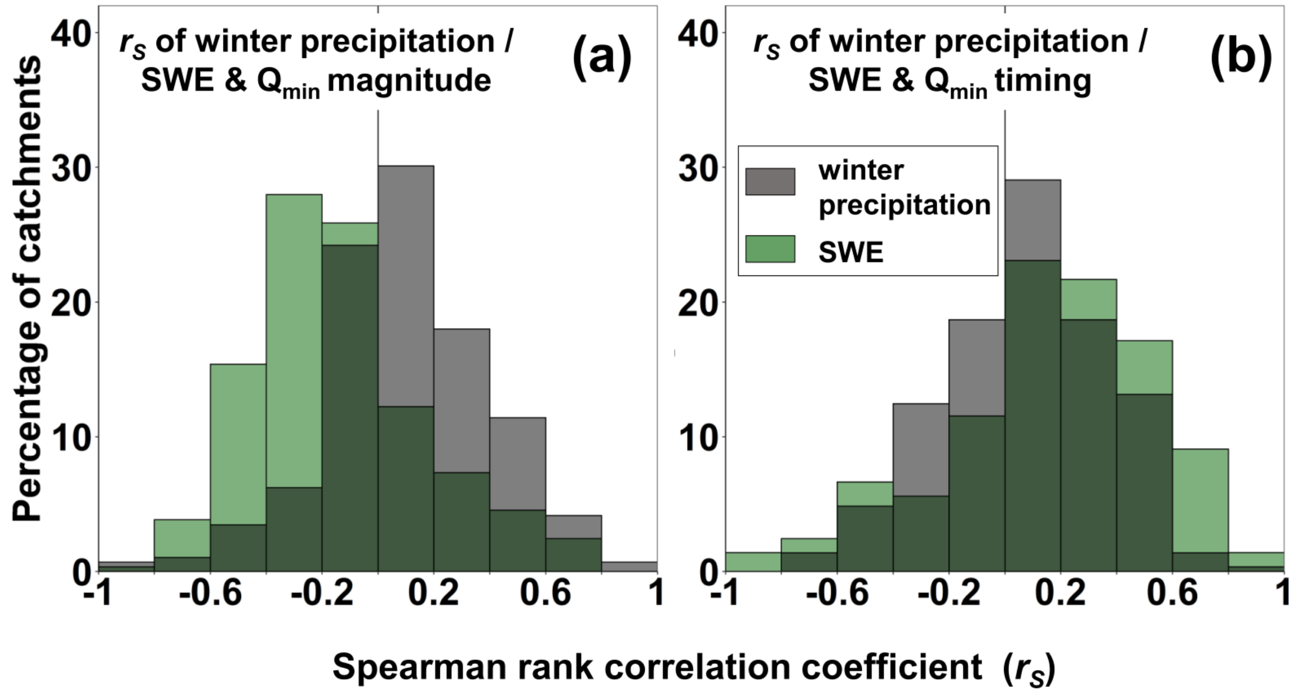



**Figure 8: Histograms of the rank correlations between winter precipitation (December through March~~ – ~~; grey bars) and March $1^{st}$ snow water equivalent (SWE~~) on March $1^{st}$ (~~; green bars) and the magnitude (a) and timing (b) of ~~summer~~warm-season low flows~~ (May through November)~~. Winter precipitation is weakly associated with higher, and later, warm-season low flows, as indicated by the positive $r_S$ for the majority of catchments~~,~~; however, overall correlations are weak, with considerable site-to-site variability.**

## 4. Discussion

### 4.1 Climate anomalies control low-flow timing and magnitude

Anomalies of precipitation and potential evapotranspiration affect the magnitude of low flows, but their influence decreases with elevation (Fig.~~1 a~~ 2a&b). This pattern is probably not unique to Switzerland, and we expect precipitation and ~~PET~~$E_p$ anomalies to also be relatively unimportant in other cold regions where low flows primarily occur in winter (e.g., Dierauer et al., 2018; Laaha & Blöschl, 2006; Van Loon et al., 2015; Wang, 2019), driven by extended freezing periods. However, warm-season low flows are more common globally (e.g., Dettinger & Diaz, 2000; Eisner et al., 2017), suggesting that summer climate anomalies are likely to be important not only for the lower-elevation catchments in Switzerland, but also across many other regions of the world.

We found that the combined ~~effect~~effects of P and ~~PET~~$E_p$ anomalies ~~shapes~~shape the occurrence and magnitude of low flows ~~whereby~~, with the more extreme low flows ~~are~~being driven by longer-duration anomalies. Typical warm-~~-~~season low flows result from climate anomalies of up to 60 days (Fig.5). In Switzerland, typical low flows result from relatively short climate anomalies, probably because precipitation does not have a strong seasonal signature. In climates that typically have frequent precipitation events, short periods (e.g., one to two months) with less precipitation than normal will most likely ~~lead to~~precede the annual low flow. Similarly~~, PET patterns are relatively comparable between years, whereby~~ short $E_p$ deviations from the norm ~~can already generate~~often precede typical annual low flows. In the years with the lowest low flows (2003, 2011, 2015 and 2018), the ~~duration~~durations of climate anomalies ~~was~~were significantly longer, and especially the ~~impact~~impacts of

~~PET~~$E_p$ anomalies ~~was~~were larger (Figure 5). This highlights precipitation and evapotranspiration as combined drivers of severe low flows, consistent with findings in several experimental catchments during the 2003 low~~-~~-flow year (Teuling et al., 2013). Our results suggest that the magnitude and duration of these precipitation and ~~PET~~$E_p$ anomalies are generally important controls on~~ severe~~ low flows in a large, diverse sample of mesoscale catchments across Switzerland. These compound effects of ~~PET~~$E_p$ and precipitation anomalies might also be important for low flows across larger regions (e.g., Stahl et al., 2010), as the climate conditions in Switzerland are comparable to those in other densely populated regions ~~in~~of the world. However, we only analyze these processes on timescales of up to half a year, so long-term memory effects in low-flow generation may not be fully captured by this approach.

The pronounced effect of ~~PET~~$E_p$ in the years with the lowest low flows might also reflect the coupling of P and ~~PET~~$E_p$ during dry and warm periods. Low precipitation and high air ~~temperatures~~temperature might lead to soil moisture depletion, forcing plants to reduce transpiration~~, resulting in lower relative humidity. These soil moisture deficits can thus lead to lower~~. Lower latent heat fluxes and greater sensible heat fluxes from the surface~~, thus increasing~~ increase air temperature ~~(~~and thus ~~increasing PET~~increase $E_p$ while reducing actual evapotranspiration~~)~~. This complementary relationship between evapotranspiration and ~~PET~~$E_p$ can amplify the apparent effect of ~~PET~~$E_p$ during (extended) dry periods~~.~~ (Granger, 1989). Conversely, in locations where transpiration is not limited by water availability (e.g., at higher elevations), high temperatures and larger vapor pressure deficits (i.e., high ~~PET~~$E_p$) may drive increases in transpiration rates, accelerating the depletion of catchment water stores and thereby reducing runoff. For example, Mastrotheodoros et al. (2020) showed how increased evapotranspiration at higher ~~altitudes~~elevations systematically amplified runoff deficits during severe low flows in 2003 across the European Alps. These processes are especially relevant in view of potential future climatic changes. In Switzerland, climate change is expected to increase temperatures by more than the global average, resulting in warmer summers with less warm-season precipitation (CH2018, 2018). Similar trends are ~~reported for~~also expected in many other regions~~ of the world~~. This highlights the effects of water removal through evapotranspiration, especially during extended dry periods, which are expected to become more severe with changing climate conditions.

A small fraction of all warm-season low flows in the period 2000 to 2018 followed periods of above-average precipitation and below-average ~~PET~~$E_p$ (4% in lower right quadrant ~~–~~of Fig. ~~2a~~3a). These anomalies are expected to lead to above-average flow conditions, but can nonetheless lead to annual low flows for at least two reasons. First, these low flows occur in years that are relatively wet, with relatively high annual low flows (Fig. 3b). Second, flow conditions in most Swiss catchments are highly seasonal (Wehren et al., 2010; Weingartner & Aschwanden, 1992), meaning that the seasonality of the flow regime can, in some years, outweigh the effects of shorter-term weather.

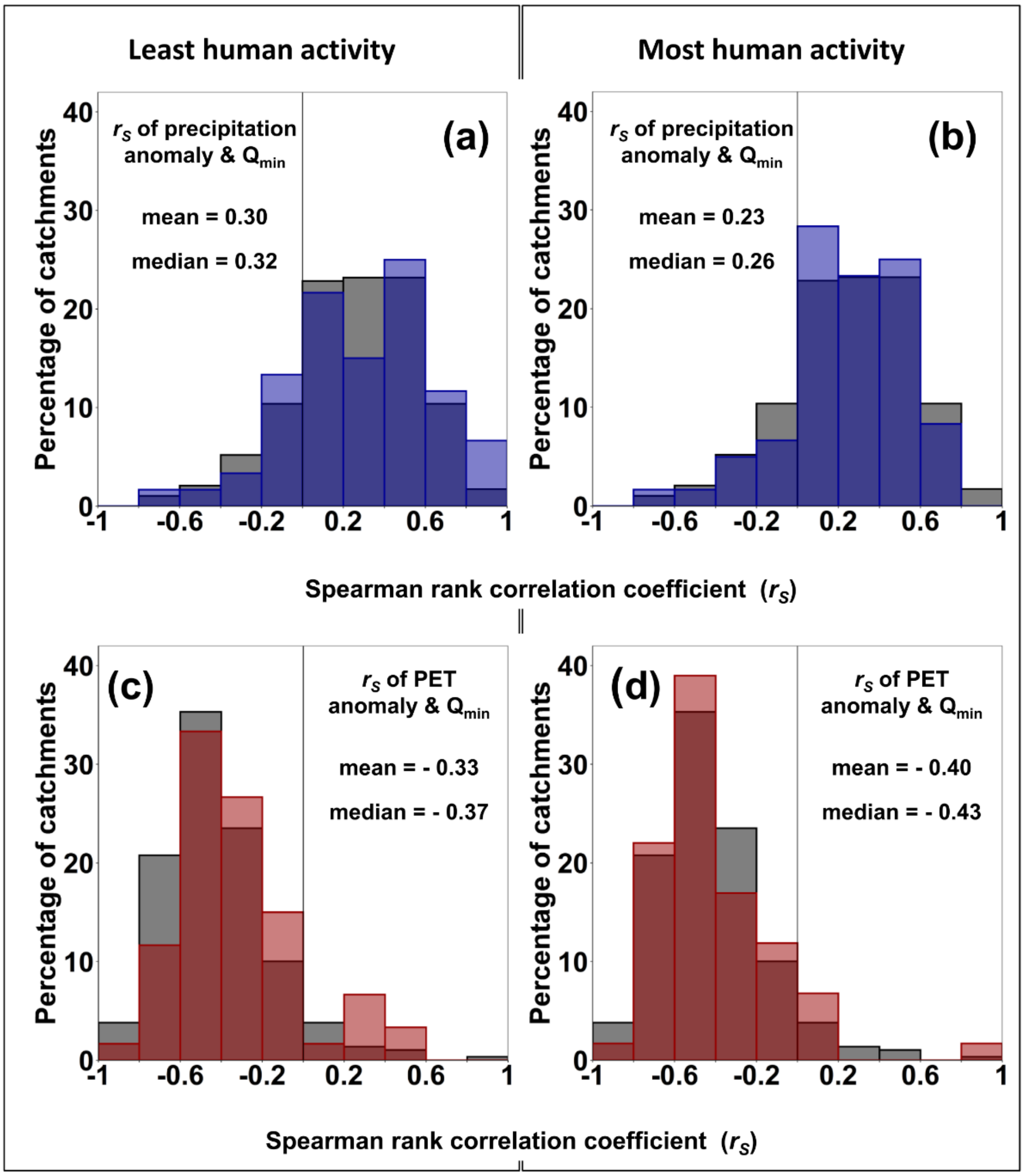
### 4.2 The influence of winter precipitation and snow on warm-season low flows

Previous work in several Swiss catchments has suggested that the snow-water equivalent (SWE) accumulated in the winter snowpack strongly affects summer low-flow magnitudes (Jenicek et al., 2016). Our more complete dataset of Swiss catchments indicates that winter precipitation ~~(December through March)~~ and SWE (on March $1^{\text{st}}$) are only weakly related to the magnitude and timing of the ~~preceding~~following warm-season low flows. In addition, these weak correlations did not significantly increase at higher~~-~~-elevation catchments, suggesting that even at the higher-~~altitude~~elevation sites, SWE is not a major control on warm-season low flows. We caution~~ the reader~~, however, that this analysis excludes many of the highest-~~altitude~~elevation catchments, in which the annual low flow occurs during the winter~~ (because we analyze only the lowest annual flows, not the lowest summer flows).~~. Thus the discrepancy between our results and those of Jenicek et al., 2016 probably arises from differences between our respective definitions of low flows. We studied annual 7-day minima, and included only the annual low flows that occur between May and November (thus excluding many high-~~altitude~~elevation sites where annual low flows occur in the winter instead), whereas Jenicek et al. (2016) studied 7-day summer minima regardless of whether they are annual minima. Thus, winter precipitation and SWE do affect summer streamflow in Alpine catchments (Jenicek et al., 2016), but our results suggest that for most of the rest of Switzerland, projected changes in winter snowpacks (e.g., Harpold et al., 2017; Mote et al., 2018) might only slightly affect the magnitude and timing of annual low flows that occur during the warm season.

### 4.3 Human impacts on warm-season low-flow statistics

~~Virtually~~Almost every catchment in Switzerland, and elsewhere where dense gauging data exist, is to some extent affected by human activity (e.g., Grill et al., 2019, Lehner et al., 2011). This could be through, for example, water management operations, water abstractions, hydropower operations, and ~~sewage~~wastewater treatment plant return flows. Especially in Central Europe, almost no pristine catchments exist and quantitative information capturing all potential human influences on streamflow at catchment scale is unavailable. As described in the methods, we removed any catchments with any obvious anthropogenic influences on streamflow (e.g., from hydropeaking or dams), however some regulation effects may still be present in the dataset.

To assess the impact of human influence ~~across the Swiss catchments~~ on the results, we recalculated Fig.~~1 c~~ 2c & d for the 20% of catchments with the largest fraction of human-affected ~~landcover~~land use, and the 20% of catchments with the smallest fraction of human-affected ~~landcover. As a proxy for human activity we use the Corine landcover dataset (CLC, 2018) and calculated the fraction of catchment area with “Artificial surfaces”. Thereby we~~land use. We thereby tested whether the relationships between the 30-day anomalies of precipitation and ~~PET~~$E_p$ and the magnitude of warm-season $Q_{min}$ are significantly different in catchments with a lot of human activity compared to catchments with relatively little human activity (Fig.~~-~~ 9). The results were broadly similar with no significant differences between the strongly affected and weakly affected catchments (p>0.2 by Student's t-test).




~~**Figure 9: Histograms of rank correlations between anomalies of precipitation (a & b) and potential evapotranspiration (c & d) and low-flow magnitudes for late summer and autumn (May through November) low flows across Swiss catchments. On the left side (a & c) we show the distributions for the 20% of catchments with the least human impact (blue & red) on top of the distributions for all data (grey). On the right side (b & d) we show the distributions for the 20% of catchments with the most human impact (blue & red) on top of the distributions for all data (grey). The observed distributions of correlations between the 30-day climate anomalies and the magnitudes of low flows are similar in catchments with the most and the least human activity.**~~

The consistency of the results may be due to the fact that, although human water ~~usage~~use during low flows will change their absolute magnitudes (and thus may affect site-to-site differences in low flows, which are not considered here), it may have a smaller effect on their relative magnitudes from year to year at any given site. Thus human influences may not greatly alter the rankings of annual low flows throughout the observation period; drier years are still expected to have lower low flows and wetter years are still expected to have higher low flows, largely independent of human influences. Therefore the Spearman rank correlation coefficient is likely to be a relatively robust index for assessing the effects of climate anomalies on the timing and magnitude of annual low flows. Recent studies across US catchments have also found limited effects of human influence on low flows compared to climate drivers (Ferrazzi et al., 2019; Sadri et al., 2016). Nevertheless, the unexplained variance in our established relationships suggests that human-induced shifts in the $Q_{min}$ ranking may have an effect on low-flow behaviors in some catchments.

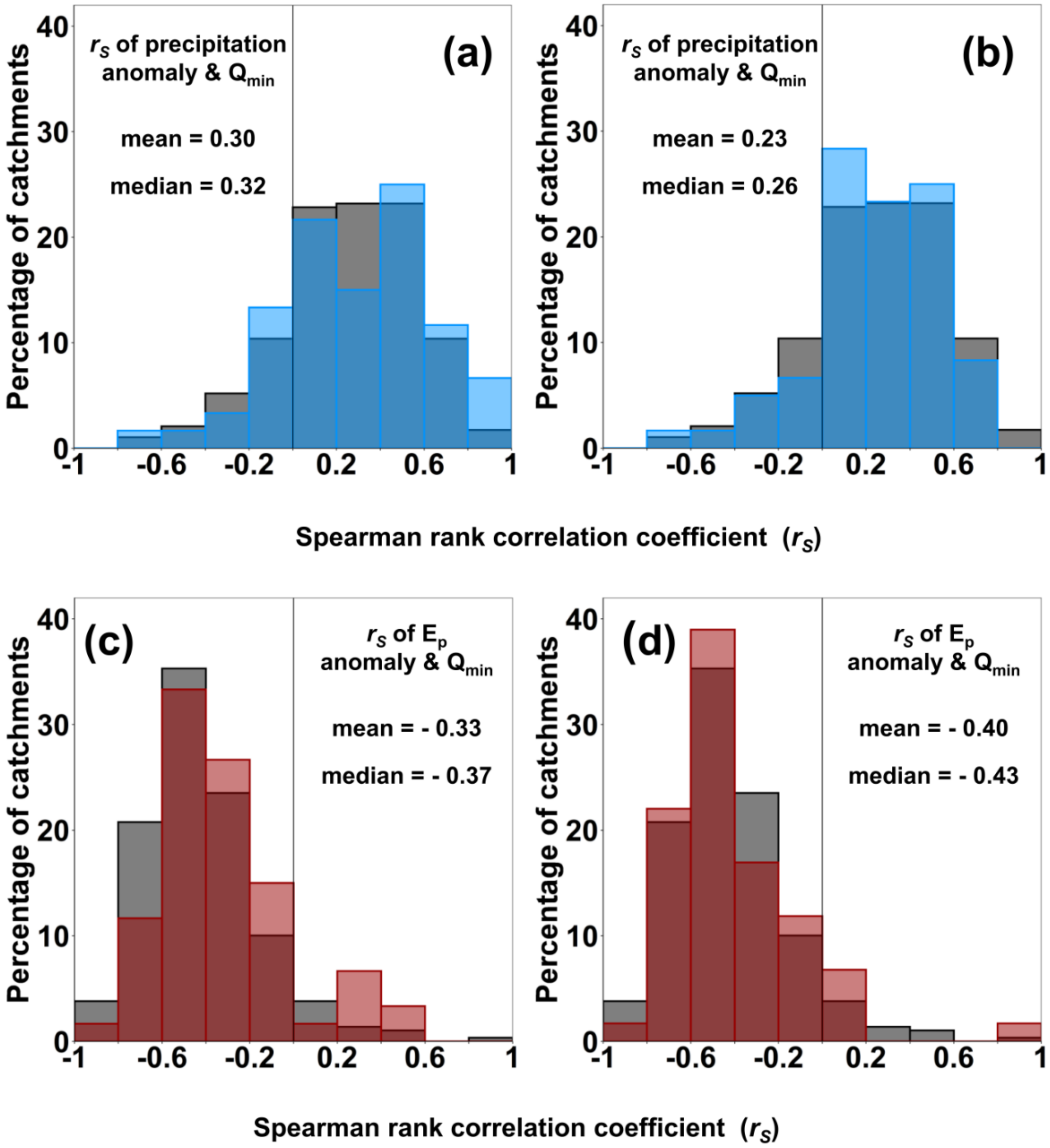



**Figure 9: Histograms of rank correlations between low-flow magnitudes and anomalies of precipitation (a & b) and potential evapotranspiration (c & d) for warm-season low flows across Swiss catchments. The left side (a & c) shows the distributions for the 20% of catchments with the least human impact (blue & red) on top of the distributions for all data (grey). The right side (b & d) shows the distributions for the 20% of catchments with the most human impact (blue & red), again plotted on top of the distributions for all data (grey). The observed distributions of correlations between the 30-day climate anomalies and the magnitudes of low flows are similar in catchments with the most and the least human activity.**

### 4.4 Broader implications

Our overall results are largely consistent with previously discussed drivers of low flows (e.g., Teuling et al., 2013; Woodhouse et al., 2016; Hannaford, 2015). Our work builds upon past research by studying a large dataset which shows the variability and consistency in low-flow/climate relationships among many catchments. We also quantify the effect of the duration of climate anomalies and analyze the interplay of P and ~~PET~~$E_p$ as drivers. Our work thereby emphasizes how both precipitation and ~~PET~~$E_p$ anomalies are important drivers of low flows, especially during severe low flows. This is in line with ~~increased attention to~~a growing literature on severe events arising from the interplay of multiple drivers (e.g., Zscheischler et al., 2018). Our study also highlights that the relevant properties of low-flow drivers are multidimensional: their magnitudes, timings, and durations all matter. For example, in a lower-elevation catchment, a precipitation anomaly in spring will not have the same impact as a similar anomaly in autumn. Likewise, periods of above-average ~~PET~~$E_p$ will have different implications for streamflow in May than they would in September. Thus, antecedent catchment conditions matter. It is not sufficient to look at climate anomalies alone as drivers of low flows, since they may have different implications at different times of the year. Although our study is based on a network of Swiss catchments, we expect our findings to be more broadly applicable to climatically similar regions as well. We see similar patterns in low-flow seasonality in other regions of the world (e.g., Laaha & Blöschl, 2006; Demirel et al., 2013; Dettinger & Diaz, 2000~~)~~), suggesting that the effects of climate anomalies in these other regions may also be largely similar. For example, the severe summer low flows in California in recent years have been driven by below-average precipitation magnified by above-average temperatures and thus potential evapotranspiration (Diffenbaugh et al., 2015). Van Loon et al. (2015) and Van Loon & Laaha (2015) reported similar driving mechanisms for low flows in Austria and Norway. Thus, our approach for assessing the effects of multiple dimensions of climate impacts (i.e., timing, duration and magnitude) on low flows ~~may~~could potentially be used to derive insight into low flows in other regions.

## 5. Conclusions

Annual low flows in Switzerland typically occur in two distinct seasons: in winter at higher elevations due to sub-freezing temperatures, and in summer and autumn at lower elevations, following periods of above-average potential evapotranspiration and below-average precipitation (Figs. ~~1a~~2a&b). The magnitudes of these climate anomalies strongly affect the magnitudes of annual low flows across our network of catchments (Figs. ~~1c&d). While both precipitation and PET anomalies can affect low flows, almost~~2c&d). Almost all (about 92%) of our catchments' annual low flows follow periods of unusually low precipitation, and many (about 70%) also follow periods of unusually high potential evapotranspiration (Fig. ~~2a~~3a). Thus, most low flows arise from the combined effects of precipitation and ~~PET~~$E_p$ anomalies. Severe low flows, such as in the years 2003, 2011, 2015 and 2018, almost exclusively occurred after anomalies in both precipitation and ~~PET~~$E_p$ (Fig. ~~2a~~3a). During these especially dry years, low flows occurred simultaneously across large parts of Europe, but their timing was highly variable across Switzerland (Fig. ~~3~~1). Longer periods of below-threshold precipitation and above-threshold ~~PET~~$E_p$ generally led to lower low flows (Fig. 4). Anomalies preceding low flows typically acted over timescales of up to 60 days, while precipitation and ~~PET~~$E_p$ anomalies in ~~severe low-flow~~unusually dry years (2003, 2011, 2015 and 2018) grew for much longer, and thus became much larger (Fig 5). Long periods of above-average ~~PET~~$E_p$ appear to be especially important drivers of the most severe low flows (Fig. 5). Typical low flows were mainly driven by precipitation anomalies~~,~~; however, the low flows in the driest years (2003, 2011, 2015 and 2018) were ~~strongly~~more related to ~~PET~~$E_p$ anomalies (Fig. 6 & 7). Total winter precipitation (and SWE) affected the magnitude and timing of ~~summer and autumn~~warm-season low flows (Fig. 8), but was less important than the climate anomalies in the month prior to the low-flow period (Figs. 1c&d). ~~However, the importance of snow processes for low flows occurring in winter remains to be analyzed.~~ Our results describe how the timing, magnitude and duration of precipitation and ~~PET~~$E_p$ anomalies drive warm-season low flows across Switzerland. In combination with seasonal weather forecasts, these results could help in predicting and managing low flows.

**Data availability:** The data that support the findings of this study are available in the ETH library open-access repository. Discharge time series can be obtained from FOEN (Swiss Federal Office of the Environment) and Swiss Cantonal Authorities; meteorological data can be obtained from MeteoSwiss, geodata from Swisstopo (Swiss Federal Office of Topography). Contact information for these agencies is provided in the Supplementary Material.

**Author contribution:** MF, WB, PM designed the study; MF performed the analyses and wrote the first draft, all authors discussed the results and edited the manuscript.

**Competing interests:** The authors declare that they have no competing interests.

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