"Progressive water deficits during multi-year droughts in central-south Chile" by Alvarez-Garreton et al.

Response to Anne Van Loon and Gemma Coxon

We thank the two Referees, Anne Van Loon and Gemma Coxon, for their constructive comments on our paper.

The main changes proposed for the revised manuscript, which we think will improve the scientific approach and will help to clarify the main insights from the work, follow both referees' suggestions and include:

1) A new section with a classification scheme that groups the catchments based on their main hydrological regimes. With this procedure, we replace the formerly "semi-arid" and "temperate" basins by two, more objectively defined, new groups: snow-dominated and pluvial basins.

2) A deeper discussion regarding the potential influence of anthropic activities on the R-R shifts and overall interpretation of results. Major anthropic activities (e.g., agriculture, allocated water rights) will be accounted for in the revised Section 2: Study area and data. Based on this analysis, and in order to enable a more robust interpretation of results, we have filtered out 14 basins having reservoirs within.

3) A discussion on the HBV model limitations and uncertainties.

Additionally, we have updated the hydro-meteorological datasets until March 2020, which allows us to include the extreme dry conditions in central-south Chile in 2019 (one of driest year in a century).

Below we provide our replies to each Referee comment. For clarity, Referee comments are given in blue text, our responses are given in plain text and the proposed paper modifications in italics.

Referee #1, Anne Van Loon:

This paper uses a recently published dataset to look at changes in rainfall-runoff relationships during multi-year drought covering a range of different conditions in Chile. The authors conclude that both groundwater and snow play an important role and that some regions are more affected by prolonged drought and others by short extreme drought. The topic of the paper is important and the range of catchments included in the dataset provides interesting insights. The analysis is done well and the paper is generally well-written. The paper can be suitable for publication in HESS after a number of (relatively minor) revisions. Below I provide my suggestions for improvement of the paper.

We thank the reviewer for her positive comments.

General comments

1) The authors do not mention potential human influence in the catchments (except in the final sentence of the manuscript, l.461). It is unclear whether these catchments are completely without any human influence on the hydrology (which I doubt because they are quite large and cover a large part of Chile, so they are unlikely not to include reservoirs, forestry plantations, agriculture). There might for example be an increase of abstraction or change of land use during multi-year drought that might influence the rainfall-runoff relationship. CAMELS-CL includes information on land use, intervention degree, water rights and it would be greatly improve the paper if this was included in the analysis. If this cannot be included in the current paper, the authors must at least mention the degree of human influence in the catchments at the start of the paper and discuss potential effects of human influences on the results at the end (in the Discussion section).

We agree with the Referee at this point. In addition to catchment runoff mechanisms and the unprecedented dry conditions experienced within the megadrought (MD), another factor that may be influencing rainfall-runoff relationships are the anthropic activities within the catchments. Local activities may be particularly important during a multi-year drought, where the total available water within a catchment decreases, while the water consumption related to human activities (forestry, irrigated agriculture, etc) most probably not. In fact, the influence of reservoirs on catchment response may be higher during droughts than in normal years, given that irrigation must supply a larger portion of the water demanded by plants. This may contribute to a different rainfall-runoff response, when compared to the historical (pre-MD) catchment response.

Quantifying the influence of anthropic factors on water availability, particularly on the observed progressive water deficits during the MD, is part of the ongoing objectives from our research group. However, to address such analyses we require some additional datasets to characterise anthropic activities during and before the MD. These datasets are currently being implemented, but that will be available in ~1 year according to our planning. Such datasets include (i) land cover maps for different periods of time to enable the quantification of land use and land cover changes within the territory (note that the CAMELS-CL land cover data correspond to a single year, 2016); (ii) the quantification of water consumption from the different economic sectors associated to the generated land use maps, i.e., 'actual' water use time series; and (iii) the temporal time series of granted water use rights, i.e., 'potential' water use time series (water use rights in CAMELS-CL dataset correspond to the accumulated granted volumes in 2018).

Based on the above, we consider that a robust analysis of the anthropic influence on drought propagation during the MD, compared to pre-MD conditions, is beyond the scope of the current paper. Notwithstanding this, and by following the Referee suggestions, in the revised manuscript we will:

- Highlight this topic in the introduction
- Provide a description of the current state (i.e., during the MD) of human activities within the catchments based on land cover, water rights and reservoirs datasets from CAMELS-CL (revised Sect. 2: Study region and data).
- Provide a discussion (Sect. 5) about the potential effects of human influences on our findings, and the limitations of the available datasets to assess such influence. Despite these limitations, in order to enable a more robust interpretation of results, we will filter out 14 basins with reservoirs from the study domain.

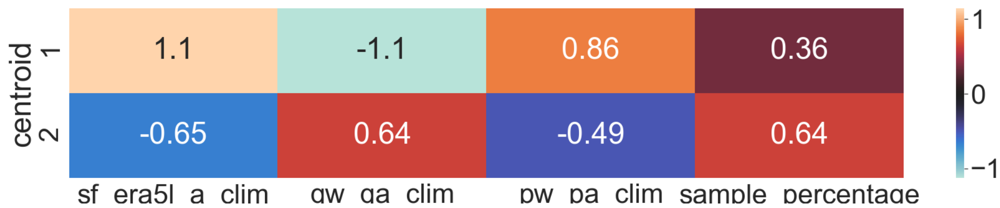
2) The authors should be more specific about the role of snow vs. groundwater when they talk about memory (for example in the abstract l.16-18). This starts with the classification of catchments in semi- arid vs. temperate catchments, which seems to be partly overlapping with snow-dominated vs. rainfall- dominated catchments but this is not clearly identified. For example, on p.5 l.111-113 the authors state that in central Chile there is an Mediterranean regime, whereas in snow-dominated basins "streamflow peaks in spring / early summer", which makes me think that the snow-dominated basins are located in southern Chile. But then the classification (l.113-118) seems to be only based on precipitation and not on snow and Fig.1 shows that there is more snow in the north. Also, an additional classification of catchments is introduced on p.7 l.183-185, where snow-dominated catchments are defined as having a snow fraction larger than 0.3. On the other hand, the authors assessed groundwater by the BFI in a continuous way, so without a classification between groundwater-dominated and not groundwater- dominated catchments. I would suggest to do the same for both snow and groundwater, so either a continuous or a binary classification.

Both Referees have commented on the way of characterising the study catchments, pointing out the confusion of using different classification schemes, such as 'semi-arid and Mediterranean basins' (based on total precipitation), and 'snow-dominated and pluvial basins' (based on snow fraction). Further, in the submitted manuscript we also assessed the role of groundwater (GW) based on a BFI computed from HBV, which can be seen as another classification scheme.

Addressing these comments, in the revised manuscript we will provide a unique classification scheme to group the basins by their main hydrological regimes, based on k-means clustering algorithm (Kanungo et al., 2002). To implement this classification, we applied k-means clustering to three key hydro-meteorological basin features (normalised variables) provided in Section 2 and summarised in the following table:

Variable name	Description (all variables are computed at the catchment scale)
Pw_Pa_clim	Ratio of mean fall-winter precipitation (april to september) to mean annual precipitation (period 1979-2018) from CAMELS-CL dataset
Qw_Qa_clim	Ratio of mean fall-winter streamflow (april to september) to mean annual streamflow (period 1979-2018) from CAMELS-CL dataset
Snow fraction	Long-term snow fraction, computed as the average of ERA5-L solid to total precipitation ratio for the period 1981-2018

Summary of classification results:

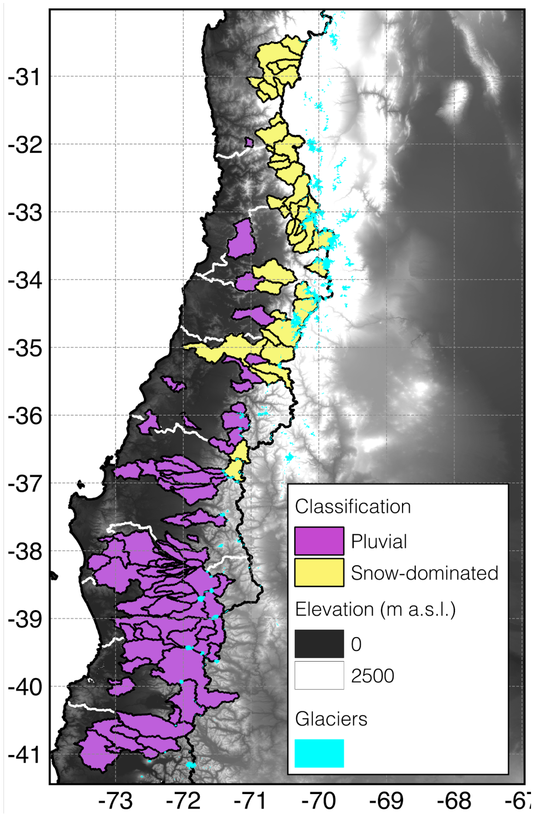


Cluster 1 (40 basins):
Proposed name: Snow-dominated
Main features: Higher snow fraction, higher streamflow summer seasonality (Qw_Qa_clim very low), higher precipitation winter seasonality (Pw_Pa_clim).

Cluster 1 (70 basins):
Proposed name: Pluvial
Main features: Lower snow fraction, higher winter streamflow seasonality (large Qw_Qa_clim values), lower winter precipitation seasonality (Pw_Pa_clim).

This revised nomenclature will be used across the complete manuscript. The classification procedure and the cluster results will be added as part of the study area description, in Sect. 2. The rest of the Figures from the manuscript will be reordered in order to keep consistency with this classification.

Below we provide the locations of the basins from the two clusters:



Reference: T. Kanungo, D. M. Mount, N. S. Netanyahu, C. D. Piatko, R. Silverman and A. Y. Wu, "An efficient k-means clustering algorithm: analysis and implementation," in IEEE Transactions on Pattern Analysis and Machine Intelligence, vol. 24, no. 7, pp. 881-892, July 2002, doi: 10.1109/TPAMI.2002.1017616.

3) Related to this, I think the authors can do a bit more to clarify the role of groundwater. On p.13 l.287-291, they state that soil properties and geology are important, but that these characteristics are commonly not available. However, the CAMELS-CL dataset does include information on these variables (and BFI) and I strongly encourage

the authors to include this in their analysis. How does the BFI based on modelled data relate to the BFI and soil and geological variables of CAMELS-CL?

Before addressing this comment, and by considering the comments related to BFI from Referee 2 as well, we want to emphasise that the modelled 'BFI' we computed from HBV is different from the BFI from CAMELS-CL:

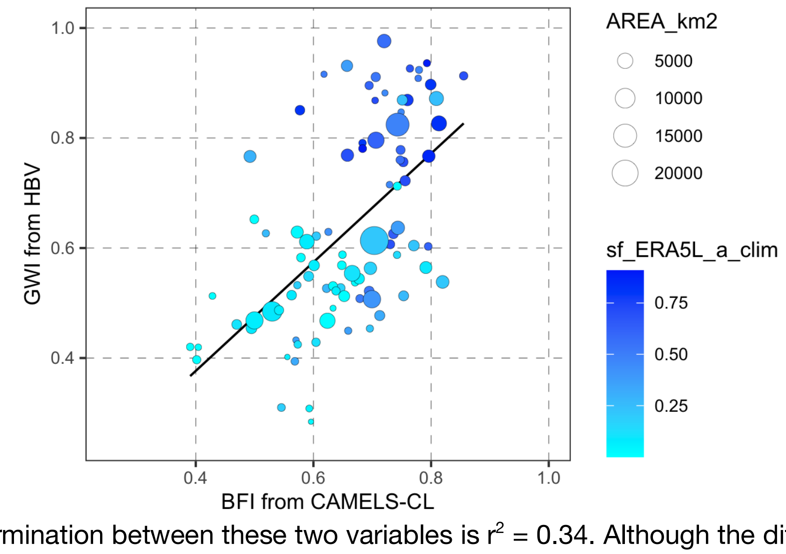
1) The BFI from CAMELS-CL dataset was computed as the ratio of mean daily baseflow to mean daily discharge. Hydrograph separation to compute daily baseflow was done by using Ladson et al. (2013) digital filter with α set to 0.925 (see Table 3, Alvarez-Garreton et al., 2018). The baseflow conceptualization refers to the dynamic components of the total runoff, where baseflow is the slow response to precipitation, while the quick flow (total flow minus baseflow) is the fast response to precipitation. This separation approach focuses on the response timing of an event; however, it does not explicitly indicate the source of the water (e.g., surface, shallow soil or deep soil).

2) The BFI from HBV presented in the manuscript was computed in this paper as the mean annual runoff from the lower GW reservoir, normalised by the mean annual runoff. By contrast to the BFI from hydrograph separation, the index computed from HBV represents the slow groundwater contribution to total streamflow. For this work, HBV was implemented with two soil boxes, the upper soil box represents faster groundwater release to total streamflow, and the lower soil box represents a slower groundwater release to total streamflow.

We realise that this different conceptualisations and computation of both BFI indices (which are not directly comparable), lead to confusion. To address this, and to emphasise the information provided by HBV groundwater boxes, in the revised manuscript we will name the HBV groundwater index (former BFI) as "GWI", which corresponds to the mean annual water coming groundwater at slower rates normalised by the mean annual streamflow.

Also, by following the Referee suggestion, in the revised manuscript we will include the BFI derived from CAMELS-CL in Section 2 (Study area and data). The text will be corrected throughout the manuscript. In addition, we will add a new section presenting the indices from HBV and the model performance, and how these relate with the two main catchment groups (snow-dominated and pluvial). The new Results Section will be named "4.3 HBV simulations and catchment runoff mechanisms".

The address the specific question of how BFI from CAMELS-CL and GWI from HBV relate, in the following Figure we plot the correlation between these two variables (colours correspond to snow fraction from ERA5-L data, and marker size corresponds to the basin area):



The coefficient of determination between these two variables is r^2 = 0.34. Although the difference of BFI and GWI will be discussed in the revised manuscript, this Figure will not be incorporated, since we do not think it helps to address the research objectives of the paper.

4) The difference between snow and groundwater storage should also be discussed more clearly in the Discussion section. On p.17 l.368-370, the authors now mention both groundwater and snow, but it is unclear to which catchments they are referring and whether both types of storages might occur in the same catchment. This is

important when they draw conclusions about the drivers for changes in RR relationships (for example on p.18 l.393-398), because the drivers are interrelated, like they also mention in the Conclusion (l.426-429). So, in a revised manuscript I would like to see a clearer discussion of the role of these two drivers and their interrelations.

We think the new classification scheme will help to clarify this point since both storages are present in snow-dominated, while only GW storages are present in pluvial basins.

Catchments in the snow-dominated group feature stronger hydrological memory beyond one year, and larger R-R shifts, which translate to progressive water deficits during multi-year droughts. On the other hand, pluvial catchments feature weaker hydrological memory and lower R-R shifts.

We agree with the Referee in that the GW and snow storages are interrelated, and we illustrate this in Fig. 6a. This plot indicates that for larger snow fraction (i.e., where snow storage is more important and more markedly dominates the hydrologic regime of a catchment), the larger the GWI is (i.e., larger portion of the total runoff comes from the deep GW storage). Please note that in this revision process, we have renamed the former BFI as GWI, to differentiate the BFI coming from CAMELS-CL and based on daily streamflow observations and the GWI computed from the HBV model (See our reply to general comment 3). In the revised manuscript, we will add these comments and clarification to the Discussion and Conclusions sections.

5) There is some unclarity about the period of the megadrought period investigated. Multiple years are mentioned, especially for the end year (2018/19/now). It is important to clarify this. It is currently for example, not clear which period your 8-yr average refers to. If you used data from 2010 to 2018, then this is a 9-year period. Different years / periods are also mentioned on, for example, l.11, 55, 128-129, 143, 150, 339, 417, 421. And in Fig.8 the MD seems to be 2007-2018. Please clarify the time period of the MD itself and which period of record you used for the analysis of the MD (I understand that these can be different).

Previous studies have identified the start of the MD in 2010. This MD has been characterised by consecutive years with precipitation deficits over a wide extension on the national territory (central and south Chile). We adopted the same initial start year (albeit the MD starts earlier in some regions), and we analysed the data up to the available date, since the MD is still present in most of the territory.

In the revised manuscript, we will add the recent hydrological year spanning from April 2019 to March 2020. Hence, the analyses now will include the extremely dry 2019, which featured precipitation deficits up to 90% in central Chile. Therefore, the MD period in the revised manuscript will be 2010-2019. We will clarify this in the revised manuscript.

6) The Discussion section needs to include a paragraph on the uncertainties in the HBV model and the classification decisions and how both of these could have influenced the results. As mentioned before, also a paragraph on anthropogenic influences should be added. I also suggest the authors to relate their work to that of Stoelzle et al. (2014).

Discussion about the classification scheme and the anthropic influence based on our previous replies will be added to the revised manuscript.

Regarding the uncertainties in HBV, we will add the following text into the discussion section:

As any hydrological modelling, our simulations using the HBV model are affected by different types of uncertainties including parameter uncertainty and model structure uncertainty (e.g. Uhlenbrook et al., 1999) and observation uncertainties (MicMillan et al., 2018). The HBV model with its simple structure does only allow for limited long-term memory effects. Actually, this is an interesting point of this study as simulation residuals can be interpreted as a consequence of this lack of more complex long-term memory effects.

McMillan, HK, Westerberg, IK, Krueger, T. Hydrological data uncertainty and its implications. WIREs Water. 2018; 5:e1319. https://doi.org/10.1002/wat2.1319

Uhlenbrook, S., Seibert, J., Leibundgut, Ch. and Rodhe, A., 1999, Prediction uncertainty of conceptual rainfall-runoff models caused by problems to identify model parameters and structure, Hydrological Sciences - Journal des Sciences Hydrologiques 44(5): 779-798.

7) I don't fully agree with the conceptualization of Carey et al. (2010) that catchments with lower storage are more resilient. You could argue that the opposite is true and those catchments are less resilient because they dry up immediately. Maybe the authors can add their view on this.

The concepts of 'resistance' and 'resilience' in Carey et al. (2010) are adopted from ecology, and may indeed be different to what we would interpret in hydrology. Here we provide some context on the conceptualisation of Carey et al. (2010), followed by our view on this.

From Carey et al. (2010):

"we define two functional traits of catchments taken from ecology: resistance and resilience (Folke et al., 2004; Potts et al., 2006). From a catchment perspective, resistance measures the degree to which runoff is coupled/synchronized with precipitation. Catchments that can store water over long time periods (months or years) and release water gradually to the stream have a high resistance, whereas catchments that systematically transfer precipitation into discharge have low resistance"

"Resilience measures the degree to which a catchment can adjust to normal functioning following perturbations from events such as drought or extreme precipitation. It is hypothesized that catchments with high resilience are able to sustain their expected precipitation–discharge relations in the light of changing inputs, whereas catchments with low resilience are sensitive to changes in inputs and exhibit enhanced threshold response behaviour."

"Catchments such as Strontian and HJ Andrews, where P >> S, have a higher resilience (P = precipitation, S = basin storage). This is particularly the case for Strontian where very low S (steep topography and thin soils) indicates that its functional relation between P and Q is insensitive to change. Conversely, catchments with low corr(Qmo,Pmo), higher S and lower P may exhibit decreased resilience, as changes in snow storage and soil storage can strongly impact the ability of the catchment to generate runoff".

Our view: The concept of 'resistance' defined by Carey et al. (2010) may be related to catchment hydrological memory, however, their concept of resilience may not be directly related to our approach. Relating the definition from Carey et al., (2010) with our analyses, a resilient catchment would be less prone to feature a shift in R-R relationship during the MD, and this would be the case for those basins where P>>S (i.e., P/S >>1), not necessarily where S is low. In fact, a catchment with low S can dry up quicker than others, as pointed out by the Referee, and this in turn may generate higher deficits during prolonged precipitation deficits. In order to highlight this, in the revised manuscript we will specify that the resilience conceptualisation from Carey et al. (2010) is based on P and S, and not only on the values of S. In this sense, our catchments featuring larger R-R shifts during the MD are related to a lower resilience, probably since P is very low, which does not mean that lower S is associated with higher resilience.

Specific comments

l.115-118: Please clarify how the distribution between semi-arid catchments was chosen. Was this based on literature, a random split, or an iterative analysis? Would your discussion of the results have been different if you would have chosen this split differently?

The initial catchment classification was based on typical regime differentiation in Chile, due the large rainfall gradient from north to south, but indeed this simple split (semi-arid & rainy) is not really the best choice regarding the purposes of this study. That's why now we use a classification scheme for snow vs. pluvial regime identification. Please see our reply to the general comment 2.

l.157: Please clarify how the two boxes were configured in HBV: in parallel or consecutive, and explain what the boxes represent and why this matches the situation in the catchments.

The HBV model was configured by two consecutive boxes, representing the soil upper zone and the soil lower zone. Each timestep a certain amount of water is percolating from the soil upper zone to the soil lower zone. The soil lower zone has one linear outflow, representing a slow groundwater flow (could be associated to a baseflow component from a hydrograph separation approach), whereas the soil upper zone has two linear outflows, representing intermediate and fast groundwater flow (could be associated to an intermediate and peak flows), of which the latter is only activated in case a certain water content threshold is exceeded.

l.164-167: I'm not convinced that HBV can correctly distinguish between soil and groundwater storage if it does not represent groundwater correctly (as explained by the authors due to the lack of drainage when streamflow ceases and because there is no surface runoff in the model so all precipitation excess and snow melt move through the soil and groundwater boxes).

Despite the limitations regarding HBV (or any other model), we do not think we can assess that HBV is not representing GW correctly. The model has fairly good performance across the different types of basins, the conceptualization of the model is representing the runoff mechanisms that are consistent with the hydrologic regimes we assessed from observations (i.e., from the classification scheme).

Despite the above limitations, the simulation of the runoff mechanisms from HBV allows us to further understand how water travels through the basins, how long does it take, and how these characteristics may relate to the intensification of drought propagation during the MD. We will add this discussion in the revised manuscript.

l.185: Why is 0.3 chosen to classify snow-dominated catchments? From literature? Have you done a sensitivity analysis on this number?

This is now part of the classification scheme. Snow-dominated basins are now characterised by high values of snow fraction and other regime features (precipitation and streamflow seasonality). Please see our reply to general comment 2).

l.187: I'm assuming that you used modelled streamflow to calculate BFI?

Yes. But we have changed the name of the former BFI computation, to avoid confusion with the BFI from CAMELS-CL. This new nomenclature will be presented in the new section 4.3 ("HBV simulations and catchment runoff mechanisms"). Please refer to our reply to general comment 3.

l.279: High model efficiencies are not a surprise in snow-dominated catchments with a clear seasonal regime. Please discuss this.

The model efficiencies are computed for daily time series. We will add further discussion to model performance metrics in the new section 4.3. ("HBV simulations and catchment runoff mechanisms"). Please refer to our reply to general comment 3. Below we provide a plot showing the NPE and KGE for the two types of basins: snow-dominated and pluvial. This Figure shows that there are no significant differences in model performance among the pluvial and snow-dominated basins.

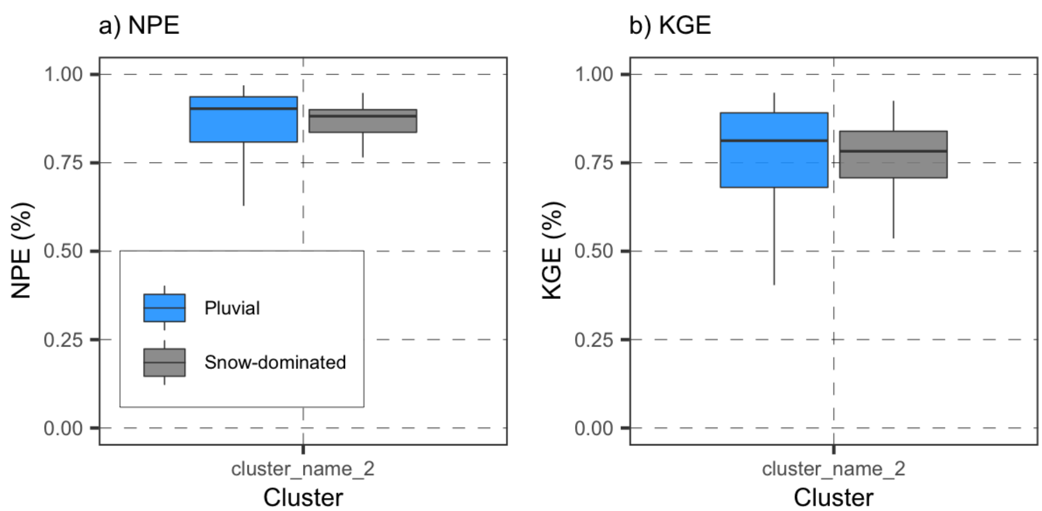


Fig.7: It would be interesting to explore a bit more the catchments that deviate from the pattern, for example the ones north of 36 degrees that have lower correlations then their neighboring catchments. Would this be related to effects of groundwater or anthropogenic influences? Please explore.

The basins of this figure will be re-ordered based on the group they belong to (snow-dominated, mixed or pluvial), thus the pattern will be not the same as the submitted manuscript. Nevertheless, we will explore a couple of basins deviating from the pattern.

l.349-351: Here you mention ET as an important factor. This is an important point that could be highlighted more, especially since ET during the recent MD is probably larger than during earlier 8-yr periods because of climate change. This should be discussed more in the Discussion section. I was also wondering why you see the effect of ET only in the temperate catchments and not in the semi-arid ones? These would correspond more to the Australian catchments Saft used in her analysis.

We agree with the Referee in that ET may contribute to the observed changes in catchment response during the MD. For similar precipitation deficits than the historic period (1979-2009), larger ET anomalies during the MD modulated by the higher temperatures for some years during the MD may lead to lower runoff generation, when compared to the historical period.

To include a deeper discussion on ET, we will add a third panel in Fig. 3 with the 8-year averages for ET within the study catchments. We will further discuss these results in the discussion as well.

l.358-362: Fig.9 needs more explanation in the text. The results presented in Fig.9 are now only mentioned in the Discussion section (l.399-404). This should be moved to the Results section. Also, how have the three cases been defined, per catchment or overall? I'm wondering whether the drought/wet years are actually the same in central and south Chile.

We will add further discussion on the results in Figure 9. In the submitted manuscript, the years of extreme droughts were selected with an overall approach, i.e., when conditions were met for more than half of the basins: mean precipitation anomalies below -50% in semi-arid basins and mean precipitation anomalies below -25% in temperate basins, preceded by a wet year (mean precipitation above average) or preceded by a dry year (mean precipitation below average).

As the Referee points out, there have been years where meteorological droughts are not experienced within the complete domain, as can be seen from Figure 2a and 2c (e.g., for the years 1979, 1981, 1983, 1994, 1995). After 1996 however, most meteorological deficits have been observed throughout the complete study domain.

The Figure will be modified based on the new classification scheme.

l.435-436: These catchments also have less ET.

Pluvial basins in southern Chile are generally wetter and then have more ET, but a lower evaporative fraction (ET/P). This will be added in the indicated text.

Technical corrections

Would the title not be better as "during a multi-year drought" (singular) as the plural suggests that multiple drought periods like the MD were analysed.

While the R-R shifts were analysed during the MD, the extremes vs persistent droughts (section 4.5) analysed other years and periods with consecutive precipitation deficits, not only the MD. In this way, our conclusions relating hydrological memory with progressive water deficits or intensification of drought propagation, are drawn for the general case of consecutive precipitation deficits, despite the specific insights we gained from the MD period.

I would suggest to check the English throughout the manuscript. There are quite a lot of issues with prepositions, for example on l.113-117, 174, 193, 234, 237, 325.

The complete manuscript will be proof read to correct typos and grammar issues.

l.24: dependant > dependent

Corrected.

l.20-23: add latitudes to central and southern Chile so that the abstract is understandable on a standalone basis. Also, when you talk about snow-dominated or semi-arid regions, please add where they are located.

Latitudes will be added to the abstract. The grouped basins will be defined by classification (see our reply to general comment 2), and their locations will be provided in the abstract.

l.43: why "potential" drought propagation?

Deleted from text.

l.56: what do you mean with "global changes"?

We used the term global changes to refer to changes not only related to global warming, but also to other anthropic-related changes, such as land cover land use changes, intensification of irrigated agriculture, etc.

l.108: "less than 100 mm in the north"

Corrected.

l. 129: "we compared them..." > what do you mean with "them"? Do you mean a value for each catchment?

Corrected. "We compared the 8-year mean values during the MD with historical eight-year average values"

l.143: 1018 > 2018

Corrected.

l.163: simulated > simulate

Corrected.

l.181: remove "then"

Corrected.

l.195 & 338-339: catchments memory > catchment memory

Corrected.

l.200: 1979-2018

Corrected.

l.201: are evident

Corrected.

Fig.2: the non-linear y-axis is confusing. You mention in the caption that each line is a catchment, but it would be helpful to indicate this on the figure axis as well.

We will clarify this in the Figure axis. Additionally, the catchments will be ordered now by their classification groups, and not by latitude.

l.223: what do you mean with “up to 90% of streamflow deficits”? Do the extremely dry years have streamflow deficits up to 90% or do 90% of streamflow deficits classify as extremely dry? Explain more clearly in the Methods section how you have calculated the deficit in % (% of what?).

We will rewrite the sentence as *“(up to 90% of streamflow deficits with a median of 57%)”.*

In Section 3.1 we explained that relative anomalies were computed as: “We computed relative anomalies of hydrological years (April-March) as deviations from climatological means (period 1979-2009, i.e., excluding the MD), normalised by the climatological mean of each time series.” We will add the following equation to avoid confusion:

Qa_anom = 100* (Qa - Qclim) / Qclim, where Qa is the annual streamflow and Qclim is the mean annual streamflow for the period 1979-2009.

Fig.3: So the boxplots exclude the MD, so only cover the period 1979-2009? Please add this in the caption.

We will add this to the Figure caption.

l.233: “presenting 8-year mean runoff”

Corrected.

l.246: “negative shift; that is, ...”

Corrected.

l.278-279: “values of 0.72, ...” > values of what? Nash-Sutcliffe model efficiency?

The performance statistic we used for calibration was the non-parametric variation of Kling-Gupta efficiency, NPE. This will be added to the text.

Fig.7: Are bar-plots the best way to visualize this? I’m assuming that the blue-grey bars are when the blue ones are below the grey, but what about the green bars then? Why not just use points?

We will try different points/bar combinations in order to help visualisation in this figure.

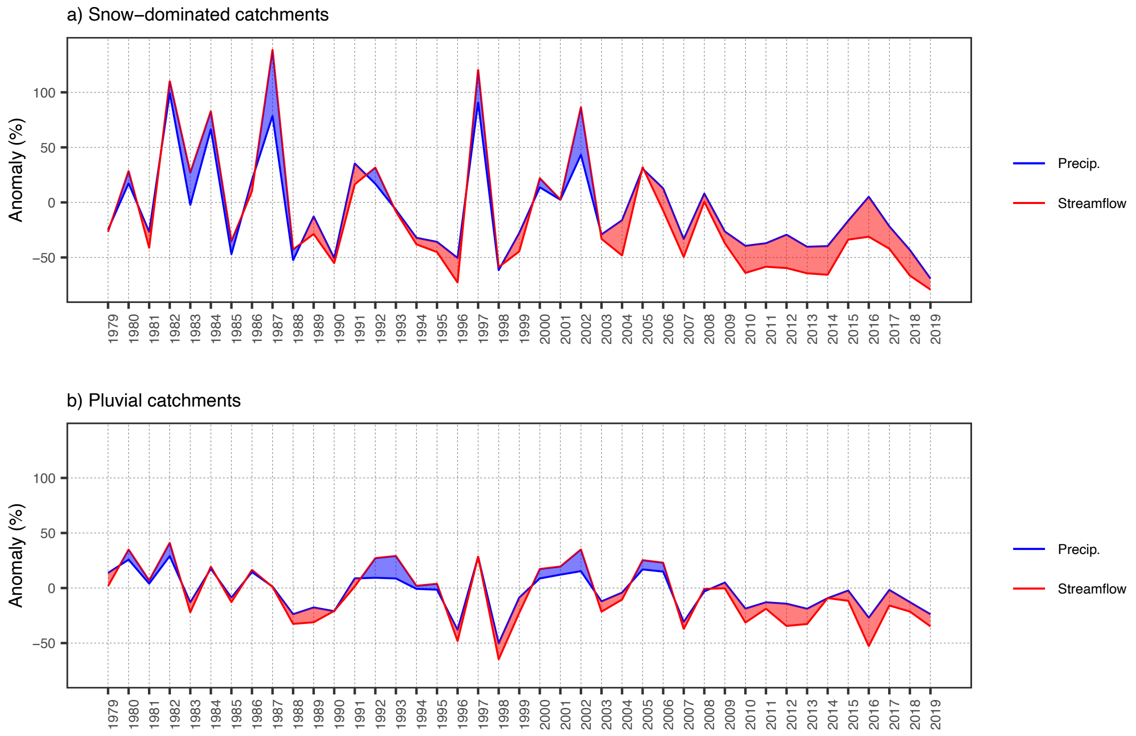
l.319: should “from the previous year” be moved forwards to after “the precipitation”? Precipitation does not influence previous year streamflow, does it?

Yes. This was a mistake. We will correct the text accordingly.

l.330: “the difference between runoff and precipitation deficits” on a yearly basis? Fig.8: how have dry years been defined?

Yes, yearly basis. We will add this to the text. In the submitted manuscript, years were selected when mean precipitation deficits were larger than 25% for any of the two basins groups over the last four decades

In order to better visualise the drought propagation and recovery, we will replace the discretisation in Fig. 8 by a plot with continuous years, as the Figure below, where average annual anomalies of precipitation and streamflow for the snow-dominated basins and pluvial basins are presented. The area between the two curves is coloured in blue when the streamflow anomaly is larger than the precipitation anomaly, and in red if not. This Figure, along with the corresponding Caption and explanation, will replace Figure 8.



l.361: persistent > multiple (two and more)?

We will specify the range considered in this case: *“iii) persistent years (2 up to 4 consecutive years) with precipitation anomalies below -5%.”*

Fig.9: Panel a > a) and b), panel b > c) & d)

We will reorder the panels as suggested, and will also include the two types of catchments.

l.403: result > results

Corrected.

l.449: dependant > dependent

Corrected.

l.453: catchments response > catchment response

Corrected.

References

Carey, S. K., Tetzlaff, D., Seibert, J., Soulsby, C., Buttle, J., Laudon, H., McDonnell, J., McGuire, K., Caissie, D., Shanley, J., Kennedy, M., Devito, K. and Pomeroy, J. W.: Inter-comparison of hydro-climatic regimes across northern catchments: Synchronicity, resistance and resilience, Hydrol. Process., 24(24), 3591– 3602, doi:10.1002/hyp.7880, 2010.

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Referee #2, Gemma Coxon:

This paper tackles an interesting topic of multi-year droughts in Chile using a large-sample dataset CAMELS-CL. It first analyses observed streamflow and precipitation data to identify shifts in rainfall-runoff behaviour during the megadrought and then explores the role of hydrological memory in controlling drought propagation intensity using simulations from HBV.

Overall I enjoyed reading this paper – the figures are very well presented, it tackles an interesting topic and there are a range of analyses to support the conclusion. However, the paper needs to discuss in more detail the limitations of the study, greater clarity is needed in the methods section and the key messages of the paper could be better highlighted. Below are my suggestions and comments, I have a couple of general (more major) comments and then a series of minor comments.

We thank the reviewer for her positive and constructive comments.

General Comments

1) Limitations. I was missing a broader discussion of the limitations of the study in the discussion section. The authors mention the absence of physical factors in the analysis (L390-392) but the authors should also discuss

(i) human impacts in these catchments – I appreciate this study focuses on physical processes but humans can also play a large part in the intensification of drought propagation. Consequently, it is important to state how human-impacted these catchments are and whether human activities increased during the mega drought (particularly if groundwater abstractions increased because of deficits in streamflow).

We agree with the Referee in that the local anthropic activities within the catchments may play an important role in drought propagation, and that the current manuscript does not deepen on this point. We have addressed this limitation in the revised manuscript, describing the current state of human activities within the basins, and highlighting the data limitations that define the scope of a robust anthropic analysis within the paper. Please refer to our reply to the general comment 1 from Referee 1.

(ii) evapotranspiration – there is a brief analysis of ET in Section 4.4, but a limitation of this study is the absence of any detailed analyses on ET or temperature. Given their role for snow processes and intensification of drought, this is an important missing process from the analysis. The figure in the supplementary info showed high ET anomalies for the semi-arid catchments which had large RR shifts.

We agree with the Referee in that ET may contribute to the observed changes in R-R response during the MD. For similar precipitation deficits than the historic period (1979-2009), larger ET anomalies during the MD modulated by the higher temperatures for some years during the MD may lead to lower runoff generation, when compared to the historical period.

Please see our reply to the Specific comments from Referee 1 where we discuss how we will address ET analysis in the revised manuscript.

2) HBV Modelling. Given the richness of the CAMELS-CL dataset, I was a little surprised that the authors went down the route of extending the analysis with a model (as great as HBV is!) rather than further exploring the meteorological (e.g. ET), physical (e.g. soils, geology, land cover) and human impact characteristics of these catchments to explain the R-R shift in the megadrought.

In addition to exploring drought propagation only by using the CAMELS-CL dataset, we decided to incorporate a hydrological model in order to address two main challenges of the analysis. Firstly, we aimed at improving our current understanding on runoff mechanisms from a process-based perspective. In particular, we aimed at assessing the role of snow and GW in runoff generation. Secondly, a process-based model overcomes some of the limitations of diagnosing the progressive water deficits only from the shift in annual R-R relationships. Recall that our hypothesis is that catchments with stronger hydrological memory (i.e., longer-than-a-year memory) feature progressive water deficits during multi-year droughts. In testing this hypothesis, a process-based model that is able to capture this memory should better simulate the observed progressive deficits, compared to the simulations from R-R regressions that only consider the precipitation of the same year.

Regarding the factors that the Referee suggest to further explore, we agree with all of them, and below we explain how each will be included in the revised manuscript:

(i) Meteorological data: the ET information will be further analysed in the revised manuscript (please see our previous reply).

(ii) Physical data (geology, soils and land cover): in the revised manuscript, we will provide a description of the catchment geological properties based on CAMELS-CL dataset. It should be noted that CAMELS-CL does not include soil properties. Land cover dataset are discussed in the following point (as part of human-related datasets)

(iii) Human-related datasets: As we explained in our reply to the general comment 1 from Referee 1, there are some limitations in the CAMELS-CL human-related datasets, related to the lack of land cover characteristics prior 2016, and the lack of human intervention characteristics prior the MD. In our opinion, these limitations should be overcome before we can attribute the R-R shifts to anthropic activities. Based on these limitations and on the scope of the paper, in the submitted manuscript we focused on the runoff mechanisms to understand the R-R shifts, which we hypothesise are among the key factors explaining the progressive water deficits during the MD. Notwithstanding this, in the revised manuscript we will incorporate a description of the current state of land cover and human intervention within the basins, as well as a discussion of their potential impacts on drought propagation.

You could have used BFI from CAMELS-CL for Figure 6 and calculated baseflow contributions from the observed flow time series for the analysis in Figure 7.

The Referee coincides with the first Referee regarding the use of BFI from CAMELS-CL in the analysis. In the revised manuscript, we will incorporate these data to the analysis (please see our reply to the general comment 3 from Referee 1).

The Referee is right, both figures relating baseflow to the hydrological memory (Fig. 6) and precipitation (Fig. 7b) could be generated based on the CAMELS-CL BFI and on the baseflow contributions computed from the digital filter applied to the observed streamflow in CAMELS-CL, respectively. However, we think that a process-based estimation of seasonal groundwater contribution to total runoff (i.e., GWI from HBV, which is the new nomenclature adopted to avoid confusion with BFI indices, as explained in our reply to the general comment 3 from Referee 1) is a better representation of the slow contribution from groundwater than the digital filter with a fixed α parameter used in CAMELS-CL. This in turn should be better related to the hydrological memory of a catchment.

The authors need to:

(i) better clarify the contribution of the modelling to the paper

In the revised manuscript, we will add the reasons for incorporating a process-based model to the analysis, as explained above.

(ii) better clarify where outputs from HBV are used in the analysis, particularly where observed streamflow or modelled streamflow is used throughout the text.

We will clarify where the outputs from HBV are used.

(iii) comment more broadly on the uncertainties and limitations of HBV in the discussion

We will add the suggested discussion. Please see our reply to general comment 6 from Referee 1.

3) Classifications. There are lots of different classifications of catchments (snow-dominated/pluvial basins in Figure 5, semi-arid/temperate in Figure 8) which is very confusing for the reader. I would use one classification and keep it consistent throughout the paper.

We agree with both Referees regarding the way the study catchments are classified, leading to confusion when different classifications are used. The revised manuscript will include a single snow/pluvial regime characterization based in an objective classification scheme. Please refer to our reply to the general comment 2 from Referee 1.

Minor Comments (in order of appearance in paper)

Abstract L16. "mediated by groundwater flows" – not just groundwater flows but surely storage in snow packs too?

Yes. This will be corrected in the revised manuscript.

Section 2 L89-90. There are multiple rainfall and PET products available in CAMELS-CL, it would be helpful to specify exactly which hydrometeorological data products you used from the dataset.

The Referee is right, this info was missing in the text. We have used the CR2MET product, which was updated until 2019 for this work. We will specify which dataset was used.

Section 2 L92-97. The infilling of the flow time series is currently not clear in the paper and I have a number of questions related to this. CAMELS-CL provides daily flow timeseries (as far as I am aware), which I then assume you aggregate up to monthly and then annual values for the rest of the analysis.

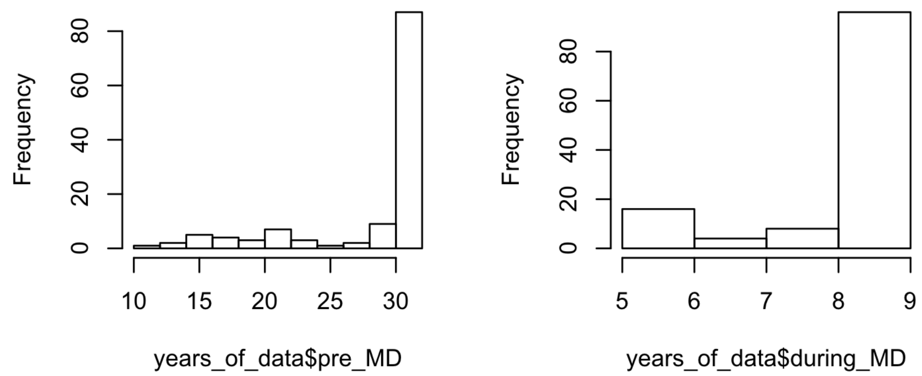
Yes, correct.

So how do you define a month where there is no streamflow data – does this mean all days from that month are missing or a threshold of xx days? Do you calculate a sum of the daily flow in that month or take a mean (a mean would be less sensitive to missing data)?

In CAMELS-CL, monthly streamflow values are calculated when 15 or more days per month have valid data. If >15 days are available, a mean monthly value is obtained as the average of the available daily streamflow. This mean monthly streamflow is then aggregated into the total number of days within the month to get total monthly runoff.

Why did you select gauges with 15 years of data, is this really sufficient coverage of the period 1979- 2018?

The 15 years threshold was chosen in order to have a minimum of points during the MD for the R-R shifts analysis. We filtered out those basins with: 1) less than 5 years of data within the MD and ii) less than 10 years of data before the MD. Although this criterion implies a minimum threshold of 15 years, the basins that fulfilled this criterion have more than 15 years of data. Below we provide the histograms of number of years with data for each basin, for the period before the MD (1979-2009, left panel) and during the MD (2010-2018, right panel):



In summary, 70% of the study catchments (87 out of 124) have 30 years of data in the historical pre-MD period. During the MD period, 77% of the catchments (87 out of 124) have 9 years of data. Thanks for pointing this out, we will clarify these results in the revised manuscript.

What was the highest number of months that needed to be gap filled for a single station?

The gap filling scheme includes several parameters, including a minimum number of valid observations, in this case set to 75% of the target period (1979-2019). That is, a station can be potentially filled up if all gaps do not exceed 25% of the period. Each missing month is then independently assessed based on a number (ensemble) of multivariate models that use covariant records from other stations as predictors. A given linear model is used if it shows a predictive power (R2) larger than 0.75.

Section 2 L108 change to “from less than 100 mm to the north to more than 3000 mm in the ..”

Corrected.

Figure 1. Given the focus on groundwater dynamics you need a map of geology in Figure 1 and a description of the geology of Chile in the study description.

Geology map will be added to Figure 1. And the geology of the study catchments will be discussed based on the clusters they belong to.

Figure 1 Caption. You need to add the source of the precipitation and temperature value either into the figure caption or the text.

Added.

Section 3.1 L128. Was there a reason for choosing 8 years to calculate the mean flux?

We chose this number to be conservative with the missing streamflow data during the MD. However, by arguing that 77% of the basins have 9 years of data during the MD (see our histograms in the previous reply), we will change this into 9-year mean values (i.e., periods equally long as the MD).

Figure 3. The red dots are quite hard to see – it may be worth increasing the size of the red dot or perhaps trying a red cross instead?

We will try a different configuration in the revised manuscript to improve visualisation.

Figure 6. I was a little confused how Figure 6 was created – is this an average from all the snow- dominated and pluvial basins? Are Q, BF and snowmelt derived from HBV for this plot?

Fig. 6 shows all the catchments together. We will clarify which variables come from the HBV model and which ones from observations.

Section 4.3. You used HBV to calculate the baseflow index. Exactly how did you calculate the baseflow index and how does this value of baseflow index differ to the baseflow index calculated from observed streamflow and provided in CAMELS-CL.

Please see our reply to general comment 3 from Referee 1 where these questions are addressed.

Figure 7. I found the overlapping bars in Figure 7 quite confusing to interpret – have you thought about an alternative way to visualise these results as currently Figure 7a and 7b are quite difficult to interpret. Also is this seasonal runoff and baseflow analysed over the whole time period (i.e. from 1979-2010)?

We will try different plot combinations in order to help visualise this figure.

Seasonal correlations were computed for the complete period of record (1979-2019 in the revised manuscript), i.e., including the MD. This will be clarified in the revised manuscript.

Section 4.4 L329. “Figure 8 presents drought propagation for 25 years with negative anomalies over the last four decades”. Do you mean negative anomalies in P and/or Q deficits? Or negative anomalies in the difference between runoff and precipitation deficits? If it is the latter then not all those years have negative anomalies (i.e. there are some years where the red dot is above 0%).

We meant negative anomalies in precipitation, although this was not very clear in the text. We decided to replace Fig. 8 by time series plots showing precipitation and streamflow anomalies for the snow-dominated and pluvial basins. Please see our reply to technical correction from Referee 1.

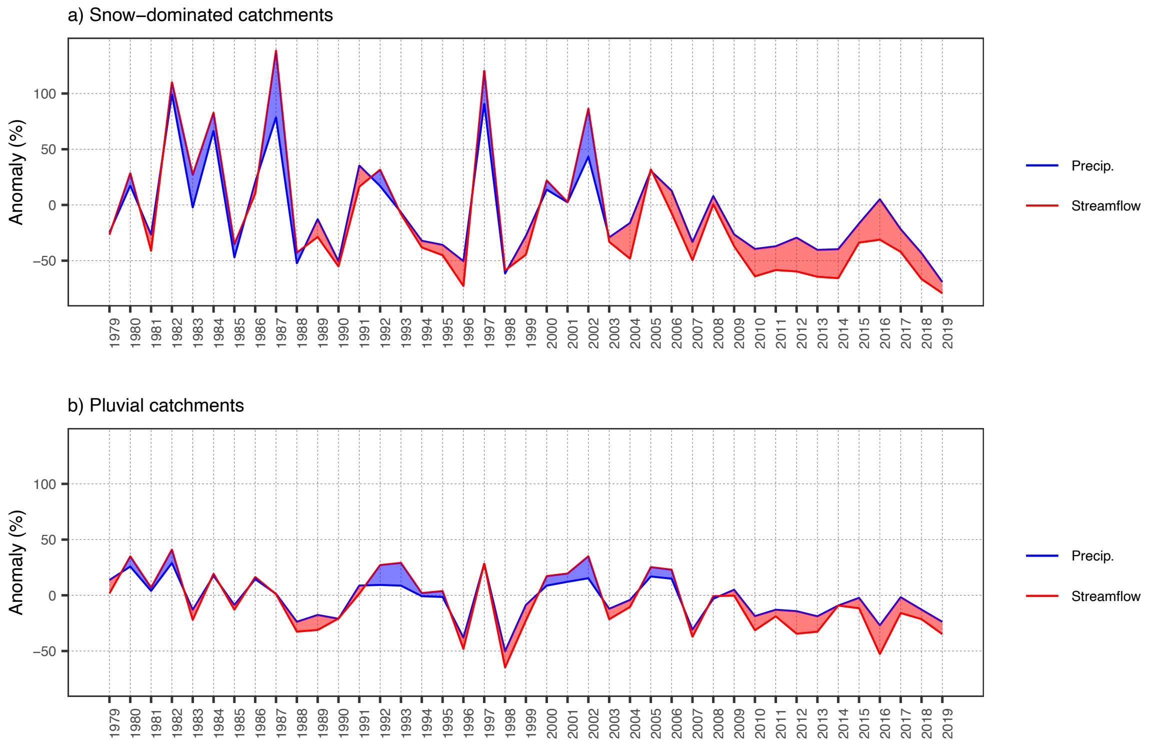


Figure 9. The text in L358-362 is essentially just a description of the figure and there should be some analysis of the results of Figure 9 here (currently, the analysis of the results is confusingly mixed into the discussion). The figure caption also needs to be more informative i.e. it refers to panel a and b but there are subplots a-d in the plot, not really clear what Q-Pred R-R is or the number of cases or what ‘1’, ‘2’, ‘3’ and ‘4’ relate to on the x-axis of Figure 9b and 9d.

This comment is in line with Referee 1 regarding the analysis of this Figure. We will move the description of results from the Discussion into the Results Section. Captions will be corrected.

Discussion L370. Do you mean baseflow contribution to runoff – rather than low flow? Discussion L397. What do you mean by “higher resistance”?

The concept of resistance was included in the discussion of Carey et al., paper. We have clarified this point in our reply to general comment 7 from Referee 1.

Conclusions. There is a lot of different analyses in this paper but the key message and results tend to get a little lost. I suggest to significantly shorten the conclusions – there is a lot of repetition in this section and removing it would better highlight the core results.

The conclusion section will be condensed, deleting repetitions.

Supplementary Material. Figure S1 needs a figure caption.

Caption will be added.

Progressive water deficits during multiyear droughts in basins with long hydrological memory: the case of Chile.

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Abstract. A decade-long (2010-2020) period with precipitation deficits in central-south Chile (30-41ºS), the so-called megadrought (MD), has led to streamflow depletions of larger amplitude than expected from precipitation anomalies, indicating an intensification in drought propagation. We analysed the catchment characteristics and runoff mechanisms modulating such intensification by using the CAMELS-CL dataset and simulations from the HBV hydrological model. We compared annual rainfall-runoff (R-R) relationships before and during the MD across 106 basins with varying snow/rainfall regimes and identified those catchments where drought propagation was intensified. Our results show that catchments' hydrological memory -modulated by snow and groundwater- is a key control of drought propagation. Snow-dominated catchments (30-35ºS) feature larger groundwater contribution to streamflow than pluvial basins, which we relate to the infiltration of snowmelt over the Western Andean Front. This leads to longer memory in these basins, represented by a significative correlation between fall streamflow (when snow has already melted) and the precipitation from the preceding year. Hence, under persistent drought conditions, snow-dominated catchments accumulate the effects of precipitation deficits and progressively generate less water, compared with their historical behaviour, notably affecting central Chile, a region with limited water supply and which concentrates most of the country's population and water demands. Finally, we addressed a general question: what is worse, an extreme single year drought or a persistent moderate drought? In snow-dominated basins, where water provision strongly depends on both the current and previous precipitation seasons, an extreme drought induces larger absolute streamflow deficits, however persistent deficits induce a more intensified propagation of the meteorological drought. Hence, the worst scenario would be an extreme meteorological drought following consecutive years of precipitation below average. In pluvial basins of southern Chile (35-41ºS), hydrologic memory is still an important factor, but water supply is more strongly dependant on the meteorological conditions of the current year, and therefore an extreme drought would have a higher impact on water supply than a persistent but moderate drought.

1 Introduction

Persistent climatic anomalies may alter catchment response to precipitation. Thus, catchment dynamics under unusually multiyear precipitation deficits might not be correctly predicted based on the interannual variability over the last decades. This applies even when past decades include severe, but shorter dry conditions (Saft et al., 2016a). In other words, stationarity as commonly assumed for streamflow projections under climate change might be an invalid assumption (Blöschl and Montanari, 2010), which poses challenges for achieving realistic structures and parameters in hydrological models (Duethmann et al., 2020; Fowler et al., 2016).

Non-stationary catchment response modulates hydrological functioning. This applies particularly to drought propagation, i.e., the process leading to soil moisture droughts and hydrological droughts (streamflow and groundwater deficits) under meteorological dry conditions (Van Loon et al., 2014). While meteorological droughts are mainly controlled by regional precipitation, soil moisture and hydrological droughts are also controlled by catchment characteristics. Therefore, under similar meteorological conditions, the severity of hydrological droughts can vary significantly within a climatic region (Van Lanen et al., 2013). Most drought-related impacts on, for instance, agriculture, ecosystems, energy, industry, drinking-water and recreation depend primarily on groundwater and streamflow deficits (Van Loon, 2015). Therefore, understanding the geographical variation in drought propagation provides critical information for drought-hazard adaptation and mitigation (Van Loon and Laaha, 2015). In addition to such spatial variability, non-stationary catchment responses to precipitation would lead to a temporal variation in drought propagation.

This temporal aspect is becoming increasingly important since many regions around the globe are experiencing unprecedented long dry spells due to climate and circulation changes, causing unforeseen impacts on water supply (e.g., Schewe et al., 2014). Recent evidence has shown that protracted droughts may propagate differently within the same catchment (i.e., same landscape characteristics and governing runoff mechanisms) under similar precipitation deficits and temperature anomalies than shorter dry events. For example, studies in south-eastern Australia have reported changes in catchment functioning (Fowler et al., 2018; Saft et al., 2015; Saft et al., 2016b; Yang et al., 2017) during the Millennium drought that took place for more than a decade (1997-2010). More recently, Garreaud et al. (2017) reported an unprecedented decrease in annual runoff during a multiyear drought in central-south Chile, the so-called megadrought (MD). The amplified response of streamflow to a drought signal may be due to variations of drainage density related to depleted groundwater levels within the catchment (Eltahir and Yeh, 1999; Van De Griend et al., 2002), a factor also emphasised by Saft et al. (2016b).

The MD experienced in Chile since 2010 (and continuing up to date) offers a great opportunity to understand the potential impacts of global changes on hydrology and water supply over wide ranges of hydro-climatic regions and landscape characteristics. The persistency and geographical extension of the MD have few analogues in the last millennia, and its causes have been partially attributed to anthropogenic climate change (Boisier et al., 2016, 2018; Garreaud et al., 2017, 2019). This uninterrupted sequence of years with precipitation deficits has impacted various sectors, including coastal ecosystems (Masotti et al., 2018), natural vegetation (Arroyo et al., 2020; Garreaud et al., 2017), fire regimes (Gonzalez et al., 2018) and water supply (Muñoz et al., 2020).

To deepen the understanding of the impacts of persistent droughts on water supply, we explore the mechanisms causing the larger-than-expected hydrological deficits in central-south Chile during the MD. We complement previous analyses of the MD in Chile (Garreaud et al., 2017; Muñoz et al., 2020) by incorporating four more years to the MD period, and by focusing on drought propagation over 106 catchments located between 30ºS and 41ºS. The conceptual framework of our analysis is based on the water balance within a catchment, where the water sourced from precipitation takes different flow pathways and is temporally retained in various stores. In this scheme, the composite of response times associated to the different physical mechanisms transferring and storing water through the basin is referred as hydrological memory (Fowler et al., 2020).

For a dry year within a long drought, we can distinguish three cases: i) stationary drought propagation, when the streamflow deficits are similar to those observed in isolated years (single year drought) with similar precipitation deficits; ii) intensified drought propagation, when streamflow deficits are larger than those observed in years with similar precipitation deficits; and iii) attenuated drought propagation, when streamflow deficits are lower than those observed in years with similar precipitation deficits. Based on previous studies relating groundwater dynamics to non-stationary catchment response to droughts (Carey et al., 2010; Eltahir and Yeh, 1999; Fowler et al., 2020; Saft et al., 2016b) we hypothesise that in catchments with longer hydrological memory (i.e., catchments where water is retained for longer time in different storages such as aquifers and snowpack), the propagation of drought during multiyear precipitation deficits is intensified (i.e., larger streamflow deficits than those observed in years with similar precipitation deficits), when compared to single dry years.

To test this hypothesis, we characterised the historical precipitation and streamflow deficits at the catchment scale, and followed Saft et al. (2015) to evaluate annual rainfall-runoff (R-R) relationships and identified those catchments where drought propagation during the MD was maintained, intensified or attenuated with respect to their historical behaviour. We analysed catchment memory from observed hydrometeorological data and from the hydrological processes simulated by a bucket-type model calibrated for each basin. We related catchment hydrological memory with shifts in R-R relationships during the MD, and with drought propagation for different types of drought, from extreme single year droughts to moderate but persistent droughts (including the MD). Finally, we addressed a general question with practical implications: what is worse in terms of water supply, a single year with extreme precipitation deficits, or several consecutive years with moderate deficits?

2 Study region and data

The study area corresponds to central-south Chile, spanning 9 out of 16 administrative regions between 30ºS and 41ºS (Fig. 1). Hydrometeorological data was obtained from the CAMELS-CL dataset (Alvarez-Garreton et al., 2018), including catchment-scale daily precipitation from the CR2MET precipitation product (DGA, 2017) and streamflow time series for the period April 1979 to March 2020. Following the precipitation, snowmelt and runoff seasonality, spanning from austral autumn to the summer of the following calendar year, the hydrological year in the study domain is considered from April to March.

Monthly streamflow values were computed when 15 or more days had valid data. For those months, a mean monthly value was computed from the available daily values, and then aggregated into the total number of days within the month to get total monthly runoff. Subsequently, gaps in monthly streamflow time series were filled up based on a procedure previously used for monthly precipitation data (Boisier et al., 2016). The method uses multivariate regression models, taking advantage of the streamflow co-variability among multiple gauging stations in the study region (within or across basins). In this procedure, a station can be potentially filled up if its missing data do not exceed 25% of the period. Each missing month is then independently assessed based on a number (ensemble) of multivariate models that use covariant records from other stations as predictors. A given linear model is used if it shows a predictive power (determination coefficient, r^2) larger than 0.75. Annual streamflow values were computed when all monthly values were available.

We computed catchment-scale solid to total precipitation fractions and daily estimates for snowmelt over the period April 1981 to March 2020 based on the ECMWF surface reanalysis ERA5-Land dataset, available at a spatial resolution of 9 km (Muñoz-Sabater, 2019).

Hypsometric curves for each catchment, required for implementing the hydrological model (Sect. 3.1.2), were processed based on ASTER GDEM (Tachikawa et al., 2011).

The CAMELS-CL dataset includes catchment characteristics such as topography, geology and hydrological signatures including the baseflow index representing the slow catchment response to precipitation. The anthropic-related data provided include land cover for the year 2016, the location of reservoirs, and granted water used rights within the basins.

From the 327 catchments located between 30ºS and 41ºS (Alvarez-Garreton et al., 2018), we selected 106 for this study based on the following criteria: i) filtering out catchments with reservoirs to exclude effects of dam operations in runoff observations (56 basins excluded), ii) filtering catchments with more than 10% of their areas covered by glaciers to exclude the effects of glacier contribution in the propagation of droughts (5 basins excluded), iii) filtering out catchments with less than 30 years of streamflow observations (96 basins excluded), and iv) filtering out catchments where the annual rainfall explained less than 50% of the variance in annual runoff ($r^2 < 0.5$ in R-R regressions from Sect. 3.2.2; 64 basins excluded)).

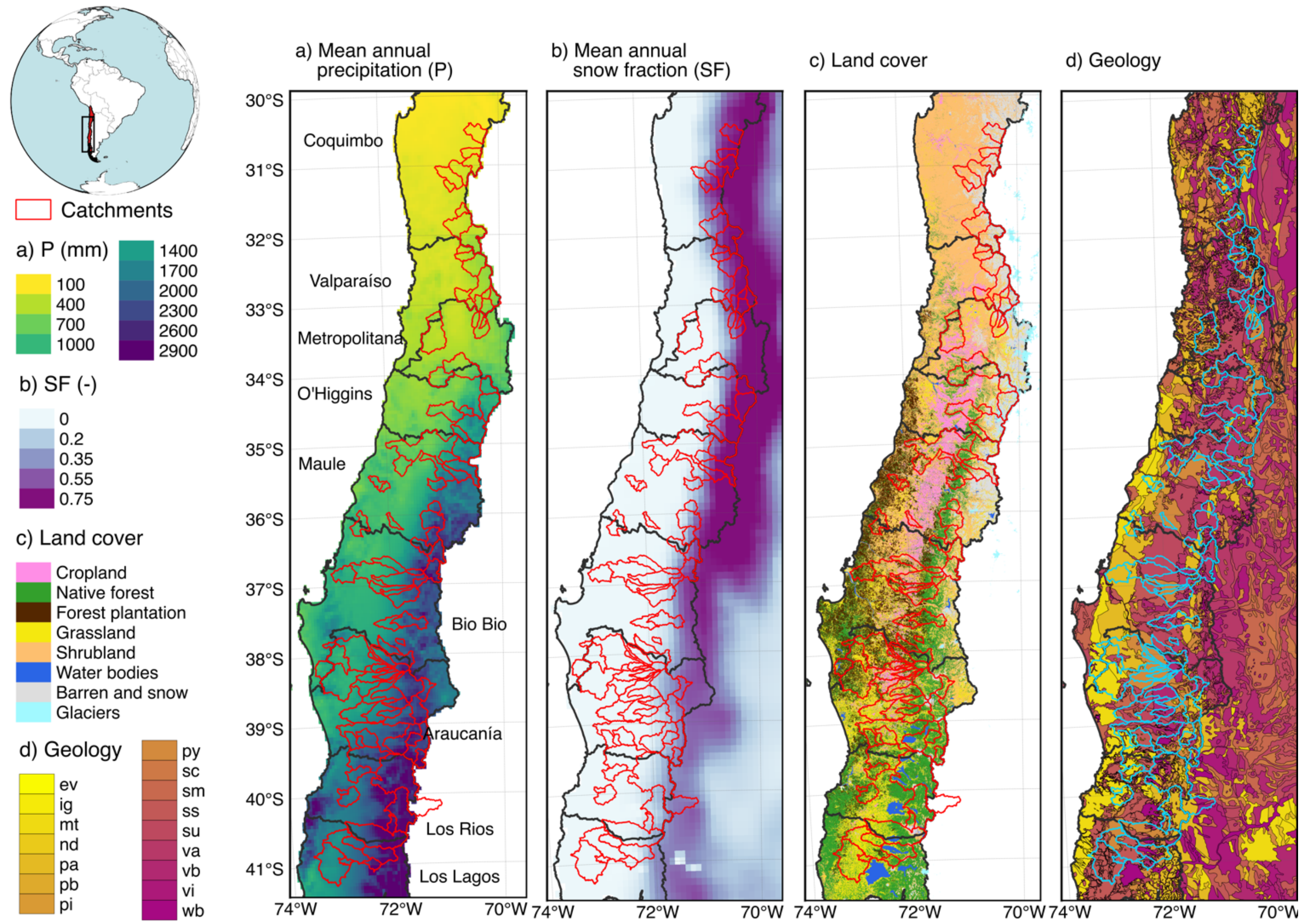

Figure 1: Characteristics of the study domain and location of catchments. Panel a shows the mean annual precipitation from CR2MET gridded dataset and the 9 administrative regions covered by the study. Panel b shows the mean annual snow fraction from ERA5-L gridded dataset. Panel c shows the gridded land cover dataset from Zhao et al., (2016)**. Panel d shows the geological dataset from** Hartmann and Moosdorf, (2012)**.**

3 Methods

3.1 Hydrological processes: regimes, modelling and memory

3.1.1 Hydrological regimes

Given the latitudinal extent and terrain complexity, the study region features very different hydroclimate regimes (Fig. 1). Annual precipitation ranges from less than 100 mm to the north to near 3000 mm in the southern part. Precipitation also increase substantially towards the west due to the orographic effect exerted by the Andes on the predominantly westerly atmospheric flow (Viale and Garreaud, 2014).

To characterise the different hydrological regimes of the study catchments, we classified them based on the hydro-climatic metrics summarised in Table 1, which represent main seasonal hydro-climatic characteristics of a catchment. The classification was based on a k-means clustering algorithm (Lloyd, 1982) implemented with the H2O.ai library in Python (H2O.ai, 2020).

Table 1: Hydro-meteorological basin features used for classification.

Variable	Description
$P_{A\text{-}S}$ ratio	Ratio of mean fall-winter precipitation (April to September) to mean annual precipitation (period April 1979 to March 2020) from CAMELS-CL dataset
$Q_{A\text{-}S}$ ratio	Ratio of mean fall-winter streamflow (April to September) to mean annual streamflow (period April 1979 to March 2020) from CAMELS-CL dataset
SF	Long-term snow fraction, computed as the average of ERA5-L solid to total precipitation ratio for the period April 1981 to March 2020

3.1.2 Process-based modelling

In addition to the analysis of the observations-based dataset from CAMELS-CL, we run the HBV model (Bergström, 1972; Lindström et al., 1997) to simulate streamflow and other fluxes for each of the 106 study catchments. With these simulations we seek to improve our understanding on runoff mechanisms from a process-based perspective, particularly regarding the role of snow and groundwater in runoff generation. The HBV is a bucket-type model that simulates the main hydrological processes in a catchment through a number of routines. In the snow routine, snow accumulation and melt are simulated based on a simple degree-day approach. A variable fraction of all melted and rainfall water is retained in the soil depending on the current soil water level. The remaining part is transferred to the groundwater routine. In this routine, groundwater storage is represented by two boxes, an upper soil box representing faster groundwater release to total streamflow, and a lower soil box representing a slower groundwater release to total streamflow, both with linear outflows. Finally, the simulated outflows from the groundwater stores are routed using a simple routing scheme, leading to the total streamflow. Besides streamflow, time series of a number of other fluxes and storages can be obtained from the model, such as actual evapotranspiration (ET), soil water storage, or the different streamflow components.

The HBV model has been implemented in several software packages. Here we used the version HBV light (Seibert and Vis, 2012). The model was calibrated using a genetic algorithm (Seibert, 2000) with parameter ranges similar to those suggested earlier (e.g., Seibert and Vis, 2012). The 14 free parameters values were derived after 3500 model runs. For each catchment, 100 independent calibration trials were performed based on the non-parametric variation of Kling-Gupta efficiency, NPE (Pool et al., 2018), which resulted in ensembles with 100 parameter sets.

To characterise the slow groundwater contribution to runoff for each basin, we computed a groundwater index (GWI) as the mean annual outflow from the lower soil box (GW) normalised by the mean annual simulated streamflow. Note that GW is referred here as the groundwater flux simulated by HBV, not the groundwater storage. In contrast to the baseflow index provided in CAMELS-CL, which is computed from a low-pass filter applied to streamflow observations and thus represents the response timings to precipitation, the GWI represents timings and also the source of the water.

3.1.3 Quantifying hydrological memory

The hydrological memory of a catchment is the composite of response times associated to the physical mechanisms transferring and storing water through the basin (Fowler et al., 2020). Such response times have been qualitatively related to the presence of aquifers, lakes and snow (Van Loon and Van Lanen, 2012), and thus, there is no unique way to quantify hydrological memory. For example, catchment memory has been assessed based on soil moisture and groundwater dynamics (Agboma and Lye, 2015; Peters et al., 2006), on streamflow recession curves (Rodríguez-Iturbe and Valdes, 1979), on lag-correlations between soil moisture and other fluxes within the catchment (Orth and Seneviratne, 2013), and based on recovery times from droughts (Yang et al., 2017).

In this study, we assessed hydrological memory based on the following indices:

1) Seasonal streamflow memory, represented by the r^2 between fall-winter (April to September) precipitation of a certain year t ($P_{A\text{-}S(t)}$) and the observed streamflow during the subsequent seasons: $Q_{OND(t)}$, $Q_{JFM(t)}$ and $Q_{AMJ(t+1)}$. These correlations represent the strength of the hydrological memory at 3, 6 and 9 months, respectively.

2) Seasonal GW memory, represented by the r^2 between $P_{A\text{-}S(t)}$ and the simulated GW during the subsequent seasons: $GW_{OND(t)}$, $GW_{JFM(t)}$ and $GW_{AMJ(t+1)}$. These correlations indicate hydrological memories of 3, 6 and 9 months, respectively.

3) Annual streamflow memory, represented by the r^2 between the residuals of the annual R-R regressions computed in Sect. 3.2.2 ($RR_{res(t)}$, i.e., annual streamflow not explained by the current annual precipitation) and the precipitation from the previous year ($P_{(t-1)}$). This index represents the information gained when the precipitation from the previous year is incorporated in the annual R-R relationships, thus indicating a hydrological memory beyond 12 months.

3.2 Drought propagation

3.2.1 Drought characteristics

Meteorological and hydrological droughts were characterised by the observed annual precipitation and streamfllow anomalies at the catchment-scale, respectively. For each basin, the relative anomaly of streamflow (${Q_a}'$) and annual precipitation (${P_a}'$) in the hydrological year t were computed as:

$$ {Q_a}'(t) = (Q_a(t) - \overline{Q_a}) / \overline{Q_a}, \quad (1) $$

$$ {P_a}'(t) = (P_a(t) - \overline{P}_a) / \overline{P}_a, \quad (2) $$

where $Q_a(t)$ and $P_a(t)$ are the annual streamflow observation and annual precipitation for the hydrological year t, respectively. $\overline{Q_a}$ and $\overline{P}_a$ are the mean annual streamflow and mean annual precipitation for the period April 1979 to March 2010 (i.e., excluding the MD), respectively. These relative anomalies are easy to interpret and commonly used in drought impact planning (Van Loon, 2015), but also have some limitations. Very large anomalies are obtained when the long-term mean is small. Furthermore, neither absolute nor relative deviations provide information about how unusual the anomalies are at specific locations. Therefore, we also computed the annual deviations of streamflow and precipitation normalised by the standard deviation of the annual time series for the period April 1979 to March 2010 (i.e., z-scores). Annual z-scores for streamflow ($Q_a{}^*$) and precipitation ($P_a{}^*$) were computed as follows:

$$Q_a{}^*(t) = (Q_a(t) - \overline{Q_a})/\, std(Q_a), \quad (3)$$

$$P_a{}^*(t) = (P_a(t) - \overline{P_a})/\, std(P_a). \quad (4)$$

To characterise the MD (April 2010 to March 2020) and to assess how unusual this 10-year period has been in comparison to previous decades, we computed the MD decadal means for each water flux (precipitation, observed streamflow and simulated ET) and compared them against historical decadal-mean values. To account for a large sample size, we computed 100 decadal mean values from random batches of 10 annual values within the historical records.

3.2.2 Intensification of drought propagation during the MD

Stationarity in drought propagation during the MD was assessed by following the procedure suggested by Saft et al. (2015) to identify significant shifts in annual R-R relationships over Australian catchments during the Millennium drought. Saft et al. (2015) showed that prolonged rainfall deficits resulted in shifts in R-R relationships at the catchment scale, and Saft et al. (2016b) related the shifts to catchment characteristics (aridity index and rainfall seasonality) and soil and groundwater dynamics. The physical mechanisms likely associated with these factors were discussed by Saft et al. (2016b), but not explicitly modelled.

In this study, we computed annual R-R relationships between annual precipitation and runoff time series for each catchment, and performed a global test to validate linear model assumptions with the R-package gvlma (Peña and Slate, 2006). From the 170 catchments fulfilling the criteria i) to iii) described in Sect. 2, we selected 106 where the linear assumptions in R-R relationships were fulfilled and where the annual rainfall explained more than 50% of the variance in annual runoff (r^2 larger than 0.5).

For each catchment, we tested if the R-R relationship during the MD (April 2010 to March 2020) was different to the R-R relationship computed with the previous period (April 1979 to March 2010), by performing the analysis of variance model from R-package aov (Chambers et al., 2017) to the intercept parameter from the linear regressions (see Eq. 1 from Saft et al. 2015). From this analysis, we defined two types of cases: i) catchments with a significant shift in R-R relationship at a 0.1 significance level, and ii) catchments that did not experience a significant shift (test p-value greater than 0.1). For those catchments experiencing a significant shift, we computed the magnitude of the shift as the relative difference between streamflow estimations from both linear regressions (prior the MD and during the MD), given a same precipitation value. This characteristic precipitation value was defined for each basin as the average precipitation during the MD period.

3.2.3 Propagation of extreme, severe, moderate and mild droughts

In addition to computing the shifts in R-R relationships, which represent an overall catchment response during the MD period, we analysed annual drought propagation over the entire period of record (April 1979 to March 2020) based on annual precipitation and streamflow anomalies (Sect. 3.2.1). Drought propagation during a hydrological year was represented by the contrast between streamflow and precipitation anomalies.

In particular, we focused on catchment responses during two types of events: i) single-year extreme and severe droughts, and ii) multiyear moderate and mild droughts. For each catchment, precipitation anomalies were classified by following the drought classification thresholds provided by McKee et al., (1995). In this way, annual anomalies between 0.5 and 0.067 quantiles were classified as mild to moderate droughts. Annual anomalies below the quantile 0.067 were classified as severe to extreme droughts. These thresholds are currently being used by the Public Works Ministry to declare water scarcity decrees (DGA resolution No 1.674 from 2012).

To analyse the hydrological memory effect on the propagation of extreme and severe droughts, we separated these events based on the precipitation anomaly of the preceding year (below or above a quantile 0.5).

4 Results

4.1 Hydrologic regimes and catchments characteristics

Based on the classification scheme described in Sect. 3.1.1, we identified 72 pluvial and 34 snow-dominated basins. Some of their main characteristics are presented in Fig. 2. Most of the snow-dominated basins are located in central Chile (30º-35ºS), given the higher elevation of the Andes at these latitudes (Fig. 2a). These basins feature mean annual precipitation values between 258 and 1882 mm (mean of 779 mm), with a markedly concentration of precipitation during the fall and winter months (April to September, Fig. 2b), while most of the streamflow is released during spring and summer months, when snowmelt occurs (October to Jan, Fig. 2b). Pluvial basins, mostly located towards the south of the study region (35º-41ºS), have mean annual precipitation values ranging from 428 to 3376 mm (mean of 1862 mm), with a significant water accumulation (mostly rainfall) outside the fall-winter season of maximum precipitation. Streamflow in pluvial basins follows closely the seasonality of precipitation (Fig. 2c).

To visualise the importance of groundwater processes within the study catchments, and their relationship with snow processes, in Fig. 2d we relate the GWI computed from HBV simulations with the SF derived from ERA5-L for each basin (Table 1). These variables come from independent datasets and show a significant correlation ($r^2 = 0.49$), which indicates the interdependence of snow and groundwater processes. The HBV model calibration resulted in overall acceptable simulation performance in snow-dominated and pluvial basins, with NPE values of 0.72, 0.88 and 0.95 for the 10th, 50th and 90th percentile, respectively. For comparison, the corresponding Kling-Gupta efficiency values (Gupta et al., 2009) were, respectively, 0.57, 0.8 and 0.92.

In addition to the climatic characteristics (e.g., precipitation, snow fraction and aridity), GW contribution to runoff depends on physical factors (e.g., geology, topography, soil properties, soil drainage density), which may explain the large scatter in Fig. 2d.

The main characteristics of snow-dominated and pluvial catchments, including P_{A-S} ratio, Q_{A-S} ratio, SF, elevation, area, baseflow index, main geologic class, main land cover class, and granted water used rights are presented in Fig. S1. By construction, there is a clear distinction in P_{A-S} ratio, Q_{A-S} ratio, and SF from both clusters, which is translated into differences in mean catchment elevations (mean elevation of snow-dominated catchments is 2667 m a.s.l., while mean elevation of pluvial basins is 599 m a.s.l.). Both clusters present similar areas, and pluvial basins present lower baseflow indices compared to snow-dominated basins. Higher baseflow indices in snow-dominated basins are consistent with the larger GWI simulated in these basins (Fig. 2d).

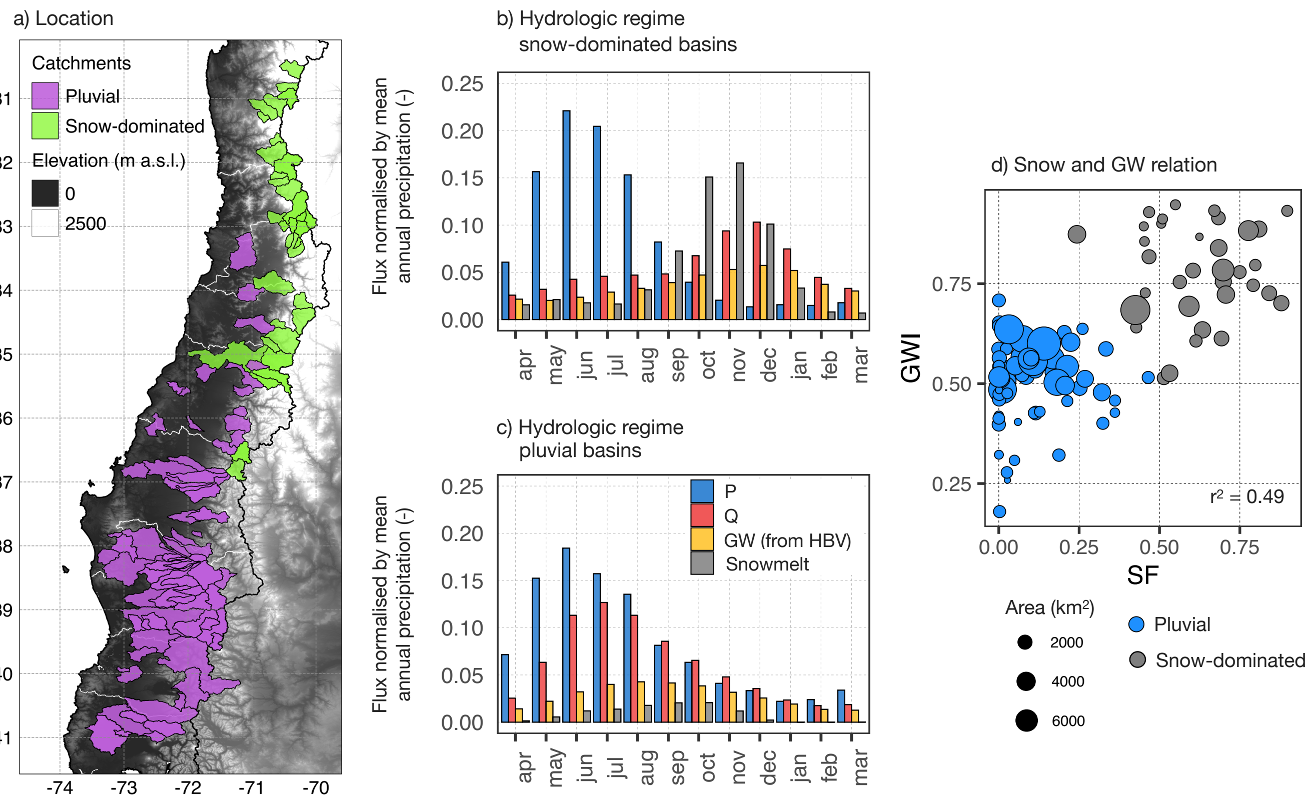

Figure 2: Characteristics of pluvial and snow dominated basins obtained from CAMELS-CL dataset. Panel a presents the catchments location. Panel b and c present the hydrologic regimes for snow-dominated and pluvial catchments, respectively. The mean monthly fluxes of precipitation (P), streamflow (Q), groundwater (GW) were normalised by the annual P from CAMELS-CL dataset for the period April 1979 to March 2020. Since snowmelt was obtained from a different dataset, the mean monthly snowmelt fluxes were normalised by the mean annual precipitation from ERA5-Land. Panel d shows the relation between GWI and SF, representing groundwater and snow storages, respectively.

The most common geologic classes in snow-dominated basins are acid volcanic rocks (main class in 59% of basins), followed by acid plutonic rocks (main class in 18% of basins) and pyroclastics (main class in 18% of basins). In pluvial basins, there is greater heterogeneity in geologic classes, with 22% of basins dominated by pyroclastics and 19% of basins by acid plutonic.

Regarding land cover, 68% of the snow-dominated catchments are mainly covered by barren soil and snow, while the rest is mainly covered by shrubland. None of these land cover classes are directly associated to anthropic activities. 94% of the snow-dominated basins have less than 5% of their areas covered by croplands.

The region where pluvial basins are located features a higher heterogeneity of land cover classes, compared to Andean region of central Chile (where snow-dominated basins are located) (Alvarez-Garreton et al., 2018). The dominant land cover class in pluvial basins is mostly native forest (main class in 61% of pluvial basins) and shrubland (main class in 11% of pluvial basins). Anthropic-related land cover classes dominate the rest of the pluvial catchments: forest plantation in 11% of basins, grassland in 9% of basins, and cropland in 7% of basins.

4.2 Hydrological memory

The correlation between fall-winter precipitation ($P_{A\text{-}S}$) and the observed streamflow and simulated GW over the following seasons are presented in Fig. 3. $P_{A\text{-}S}$ was used instead of annual precipitation since it is more directly related to snow dynamics. Precipitation in fall and winter represents between 50 and 100% of the total precipitation volume (Garreaud et al., 2017).

Figure 3a indicates that $P_{A\text{-}S}$ explains more than half of the variance in spring and summer streamflow (Q_{OND} and Q_{JFM}, respectively) in snow-dominated catchments, which is consistent with the seasonal-lag hydrological memory produced by snow accumulation and melting processes. In general, the $P_{A\text{-}S}$ control on streamflow in these basins is stronger during spring and decreases towards summer (larger blue bars compared to cyan bars in Fig. 3a). This memory effect drastically decreases during the subsequent fall season (Q_{AMJ}, represented by the green bars in Fig. 3a) for most snow-dominated basins, which indicates that streamflow during fall is more influenced by the current seasonal precipitation than by the precipitation of the preceding year. These correlations, representing memory times of 3 to 9 months (Sect. 3.1.3), are consistent with the streamflow and snowmelt seasonality presented in Fig 2b.

Interestingly, the correlation between $P_{A\text{-}S}$ and the spring and summer GW generally increases towards the summer months (Fig. 3b). This indicates a longer response time of GW to the solid fall-winter precipitation, compared to the streamflow time response. In consistency with this longer GW memory, the correlation to $P_{A\text{-}S}$ does not decrease so drastically after summer as streamflow does (larger green bars in Fig. 3b compared to Fig. 3a). These large r^2 values (up to 0.75 in some catchments) indicate that fall-winter precipitation contributes to the following year runoff as GW, since snowmelt is mostly finished by January (Fig. 2b).

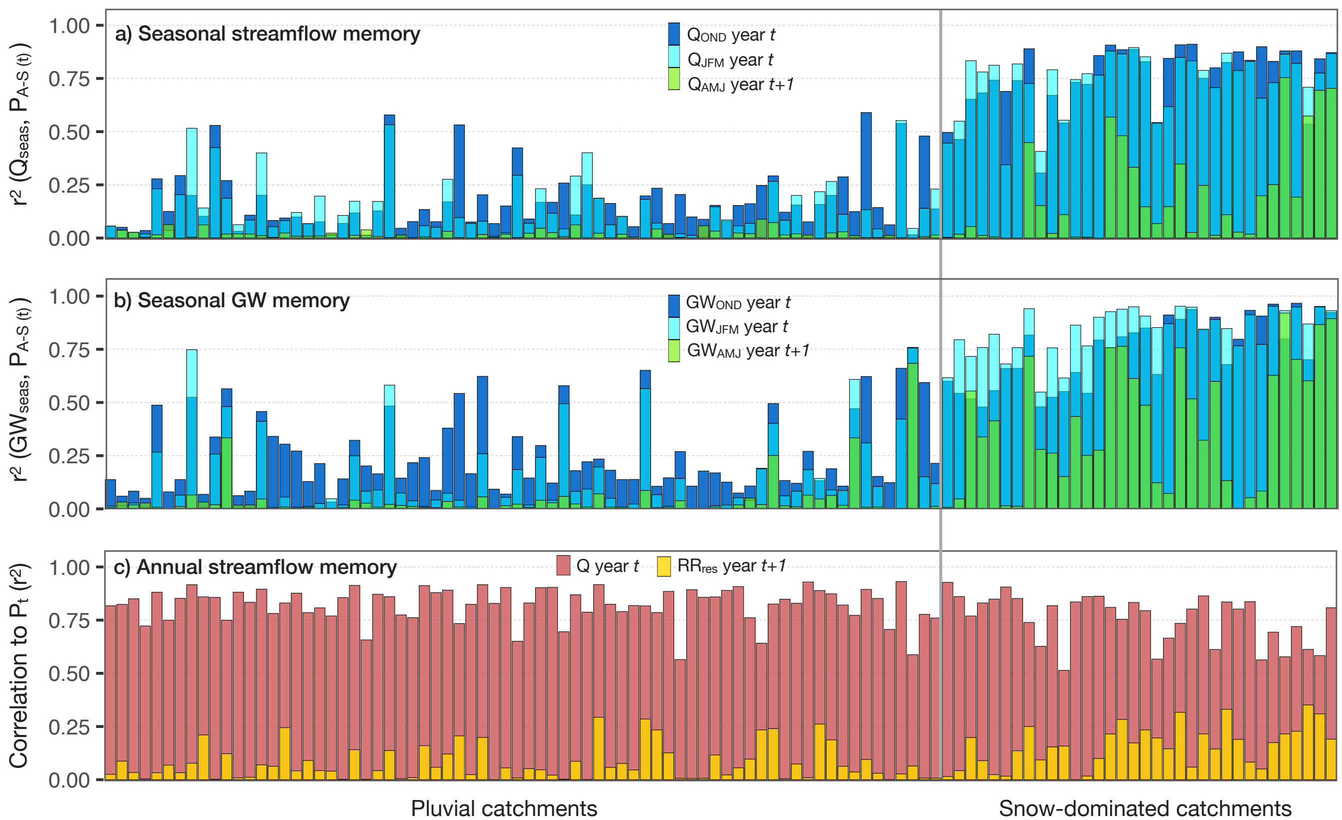

Figure 3: Hydrological memory represented by different indices. Panel a presents the variance in seasonal streamflow explained by the variance in fall-winter precipitation of year t ($P_{A-S(t)}$). Panel b presents the seasonal GW correlation to $P_{A-S(t)}$. Panel c shows the r^2 between annual precipitation and annual streamflow (r^2 of R-R regressions), and the variance of the R-R residuals explained by the precipitation from the preceding year.

The control of P_{A-S} on subsequent seasonal streamflow is consistently weaker in pluvial catchments compared to snow-dominated ones, which is expected given the more direct runoff generation from rain. Also, in pluvial basins, the spring precipitation is larger than in northern basins and explains most of the streamflow generated during the same season, hence overshadowing the streamflow dependency to the previous season precipitation. The spring GW memory in most pluvial catchments is stronger than the streamflow memory (larger blue bars in Fig. 3b compared to 3a), which indicates a 3-month GW memory after winter precipitation. The GW memory during spring decreases towards summer (cyan bars in Fig. 3b) and mostly disappears towards the fall of the following year (green bars in Fig. 3b close to zero).

To remove the effect of the precipitation of the current year, Fig. 3c presents the dependency of the R-R regression residuals from Sect. 3.2.2 (i.e., annual streamflow not explained by the current precipitation) to the precipitation from the previous year. The r^2 values in Fig. 3c (all corresponding to positive correlation coefficients; not shown here) represents the control that the precipitation from the previous year exerts on the annual streamflow, and thus indicate hydrological memory beyond one year. Interestingly, although the residual r^2 are larger in snow-dominated catchments, there are also significant values in the pluvial basins, suggesting that residence times associated to GW processes in pluvial catchments also contribute to more extended catchment memory.

The relationship between hydrological memory beyond one year and catchment storage dynamics driven by GW and snow processes, is further explored in Fig. 4. The GWI derived from HBV simulations (Sect. 3.1.2) and SF (Table 1) are used to summarise GW and snow processes within a catchment in Fig. 4. These plots show that both snow and GW mechanisms contribute to the hydrological memory, which is consistent to the time lags these processes introduce to the pathways of precipitation within a basin. The adopted approach to compute the memory of a catchment, based on seasonal streamflow and GW flows at the catchment outlet, represents the composite response times of all catchment mechanisms. Therefore, there might be other factors contributing to the overall response time of a catchment, including topography, soil properties, geology, drainage area and water table levels (Robinson and Ward, 2017), which may explain the large scatters in Fig. 4.

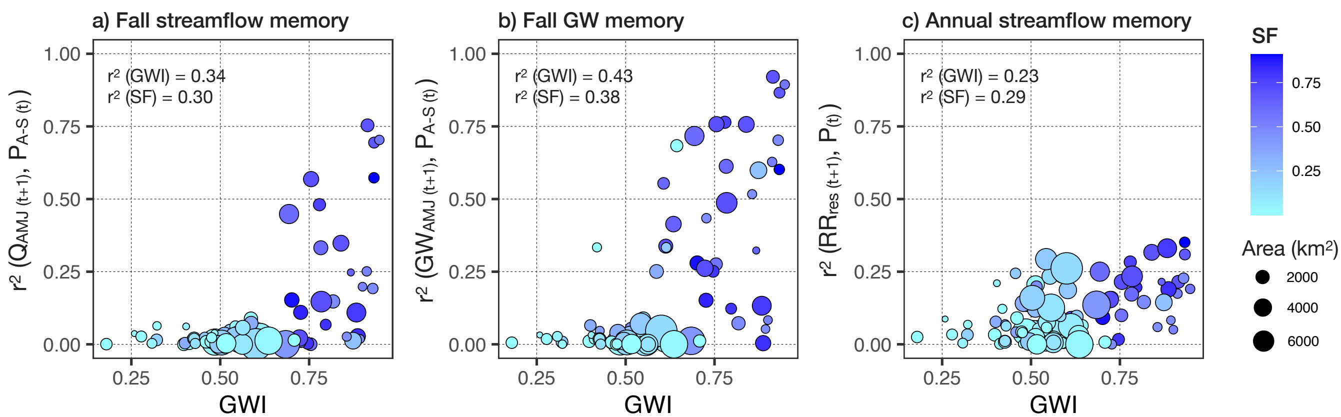

Figure 4: Relationship between hydrological memory and indices of groundwater and snow storages (GWI and SF, respectively). Panel a shows the fall streamflow (9-months) memory to the fall-winter precipitation of the preceding year. Panel b shows the fall GW (9-months) memory to the fall-winter precipitation of the preceding year. Panel c shows the (>12-months) memory of streamflow the precipitation of the preceding year.

4.3 Droughts over the last decades

Given the markedly north to south precipitation gradient (Fig. 1), droughts characteristics in this section are analysed at the catchment scale, but following a latitudinal order. In the following sections we analyse drought propagation per hydrologic regimes. Heatmaps in Fig. 2 illustrate the precipitation and streamflow annual anomalies (Fig. 5a and 5) and z-scores (Fig. 5c and 5d). The unprecedented dry conditions during the last decade are evident. The temporal and spatial extent of precipitation deficits is shown by general negative anomalies for the 106 catchments between 30°S and 41°S (Fig. 5a). Over the previous three decades, there are few analogues showing such spatial pattern, such as the 1988-1990 three-year drought, and the single-year droughts in 1996 and 1998 (one of the driest years in the last millennium, Garreaud et al., 2017) and 2007. The decade-long persistence of the MD spatial pattern, however, has no analogue in the studied period, nor in the last century (Garreaud et al., 2017).

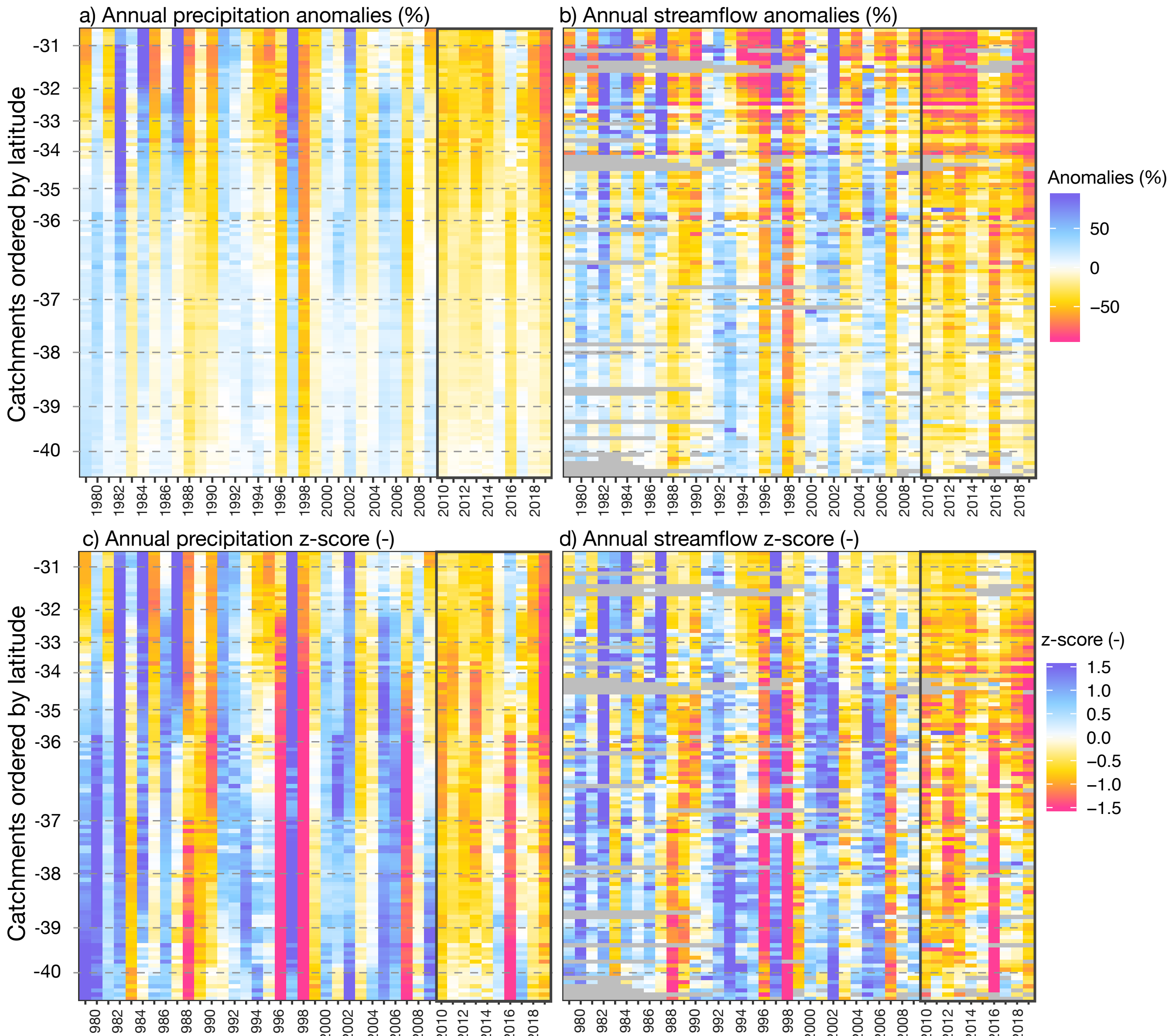

Figure 5: Relative annual anomalies of catchment-scale precipitation (panel a) and streamflow (panel b). Panels c and d present the z-score of annual precipitation and streamflow. The MD period (April 2010 to March 2020) is highlighted in a grey box. Each row in the heatmaps corresponds to one study catchment and the catchments are sorted from north to south to illustrate regional drought patterns.

The relative precipitation anomalies are consistently higher in catchments north of 35ºS (Fig. 5a), which is partly due to the very low annual precipitation values in the northern region compared to the southern region. The probability of having high anomalies is larger in this northern region (z-scores closer to zero in Fig. 5c), where few meteorological events contribute to most of the annual accumulation. Thus, the interannual variability is higher than in the southern region (south of 35ºS, where most pluvial basins are located, Fig. 2), where several precipitation events occur during the year. During the MD, annual precipitation in basins south of 35ºS decreased up to 1.5 times below the historical standard deviation of annual precipitation, which represents an exceedance probability of 94.3%. Z-scores during the MD have been usually lower in the southern region, compared to central Chile (30-35ºS).

The annual streamflow relative anomalies (Fig. 5b) present larger values and larger variations in space and time than precipitation, which is due to the lower absolute values compared to precipitation and the dependency of streamflow on local terrestrial characteristics. If we compare the spatial patterns of anomalies (Fig. 5b) and z-scores (Fig. 5d) during the MD, we see that consistently with precipitation, larger anomalies have been observed in catchments north of 35ºS (extreme dry years up to 90% of streamflow deficits with a median of 57%). Still, the moderate deficits experienced in the southern region (median deficit of 25%) have a lower probability of occurring (lower z-score values, indicating higher exceedance probabilities).

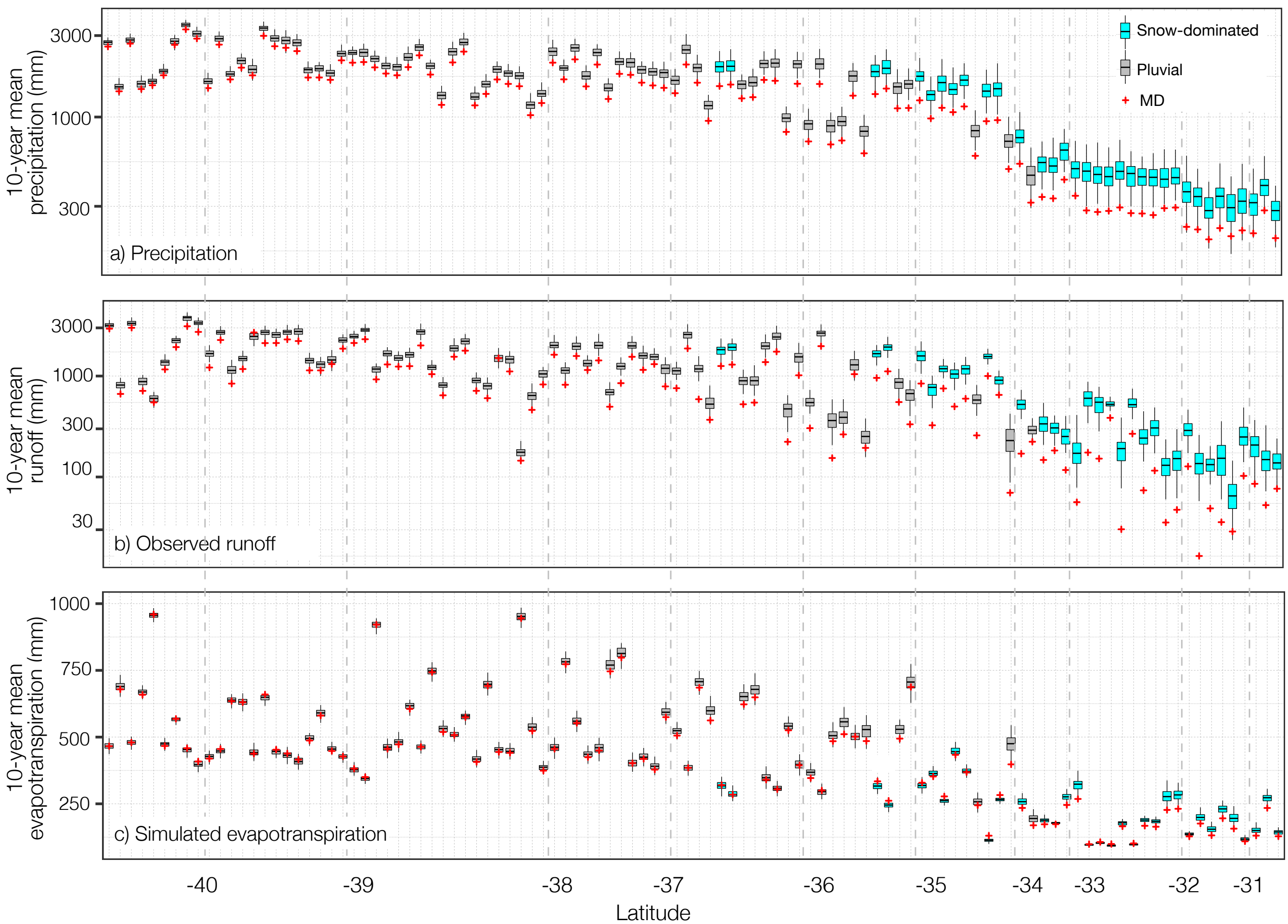

Figure 6: Boxplots of 10-year mean precipitation (panel a), observed runoff (panel b) and simulated ET from HBV (panel c) for the period April 1970 to March 2010 (i.e., excluding the MD). The red marks correspond to the decadal means during the MD (April 2010 to March 2020). Please note the log-scale of the Y-axes in panels a and b.

To further characterise the hydro-climatic anomalies during the MD, Fig. 6 presents the frequency distribution of 10-year mean precipitation, observed streamflow and simulated ET for each basin, with the mean values during the MD plotted in red dots. These plots indicate that the MD has been extremely unusual in terms of precipitation and streamflow. The average precipitation during the MD is within the first decile for 91% of the study catchments (96 out of 106). The average runoff during the MD has been more extreme than precipitation deficits, with 96% of catchments (102 out of 106) presenting 10-year mean runoff values within the first decile. These values represent the minimum value over the last four decades for some basins located north to 32ºS and correspond to an outlier of the historical distribution for the rest of the catchments. The average 10-year ET during the MD has been less unusual than precipitation and streamflow anomalies, with only 20% of catchments (21 out of 106) within the first decile, and 73% of basins below the median (quantile 0.5) historical 10-year ET values. This indicates that in general, the estimated ET within the study basins during the MD have not been as distinct as precipitation and streamflow. This also shows that, despite the higher mean temperatures due to the warming trend experienced in the region (Boisier et al., 2018), ET is closely related to precipitation, notably in the northern (water-limited) basins.

4.4 Shifts in R-R relationships during the MD

Given the relatively small scale of catchments in Chile, runoff in most of them has a strong dependency to the interannual precipitation variability, explaining typically ~ 75% of the streamflow variances. Yet, the annual R-R relationships observed during the MD changed significantly for some of the catchments within the study region (examples in Fig. 7b, 7c, 7e, 7f), while other catchments showed no significant change (Fig. 7a, 7d). Table 2 summarises the number of catchments that experienced a significant shift in R-R relationship during the MD, and their associated shift magnitudes. This table also shows the results for those catchments with no change. From the 106 studied catchments, 61.3% had a significant change in the R-R relationship during the MD and 38.7% had not (Table 2).

For the 65 catchments showing a change, the historical R-R regressions consistently underestimate the runoff deficits during the MD. 95% (62 out of 65) of the catchments with significant change in R-R relationship during the MD, had a negative shift; that is, an intensification in drought propagation. For similar precipitation deficits as other dry years, observed streamflow during the MD in snow-dominated catchments were up to 57% lower than those predicted by the historical R-R relationship. In pluvial catchments, these shifts reached up to 37% (Table 1).

For those catchments with significant change, higher GWI values are associated to larger shifts in R-R relationships (r^2 = 0.40, not shown here), and thus to the intensification of drought propagation during the MD, with respect to historical annual responses to droughts. The relationship between snow fraction and R-R shifts is weaker (r^2 = 0.29, not shown here), probably because snow processes control the hydrologic response of a subset of catchments experiencing significant change in R-R relationship, whereas GW is inherent to all basins.

While these results provide insights about changes in R-R relationship during a multiyear period, they do not indicate if the changes are progressive, i.e., if the basins progressively generate less water for a given precipitation amount, compared with their historical behaviour. We address this in the following section, where annual drought propagation is analysed in detail.

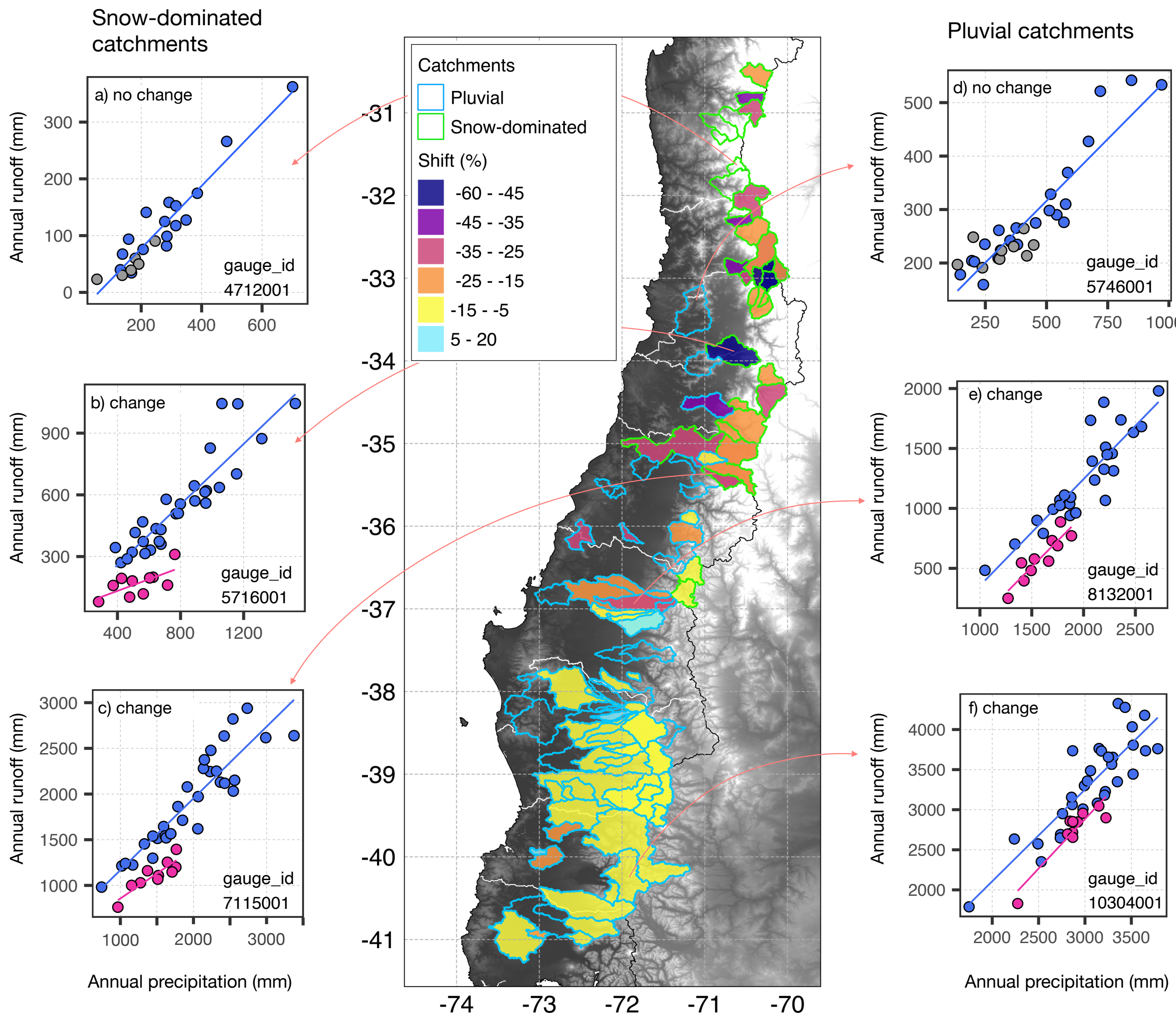

Figure 7: Annual runoff (y-axes) and precipitation (x-axes) for selected snow-dominated catchments with and without a significant change in R-R relationship during the MD (panels a-c). Panels d-f show three selected pluvial basins with and without change. The years within the MD are highlighted in magenta when there was change and grey when there was no change in R-R regressions. The map shows the catchments with change coloured by their shift in R-R relationship.

Table 2: Number of catchments with significant shift and no shift in R-R relationship during the MD. The shift magnitude in catchments with change is also presented.

	Snow-dominated	Pluvial	Total
Change Mean shift (min, max)	26 -31% (-57%, -12%)	39 -11% (-37%, 27%)	65 -19% (-57%, 27%)
No change	8	33	41
Total	34	72	106

4.5 Annual drought propagation

Figure 8 presents the time series of annual precipitation and streamflow anomalies averaged across snow-dominated catchments (Fig. 8a) and pluvial catchments (Fig. 8b) over the last four decades. Drought propagation is represented by the difference between average runoff and precipitation anomalies (secondary y-axis in Fig. 8). To focus on drought propagation and not on the propagation of positive anomalies, the difference in runoff to precipitation anomalies was computed only for those years with negative streamflow anomalies (red line in Fig. 8).

In snow-dominated basins, the difference between runoff and precipitation anomalies consistently increases (becomes more negative) in the second year of precipitation deficits, showing that in catchments with longer hydrological memory consecutive years with precipitation deficits are associated to intensified drought propagation. This plot also provides insights about hydrological recovery, understood as the hydrological condition after a meteorological drought has ceased (Yang et al., 2017). While 2016 had near average precipitation in snow-dominated basins, probably there was not enough water entering the system over enough time to recharge groundwater systems up to levels such as those before the MD (similarly to the conceptual drought propagation illustrated in Fig. 3 from Van Loon, 2015). This is reflected by the larger streamflow deficits in 2016 compared to 2008, even when the above-mean precipitations in 2008 following the deficits in 2007, are comparable to those in 2016 and 2015, respectively. This can be related to the catchments' memory (Sect. 4.2) and the 7-year (2009 to 2015) precipitation deficits prior 2016, which probably prevented a full hydrological recovery after a single year of above-average precipitation. These results are consistent with large recovery times reported for semi-arid Australian catchments following extreme droughts (Fowler et al., 2020; Yang et al., 2017). In this way, hydrological memory would be an explanatory factor for both the intensification in drought propagation as well as a delayed hydrological recovery.

For pluvial catchments (Fig. 8b), prior to 2010, the propagation of meteorological to hydrological drought has been around 0 to 15% (i.e., streamflow anomalies have been, on average, up to 15% lower than precipitation anomalies), independently of the precipitation deficits of previous years. Such propagation was observed even in the driest two years of the historical record, 1996 and 1998. After 2010, there are two years (2012 and 2016) where drought propagation has been intensified up to 25%. These larger streamflow deficits during the MD may be due to different factors, including the large ET in 2012 and 2016 (positive anomalies and z-scores above 1.5 as can be seen in Fig. S2) combined with large precipitation deficits.

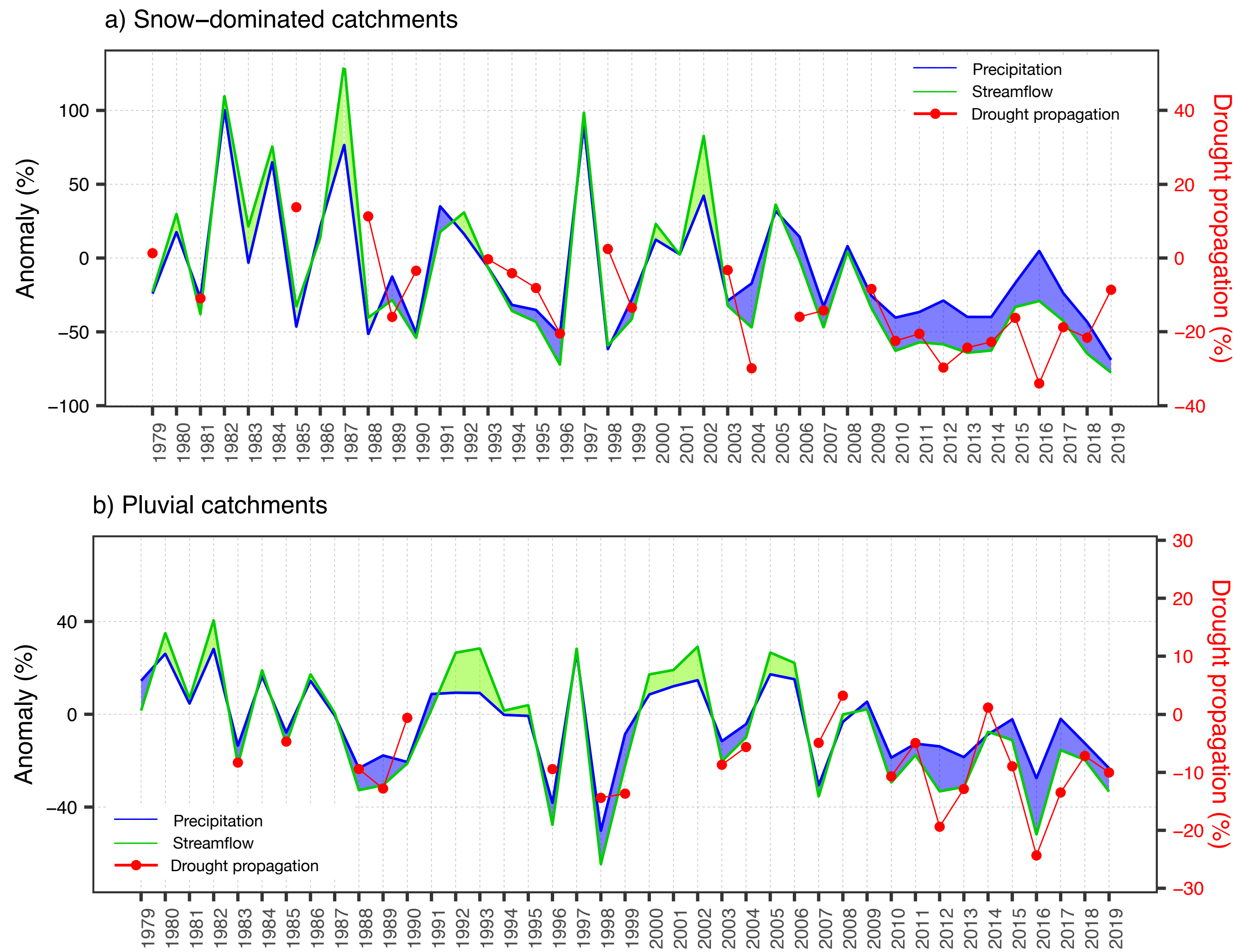

Figure 8: Precipitation and runoff anomalies in snow-dominated (panel a) and pluvial catchments (panel b). The blue shaded area between curves represents precipitation anomalies larger than streamflow anomalies, and green shaded area represents the opposite. The meteorological to hydrological drought propagation, represented by the difference between runoff and precipitation anomalies for those years where runoff anomaly is below zero, is shown in the secondary y-axis by red points connected with red lines between consecutive years.

Regarding the overall response during the MD, since R-R relationships do not explicitly account for variations in ET, the positive ET anomalies during specific years of the MD (2012, 2016 and 2018, Fig. S2) may partly explain the R-R shifts identified in some pluvial catchments (Fig. 7). Towards the south of the study region, basins move from water-limited to energy-limited (Alvarez-Garreton et al., 2018). Therefore, ET in pluvial catchments is modulated by both the available water and the available energy, in contrast to snow-dominated catchments, where ET is primarily driven by precipitation (these are water-limited basins). This suggests that ET may be a factor influencing the intensification of drought propagation during the MD in pluvial catchments. However, despite higher ET in three years during the MD, the average ET during the 10-year MD period has been lower than other 10-year windows (Fig. 6c). Therefore, the hydrological memory beyond one hydrological year in pluvial basins (Fig. 3) is likely another factor contributing to the R-R shifts in pluvial catchments.

Figure 9 presents the observed and simulated drought propagation during single-year severe and extreme droughts and during persistent mild and moderate droughts, for snow-dominated (Fig. 9a, 9b) and pluvial catchments (Fig. 9c, 9d). Consistently with the hydrological memory in snow-dominated catchments, we observe that drought propagation in these basins is highly dependent on the meteorological conditions from the previous year (Fig. 9a), which define the initial condition of soil water storages. If a severe or extreme drought happens after a wet year, such as 1981, 1985, 1988, 1998, 2007 and 2009 (Fig. 9a), drought propagates without amplification, i.e., streamflow deficits are lower than precipitation deficits. By contrast, if the extreme drought happens after a dry year in contrast, such as 1995, 1996, 2013 and 2019, meteorological droughts are amplified by nearly 20% (difference between median streamflow and median precipitation deficits in Fig. 9a). This is also observed in persistent but moderate droughts, when under similar precipitation deficits, the surface water supply decreases after one year with below-average conditions.

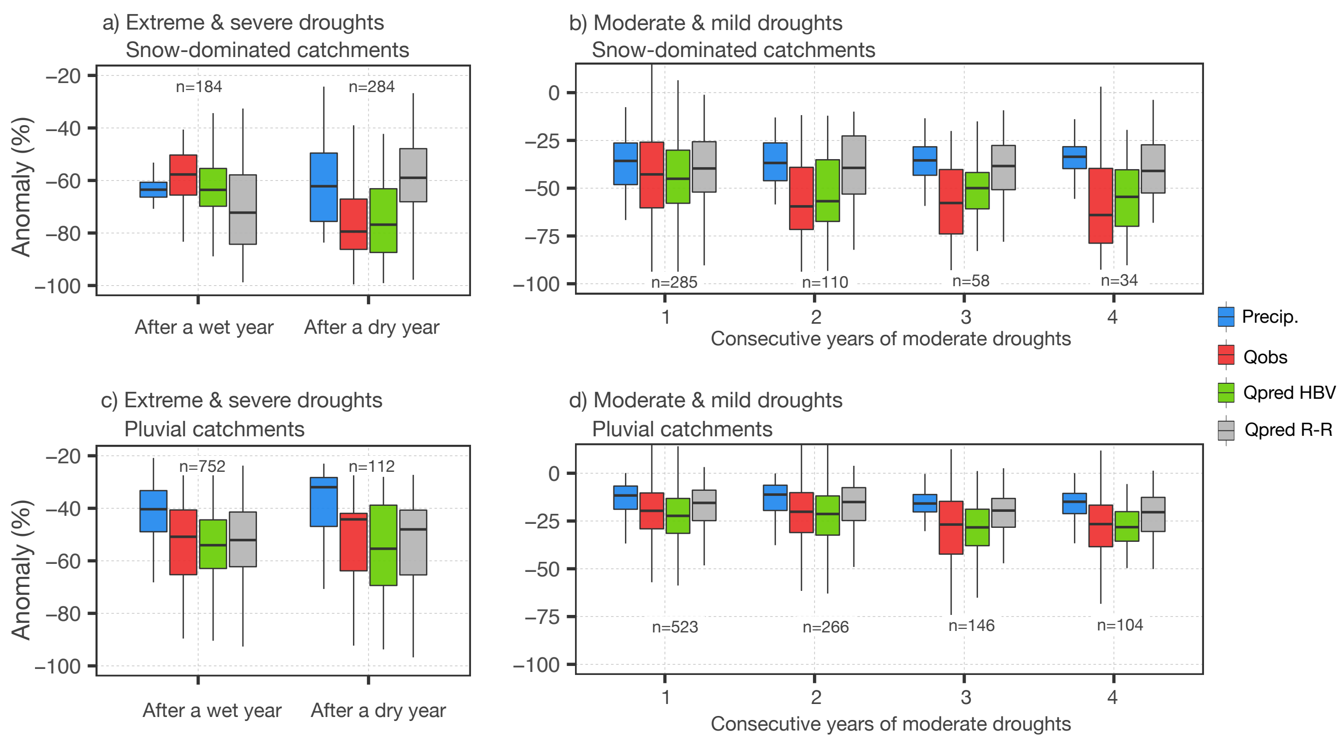

Figure 9: Observed and simulated annual drought propagation for consecutive dry years. Panel a presents the results for snow-dominated catchments, and panel b for pluvial catchments. The number of cases is presented for each set of boxplots.

If we look at streamflow predictions, these plots indicate that the HBV model represents catchment response for extreme and persistent droughts well, consistently outperforming the prediction from R-R regressions. It should be noted though that HBV allows memory effects only to a certain extent given the groundwater storage capacity defined by calibration.

Pluvial basins in the study region have shorter hydrological memory compared to snow-dominated catchments, which leads to a more similar behaviour under extreme meteorological droughts occurring after a wet and a dry year (difference in streamflow to precipitation anomalies between 10-20%, Fig. 9c). However, even when these basins are largely controlled by precipitation during the same year, there is some over-one-year memory (Fig. 3c), which may be influencing the observed decrease in streamflow generation after two years of consecutive precipitation deficits (Fig. 9d). This effect is well captured by the HBV model, while the annual R-R relationship tends to overestimate observed runoff. This indicates that a good representation of fluxes such as ET, soil moisture and groundwater dynamics, allow foreseeing catchment response to persistent droughts and to extreme droughts.

5 Discussion

Hydrological memory is related to slow groundwater and subsurface flows transferring precipitation from previous seasons, especially from winter (Fig. 3 and Fig. 4). If the winter snow pack is large, hydrological memory is further extended, not only by the season-lag resulting from the snowmelt contribution to streamflow in spring and summer, but also by the slow GW contribution during the next fall, when snow has already melted.

We showed that the importance of GW contribution to runoff is positively correlated with snow accumulation (Fig. 2d). This relationship between snow and groundwater contribution to downstream streamflow supports the GW recharge conceptualisation recently proposed by Taucare et al. (2020) for the Western Andean Front in central Chile. In contrast to former assumptions of no GW recharge in high elevated Andean areas, Taucare et al. (2020) demonstrated the existence of GW circulation in fractured rocks originating from rain and snowmelt above ~2000 m a.s.l. (the mean elevation of the snow-dominated basins in this study range from 737 to 3783, with a mean of 2667 m a.s.l.).

This conceptualisation is also supported by the groundwater recharge mechanisms driven by snowmelt shown by Carroll et al., (2019) in a Colorado River headwater basin. Snowmelt infiltrates in situ, where ET is low compared to precipitation, the soil storage is shallow and there is a low permeability bedrock underneath. Infiltrated snowmelt is routed through the steep topography as shallow ephemeral interflow, which supports large recharge rates in topographic convergence zones, where ET is still moderate and ephemeral stream channels in the upper basin appear (Anderson and Burt, 1978). At high elevations where snowmelt starts, topography and soil permeability would have a larger control in groundwater recharge than precipitation. That is, the rates at which snowmelt infiltrates are more sensitive to catchment characteristics than to the snowpack volume (Carroll et al., 2019). This suggests that during dry years, the portion of snowmelt directly contributing to runoff would decrease while the portion of GW from snowmelt infiltration would increase.

The large snowmelt infiltration rates at high elevations during snowmelt season, combined with the absence of precipitation events (precipitation is concentrated in winter season) would explain the higher GWI in snow-dominated basins.

High snow fraction ratios also indicate an important spatial variation of precipitation within the basin, with most precipitation falling in the upper part of the basin and therefore, traveling longer paths to reach the outlet where streamflow is recorded. Longer paths lead to longer travel times (i.e., longer hydrological memory), which may support groundwater recharge from interflow.

Regarding drought propagation, our results show that precipitation influence for longer times in basins where snow and GW processes dominate the hydrological response. Snow-dominated catchments feature longer memory than pluvial basins, and have been more affected by the persistency of precipitation deficits during the MD, causing a significant change in overall catchment response to precipitation over the last decade. These results complement previous findings in Australia (Saft et al., 2015, 2016b, 2016a), providing new evidence of the vulnerability of catchments to drying climatic trends. In particular, our results reveal that snow processes are tightly associated to the intensification in drought propagation, an insight that was not drawn by the analysis of the Australian Millennium Drought given the lower elevation of the analysed Australian basins (mean elevations below 1500 m a.s.l.).

The role of snow in hydrological memory and its impacts on water provision during droughts highlights the need to further understand the seasonal characteristics of drought propagation. The effects of spring-summer precipitation deficits may be different from those of fall-winter winter deficits (Berghuijs et al., 2014; Jasechko et al., 2014). This is particularly important in central-south Chile, where modelled shifts in precipitation and streamflow seasonality due to anthropogenic climate change have already been detected in observations (Boisier et al., 2018; Bozkurt et al., 2018; Cortés et al., 2011).

Our results also provide insights regarding model representation of hydrologic mechanisms. The HBV process-based model overcome some of the limitations of diagnosing the progressive water deficits only from shifts in annual R-R relationships. A model that is able to capture catchment memory is more suited to represent deficits in streamflow under persistent drought, compared to the simulations from R-R regressions that only consider the precipitation of the same year (Fowler et al., 2020). Nevertheless, the HBV model is a simplified representation of actual hydrological processes, which limits its capability to simulate long-term memory effects. Memory effects in the HBV model are caused by soil water storage as this store can accumulate precipitation deficits. The groundwater stores in HBV cannot drain below the level where streamflow ceases and, thus, represent only the dynamic storage in a catchment (Staudinger et al., 2017), which means that memory effects caused by groundwater stores are limited in the model. This is consistent to the limitations of conceptual bucket-type models to simulate long, slow hydrological processes demonstrated by Fowler et al., (2020). The effects of multiyear drought cannot accumulate in models where the time constants (usually months) are shorter than the observed memory (seasonal and longer). In this way, catchments that are more prone to a non-stationary hydrologic response under persistent droughts, pose greater challenges for projecting the impacts of a drying climate. This highlights the need to advance towards robust modelling frameworks in order to achieve reliable streamflow predictions under drier climate projections.

The proposed approach focuses on understanding the causes of intensified drought propagation by analysing the basins runoff mechanisms and the hydrological memory within the basins. However, anthropic factors such as irrigated agriculture, reservoirs and water abstractions for human consumption may also contribute to different catchment responses to precipitation during persistent droughts. While the water used by natural ecosystems are related to the incoming precipitation (e.g., in water-limited basins ET is proportional to the precipitation), the water used to supply human demands may remain similar to pre-drought conditions if the associated infrastructure allows it (e.g., deep pumping wells or large reservoirs). This may cause a decrease in runoff which is not directly related to precipitation deficits. In this study, we aimed at removing some of these anthropic effects by filtering out catchments with reservoirs, but there are still anthropic-activities within the analysed sample. In particular, pluvial basins feature human-induces land cover classes such as cropland, forest plantations and grassland. Previous findings have related these classes to differences in water provision, particularly during dry years (Alvarez-Garreton et al., 2019). Hence, drought propagation within these basins is likely a combined result of climatic conditions, hydrological mechanisms and anthropic effects. In contrast, the sample of snow-dominated catchments are less prone to anthropic effects given their location in high elevated areas of the Andes cordillera (no human-related dominant land cover classes within the basins, Sect. 4.1). This suggests that the intensification of drought propagation in these basins is mainly due to climatic conditions and hydrological mechanisms.

6 Conclusions

Our analysis of 106 basins along central Chile indicates that larger solid precipitation fraction within a catchment leads to increased slow GW contribution to runoff thus connecting precipitation anomalies in a given winter with streamflow until fall of the next year. In this way, snow-dominated catchments feature a larger memory compared to pluvial basins, where the annual streamflow is mostly explained by the precipitation of the current year.

These different hydrological memories have led to contrasted drought propagation during the MD. The MD in central-south Chile has been extraordinary because of its persistence (10 years to date) and extended spatial domain (~1000 km). Annual precipitation anomalies during the MD have been larger in snow-dominated catchments (mostly located between 30ºS-35ºS) compared to pluvial catchments (mostly located between 35ºS-41ºS). However, observing such large annual deficits in the northern region is not unusual given the highly variable rainfall regime. The annual precipitation anomalies experienced in the southern region, on the other hand, have been highly unusual with respect to the last four decades.

Catchments with longer hydrological memory showed larger shifts in R-R relationships during the MD, compared to their historical behaviour, revealing the intensification of drought propagation during multiyear droughts. For snow-dominated catchments, after one year of precipitation deficits, the surface water supply –under equivalent precipitation deficits– significantly decreases. That is, the basins progressively generate less streamflow for a given precipitation amount compared with the historical behaviour, because snowmelt infiltrates into depleted levels of GW and does not reach the catchment outlets during the same hydrological year. In pluvial basins on the other hand, there is a weaker decrease in water supply after consecutive years of precipitation deficits.

What is worse, an extreme single year drought or a persistent moderate drought? We have shown that for any type of drought, hydrological memory and initial storages conditions are key factors modulating catchment responses. In snow-dominated basins located in Andean semi-arid region of Chile, catchments strongly depend on both the current and previous precipitation seasons. In absolute terms, single year extreme droughts induce larger absolute streamflow deficits (i.e., less water supply). However, moderate but persistent deficits induce a more intensified propagation of the meteorological drought (larger streamflow deficits relative to precipitation). The worst scenario would be an extreme meteorological drought following consecutive years of below average precipitation, as occurred in 2019. In pluvial regimes, initial conditions and hydrologic memory are still important factors to represent catchment response fully. However, water supply is more strongly dependent on the meteorological conditions of the current year, and therefore an extreme drought would have a higher impact on water supply than a persistent but moderate drought.

Snow-dominated catchments store water that is then released during dry seasons, a characteristic particularly valuable in regions with limited water supply and severe risk to droughts, such as in central Chile. We have demonstrated that these basins are prone to intensify the propagation of persistent droughts, which pose additional challenges to water management adaptation in central Chile given the drying projected trends for the region.

Data availability. CAMELS-CL catchment dataset was obtained from the Center for Climate and Resilience Research website (http://www.cr2.cl/camels-cl/). ECMWF ERA5-Land dataset was downloaded from https://www.ecmwf.int/en/era5-land. ASTER GDEM elevation data were downloaded from the NASA Earthdata website (https://search.earthdata.nasa.gov/search/).

Author contributions. This research was conceived and design by CAG, JPB and RG. JS and MV implemented the HBV model. CAG wrote the manuscript with input from all co-authors. All the authors have been involved in interpreting the results, discussing the findings, and editing the paper.

Competing interests. The authors declare that they have no conflict of interest.

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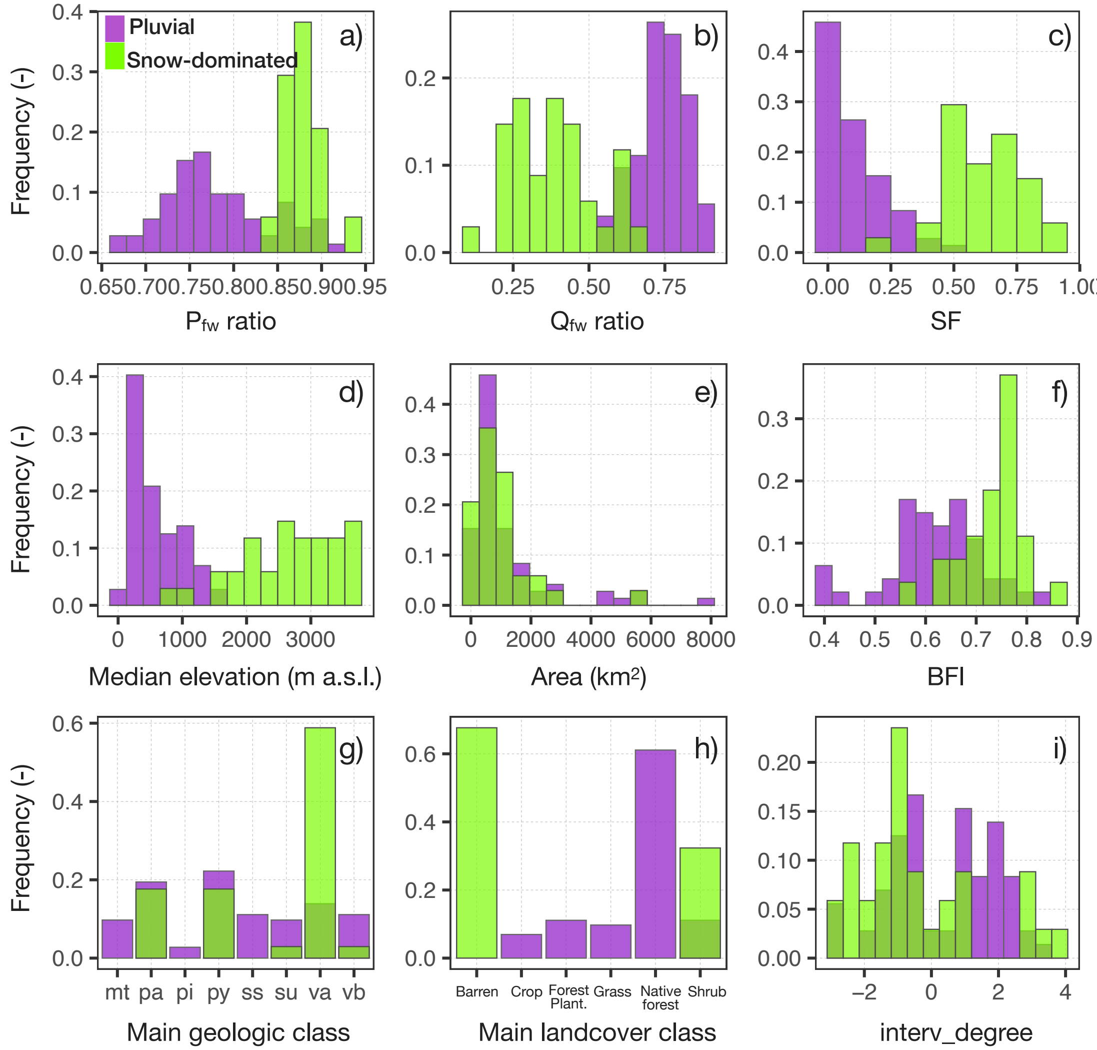
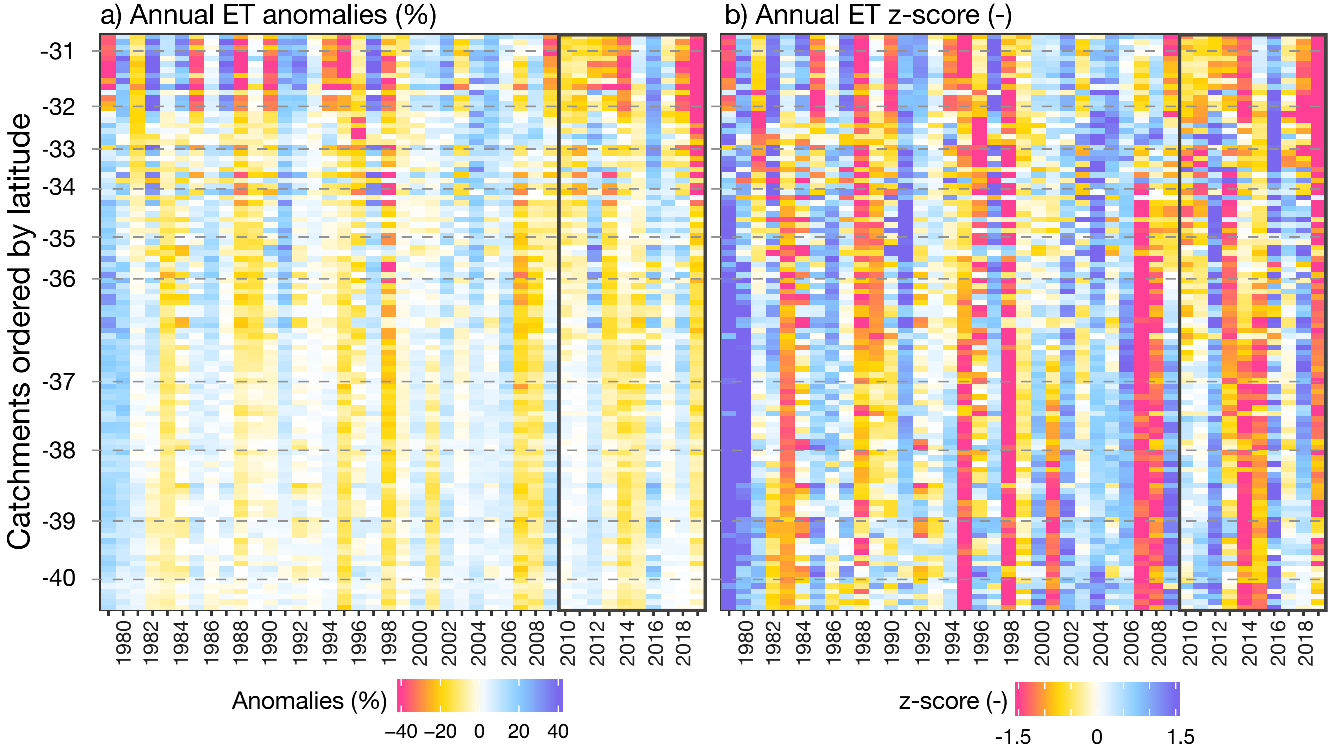


Figure S2: Main characteristics of snow-dominated and pluvial catchments, including P_{A-S} ratio (panel a), Q_{A-S} ratio (panel b), SF (panel c), mean elevation (panel d), area (panel e), baseflow index (panel f), main geologic class (panel g), main land cover class (panel h), and granted water used rights (panel i).



725 **Figure S2: Panel b presents the z-score of simulated annual ET (computed as deviations from mean normalised by standard deviation). The MD period (April 2010 to March 2020) is highlighted in a grey box. Each row in the heatmaps corresponds to one study catchment and the catchments are sorted from north to south to illustrate regional patterns.**