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Progressive water deficits during multi-year droughts in central-south Chile

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Abstract. A decade-long (2010-2019) period with precipitation deficits in central-south Chile (30-41ºS), the so-called megadrought (MD), has led to larger than expected hydrological response and water deficits, indicating an intensification in drought propagation. We used the CAMELS-CL dataset and simulations from the HBV hydrological model to explore the causes of such intensification. Across 124 basins with varying snow/rainfall regimes, we compared annual rainfall-runoff (R-R) relationships and runoff generation mechanisms before and during the MD, and identified those catchments where drought propagation was intensified. We show that catchments' hydrological memory -mediated by groundwater flows- is a key control of drought propagation intensity, and that baseflow contribution to runoff is positively correlated with snow accumulation preceding the year affected by a drought. Hence, under persistent drought conditions, snow-dominated catchments progressively generate less water, compared with their historical behaviour, notably affecting the semi-arid regions in central Chile. Finally, we addressed a general question: what is worse, an extreme single year drought or a persistent moderate drought? In semi-arid regions, where water provision strongly depends on both the current and previous precipitation seasons, the worst scenario would be an extreme meteorological drought following consecutive years of precipitation below average. In temperate regions of southern Chile, where catchments have more pluvial regimes, 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 cause alterations in catchment response to precipitation. Catchment dynamics under unusually multi-year precipitation deficits might, thus, 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 not exist (Blöschl and Montanari, 2010), which poses challenges for hydrological model calibration (Duethmann et al., 2020; Fowler et al., 2016).

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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). The severity (duration and deficit) of meteorological, soil moisture and hydrological droughts vary depending on climate and catchment characteristics. While meteorological droughts are mainly controlled by regional precipitation, soil moisture and hydrological droughts are additionally 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 hydrological droughts provides critical information for drought-hazard adaptation and mitigation (Van Loon and Laaha, 2015). In addition, non-stationary catchment responses to precipitation and precipitation deficits result in a temporal variation of potential drought propagation.

This temporal aspect is becoming increasingly important since many regions around the globe are experiencing unprecedented long dry spells due to global warming and circulation changes, causing unforeseen impacts on water supply (e.g., Schewe et al., 2014). Recent evidence has shown that under persistent dry conditions, 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 other years from the historical records. For example, studies in south-eastern Australia, where the Millennium drought took place for more than a decade (1997-2010), reported changes in catchment functioning (Fowler et al., 2018; Saft et al., 2015; Saft et al., 2016b; Yang et al., 2017). More recently, Garreaud et al. (2017) reported an unprecedented decrease in annual runoff during of a multi-year drought in central-south Chile —the so-called megadrought (MD). This 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).

In this context, the MD experienced in central-south Chile since 2010 (continuing up to date) offers a unique 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 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 led to water scarcity problems affecting various sectors of the socio-ecological system, including impacts on coastal ecology (Masotti et al., 2018), fire regimes (Gonzalez et al., 2018) and water supply (Muñoz et al., 2020).

To deepen the understanding of the impacts of multi-year dry conditions on water supply, we explore the mechanisms causing the larger-than-expected hydrological deficits in central-south Chile, with a particular focus on the MD. We complement previous analyses of the MD in Chile (Garreaud et al., 2017; Muñoz et al., 2020) by incorporating three more years to the MD period, and by focusing on drought propagation over 124 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

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precipitation takes different flow pathways and is temporally retained in various stores. 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; 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, snowpack and glaciers), the propagation of drought during multi-year precipitation deficits is intensified (i.e., larger streamflow deficits than those observed in years with similar precipitation deficits), when compared to single dry years.

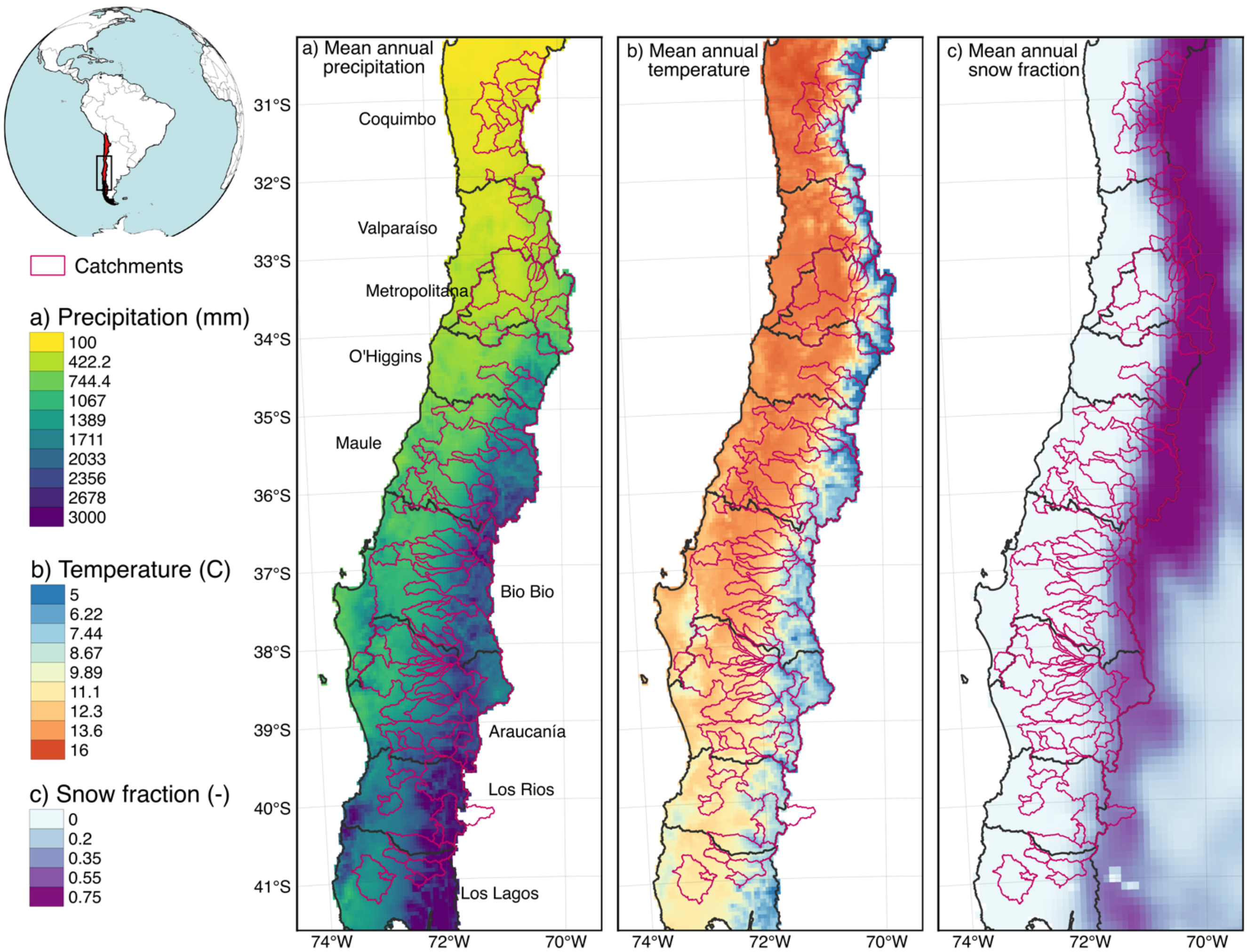
To test this hypothesis, we characterised the historical precipitation and streamflow deficits at the catchment scale, and followed Saft et al. (2015) to evaluate annual rainfall-runoff (R-R) relationships over the last decades and identified those catchments where drought propagation during the MD was 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. Finally, 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). Furthermore, 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 124 catchments in 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, potential evapotranspiration and streamflow time series for the period 1979-2018. This dataset also includes catchment characteristics such as topography, land cover, and boundaries. Hypsometric curves for each catchment were processed based on ASTER GDEM (Tachikawa et al., 2011).

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). Thresholds on the model performance (determination coefficient, r^2, larger than 0.75) and on the record length (75% of valid data within the target period) defines the locations and months to be filled-up. From the 516 CAMELS-CL catchments, we selected those with at least 15 years of streamflow data (n=343).

The CAMELS-CL dataset provides snow-data (daily snow water equivalent time series) only for basins located between 25ºS and 37ºS, and only for 1985-2015. Therefore, we computed catchment-scale solid precipitation fractions and daily estimates for snowmelt over the period 1981-2018 based on the ECMWF ERA5-Land dataset, a land-surface reanalysis driven by the ERA5 atmospheric reanalysis. ERA5-Land results from an offline, post-simulation carried out with land surface component used in ERA5, including a higher spatial resolution (9 km) and other improvements (Copernicus Climate Change Service, 2019).



105 **Figure 1: Study catchments with mean annual precipitation (panel a), mean annual temperature (panel b) and mean annual snow fraction (panel c) for the period 1979-2018. Panel a presents the 9 administrative regions covered by the study.**

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 more 3000 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. The elevation of the Andes range also modulates the snowfall/rainfall partition, being larger in the semi-arid, northern

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part of the study region, and leading to contrasted precipitation and runoff seasonal cycles. In central Chile precipitation has a marked Mediterranean-type regime, with most storms occurring during the winter and with very dry summer conditions. Streamflow, instead, peaks on spring and early summer in snow-dominated basins. Based on this range of climatic conditions within the study catchments, which in turn affect hydrologic behaviour and drought propagation (as analysed in the following sections), we classified the study catchments into two groups. We refer as semi-arid catchments to the basins located between 30ºS and 34ºS, characterised by long-term annual precipitation values of 448 mm on average (ranging between 253 to 980 mm). The basins located between 34ºS and 41ºS are referred as temperate catchments and feature long-term annual precipitation values of 1824 mm on average (ranging between 672 to 3379 mm).

3 Methods

3.1 Drought characterization

Droughts were characterised by annual precipitation and streamfllow anomalies at the catchment-scale. 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. 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 deficits are at specific locations. Therefore, we also computed the annual deviations normalised by the standard deviation of the complete time series for the period 1979-2009 (i.e., z-scores).

To characterise the MD and asses how unusual this period has been in comparison to previous decades, we computed the 8-year mean for each water flux (precipitation and streamflow) during the MD. We compared them with historical eight-year average values. To increase sample size, we computed 100 synthetic values by randomly sampling and averaging eight annual values from the historical records.

3.2 Changes in catchment response during multi-year droughts

Stationarity in drought propagation under several consecutive years of precipitation deficits (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. These authors 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, for each catchment, we linearized annual R-R relationships by applying log-transformation to annual precipitation and runoff time series. We performed a global test to validate linear model assumptions with the R-package

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gvlma (Peña and Slate, 2006). From the initial sample (*n*=343), we selected 124 basins where the linear assumptions 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 (2010-1018) was different to the R-R relationship during the previous 40 years (1979-2009), 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 5% significance level, and ii) catchments that did not experience a significant shift (test p-value greater than 0.05). For those catchments experiencing a significant shift, we computed the degree of change in R-R regressions, as the relative difference between streamflow estimations from both linear regressions, given the same precipitation value. This characteristic precipitation value was defined for each basin as the average precipitation during the MD period (2010-2018).

3.3 Hydrological model

Since observations of groundwater storages and fluxes were not available, we run the HBV model (Bergström, 1972; Lindström et al., 1997) to simulate streamflow and other fluxes for each of the 124 study catchments. The HBV is a bucket-type model that simulates the main hydrological process 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, 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, also time series of a number of other fluxes and storages can be obtained from the model, such as actual evaporation, soil water storage, or the different streamflow components (baseflow, intermediate flow and peakflow).

As a result of the continuous simulation of the different storages within a catchment, the HBV model allows considering memory effects. However, it has to be noted that the model is a simplified representation of actual hydrological processes, which limits its capability to simulated 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 makes the model a useful tool to distinguish between memory effects caused by soil water storage and groundwater storage. The HBV model has been implemented in several software packages. Here we used the version HBV light (Seibert and Vis, 2012).

The HBV 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 (Pool et al., 2018), which resulted in ensembles with 100 parameter sets.

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3.4 Runoff mechanisms and hydrological memory

The hydrological memory of a catchment is a composite of the response times associated to the different physical mechanisms transferring and storing water through the basin. Thus it has been qualitatively related to the presence of aquifers, lakes and snow (Van Loon and Van Lanen, 2012). As a consequence, 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 analysed the main runoff generation mechanisms within the 124 study catchments and then assessed hydrological memory by computing different lag-correlation statistics. The mechanisms were explored by characterising the hydrological regimes of the study basins and identifying snow-dominated and pluvial catchments. Snow-dominated catchments were defined as those where the long-term snow fraction, computed as the average of ERA5-L solid to total precipitation ratio for the period 1981-2018, was larger than 0.3. We assessed the importance of groundwater mechanisms on streamflow generation based on the baseflow index (BFI), computed for each basin as the mean annual baseflow (defined as flow from the lower groundwater box in the HBV model) normalised by mean annual streamflow for the entire 1979-2018 period.

To assess the hydrological memory, we computed the correlation between precipitation (concentrated mainly in winter of a certain year *n*) and the generated streamflow and baseflow of the following seasons (up to fall of year *n+1*). Further, to remove the effect of the precipitation of the current year in annual R-R regressions, we computed the correlation (r^2) of the R-R regression residuals from Sect. 3.2 (i.e., annual streamflow not explained by the current precipitation) to the precipitation from the previous year. This represents the information gained when the precipitation from the previous year (lagged precipitation) is incorporated in the R-R relationships. We discuss the physical mechanisms explaining hydrological memory, and relate catchments memory with the shifts in R-R relationships and the propagation from meteorological to hydrological droughts during extremes dry years.

4 Results

4.1 Droughts over the last decades

Heatmaps in Figure 2 illustrate the deviations of precipitation and streamflow with respect to their climatological mean values for the period 1979-2009, normalised by mean values (relative anomalies, panels a and b) and normalised by standard deviations (z-scores, panels c and d). The unprecedented dry conditions during the last decade is evident. The spatial pattern of precipitation deficits for single years during the MD is characterized by general negative anomalies for the 124 catchments between 30°S and 41°S (Fig. 2a). Over the last four decades, we see few analogues to this spatial pattern,

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including 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 multi-year persistence of the MD spatial pattern, however, has no analogue over the study period and the last century (Garreaud et al., 2017).

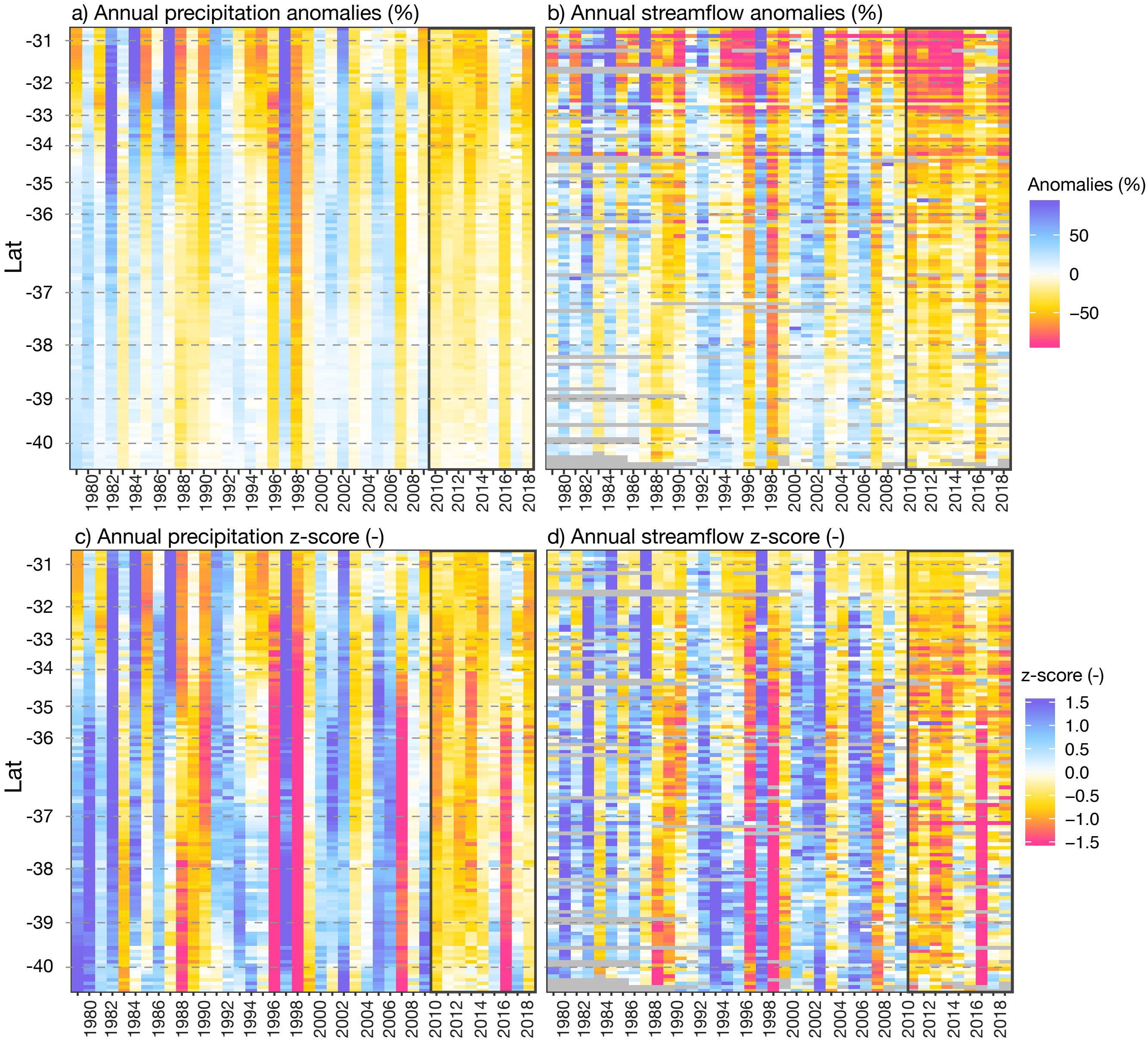

Figure 2: Annual deviations from climatology (1979-2010) for catchment-scale precipitation (panel a), streamflow (panel b). Panels c and d present the z-score of the annual precipitation and streamflow, respectively (computed as deviations from mean normalised by standard deviation). The MD period (2010-2018) 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.

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The relative anomalies in precipitation are consistently higher in semi-arid catchments (north of 34ºS) (Fig. 2a), 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 semi-arid catchments (z-scores closer to zero in Fig. 2c), where few meteorological events contribute to most of the annual accumulation. Thus, the interannual variability is higher than in southern basins, where several precipitation events occur during the year. During the MD in particular, annual precipitation in temperate basins decreases 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 are usually lower for these catchments, compared to semi-arid ones (north of 34ºS).

For the case of streamflow, annual anomalies (Fig. 2b) present larger values and larger variations in space and time than precipitation, which is due to the strong dependency of streamflow on local terrestrial characteristics. If we compare the spatial patterns of anomalies (Fig. 2b) and z-scores (Fig. 2d) during the MD, we see that consistently with precipitation, larger anomalies are observed in semi-arid catchments (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).

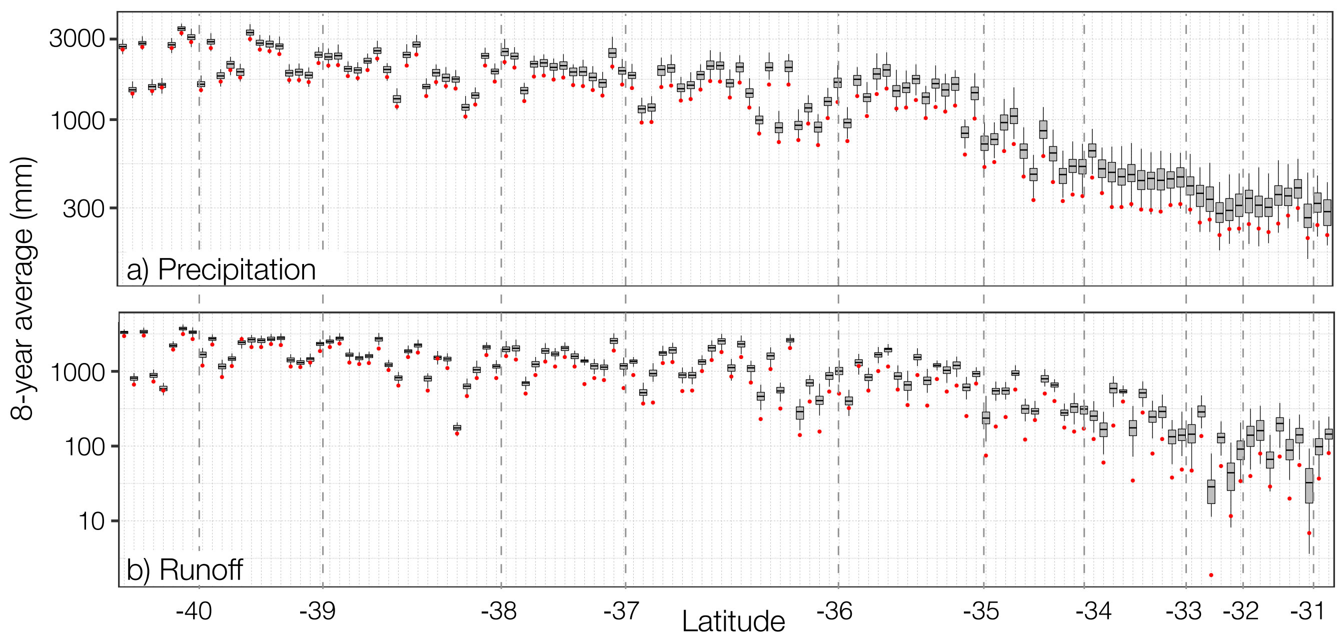

Figure 3: Boxplots of 8-year mean precipitation (panel a) and runoff (panel b). The red points correspond to the mean values during the MD (2010-2018). Please note the log-scale of the Y-axes.

To further characterize the MD anomaly, Fig. 3 presents the frequency distribution of 8-year mean precipitation and streamflow for each basin (Sect. 3.1), 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 87% of the study catchments (108 out of 124). The average runoff during the MD has been more extreme

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than precipitation deficits, with 94% of catchments (117 out of 124) presenting 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.

4.2 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. 4, a–c), while other catchments showed no significant change (Fig.4, d-f). Table 1 summarises the number of catchments that experienced a significant shift in R-R relationship during the MD, and their associated sifts. This table also summarises the results for those catchments with no change. From the 124 studied catchments, 66.9% had a significant change in the R-R relationship during the MD and 33.1% had not (Table 1).

For the catchments experiencing a change, the historical R-R regressions consistently underestimate the runoff deficits during the MD. 99% (82 out of 83) 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 semi-arid catchments was up to 77% lower than those predicted by the historical R-R relationship. In temperate catchments, these shifts reached up to 43% (Table 1).

While these results provide insights about changes in R-R relationship during a multi-year period, it does not indicate if the changes are progressive, i.e., if the basins progressively generate less water for a given precipitation amount, compared with the historical behaviour. We address this in the following sections, where runoff generation mechanisms, hydrological memory, and drought propagation are analysed in detail.

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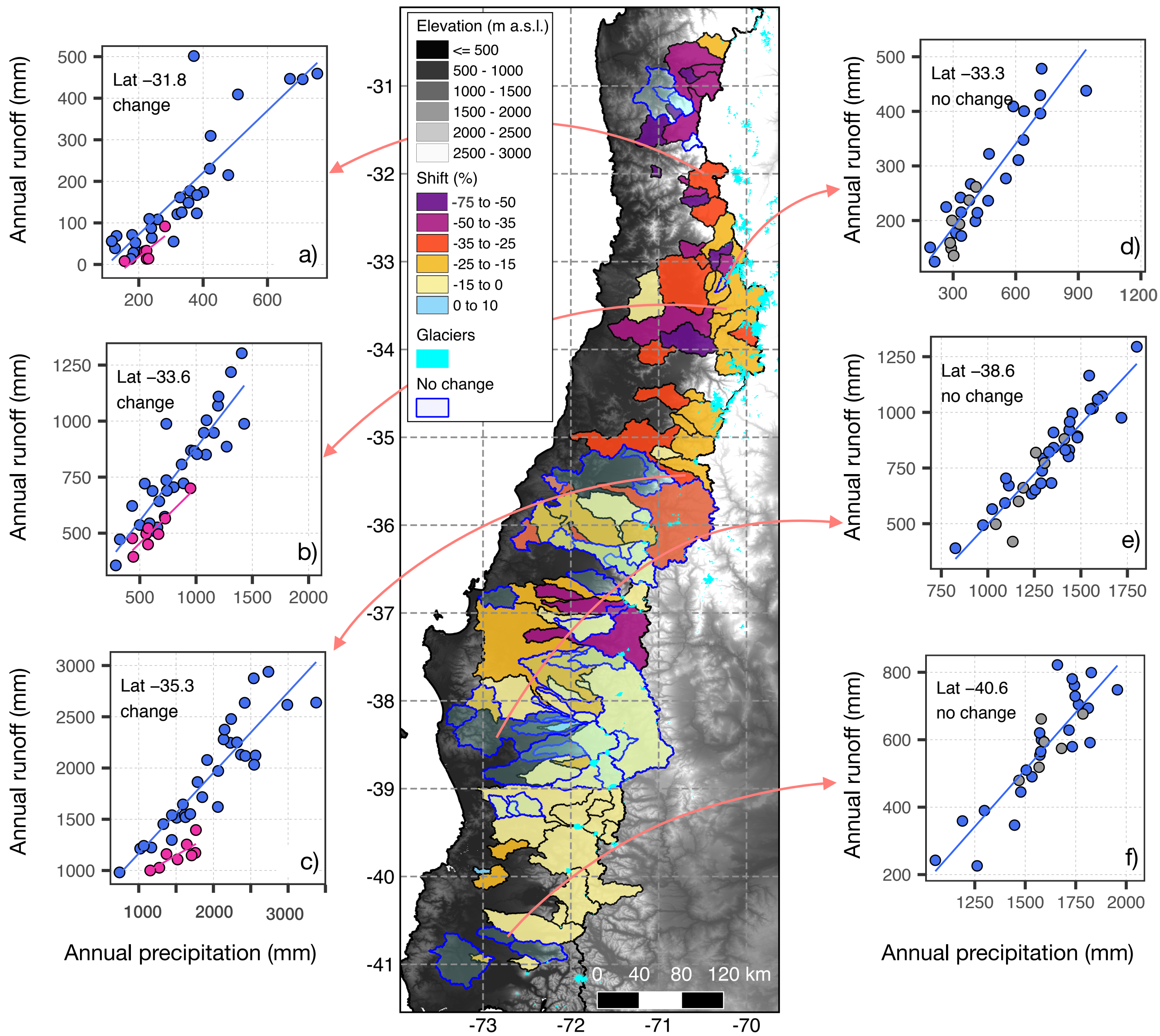

255 **Figure 4: Annual runoff (y-axes) and precipitation (x-axes) for 6 selected catchments with a significant change in R-R relationship during the megadrought (panels a-c) and without change (panels d-f). The years within the MD are highlighted in magenta (panels a-c) and grey (panels d-f). The map shows the catchments with change, coloured by their shift in R-R relationship. The 41 catchments with no significant change are outlined in blue.**

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Table 1: 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.

	Semi-arid (30ºS-34ºS)	Temperate (34ºS-41ºS)	Total
Change Mean shift (min, max)	31 -38% (-77%, -13%)	52 -16% (-43%, 27%)	83 -24% (-77%, 27%)
No change	5	36	41
Total	36	89	124

4.3 Hydrological memory

The typical hydrological regimes of the study basins are presented in Fig. 5. Based on a long-term snow fraction threshold of 0.3, we classified 49 catchments as snow-dominated and the remaining 75 as pluvial catchments. Most snow-dominated basins are located towards the north of the study region, given the higher elevation of the Andes in central Chile (Fig.1). 83% (30 out of 36) of semi-arid catchments were classified as snow-dominated, while 78.4% (69 out of 89) of temperate catchments were classified as pluvial. Towards the south, temperate catchments are controlled by winter precipitation with a seasonal synchronicity between precipitation and streamflow. If solid precipitation does occur, it melts within the same season.

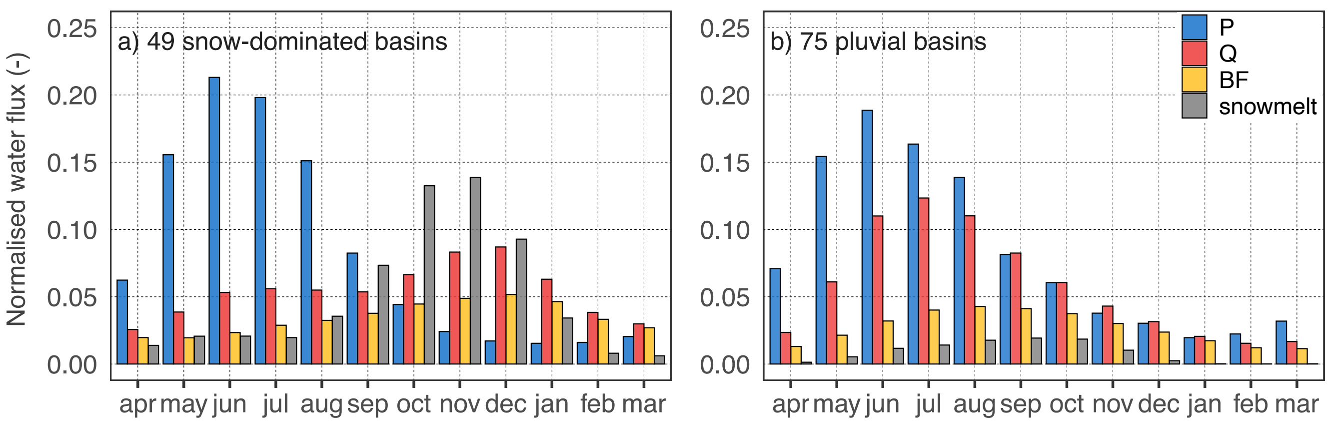

Figure 5: Hydrologic regimes for snow-dominated catchments (panel a) and pluvial catchments (panel b). The mean monthly fluxes of precipitation (P), streamflow (Q), baseflow (BF) are normalised by the annual P from CAMELS-CL dataset for the period 1979-2018. Since snowmelt was obtained from a different dataset, the mean monthly snowmelt fluxes are normalised by the mean annual precipitation from ERA5-Land.

To explore the importance of groundwater within the study catchments, in Fig. 6 we present the BFI computed from HBV simulations. The HBV model calibration resulted in overall acceptable simulation performance, with values of 0.72, 0.89 and

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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.

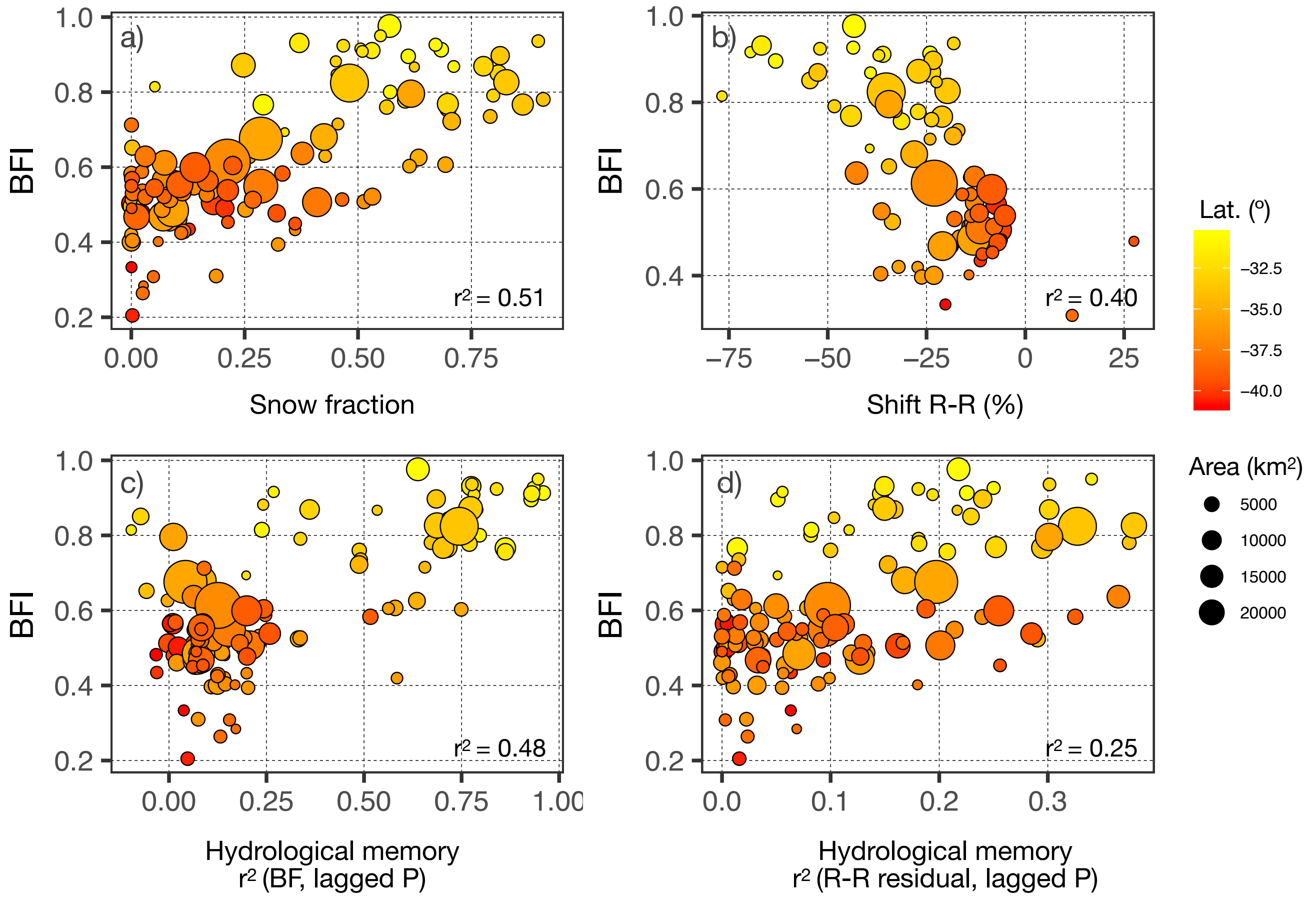

Figure 6: BFI as a function of catchments snow fraction (panel a), and the shift in R-R relationships (panel b). Panel c relates BFI with hydrological memory quantified as the r^2 between winter precipitation and fall-baseflow from the following year. Panel d relates BFI with hydrological memory quantified as the r^2 between the residuals in R-R regressions, with the annual precipitation from previous year.

Although the BFI does not provide explicit information about the processes behind the slow flow contribution to runoff (e.g., subsurface routing and drainage density, storages), it is a proxy of the overall baseflow contribution to runoff. Groundwater mechanisms depend on several factors that vary across basins, including topography, soil properties, geology, drainage area and water table levels (Robinson and Ward, 2017). Observations from most of these components are commonly not available, so here we focus on the water entering the soil routine in HBV (total precipitation minus evapotranspiration) and the water leaving the system as baseflow (represented by the BFI). These two components are related (Fig. 6a), with snow-dominated catchments having a larger contribution of baseflow to runoff (r^2 = 0.51). In Fig. 6b we show that, for those catchments with significant change (Sect. 4.2), higher BFI values are associated to larger shifts in R-R relationships (r^2 = 0.51), and thus to the intensification of drought propagation during the MD, with respect to historical annual responses to

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droughts. The relationship between snow fraction and R-R shifts is not strong ($r^2 = 0.11$, not shown here), probably since snow processes control the hydrologic response of a subset of catchments experiencing significant change in R-R relationship, whereas baseflow is inherent to all basins.

The correlation between fall-winter precipitation and the resulting streamflow (Fig. 7a) and baseflow (Fig. 7b) over the following seasons allows exploring the hydrological memory further. Fall-winter precipitation 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 7a indicates that fall-winter precipitation explains more than half of the variance in spring (OND) and summer (JFM) streamflow in catchments located north of 36°S. This indicates that snowmelt governs runoff generation in these catchments.

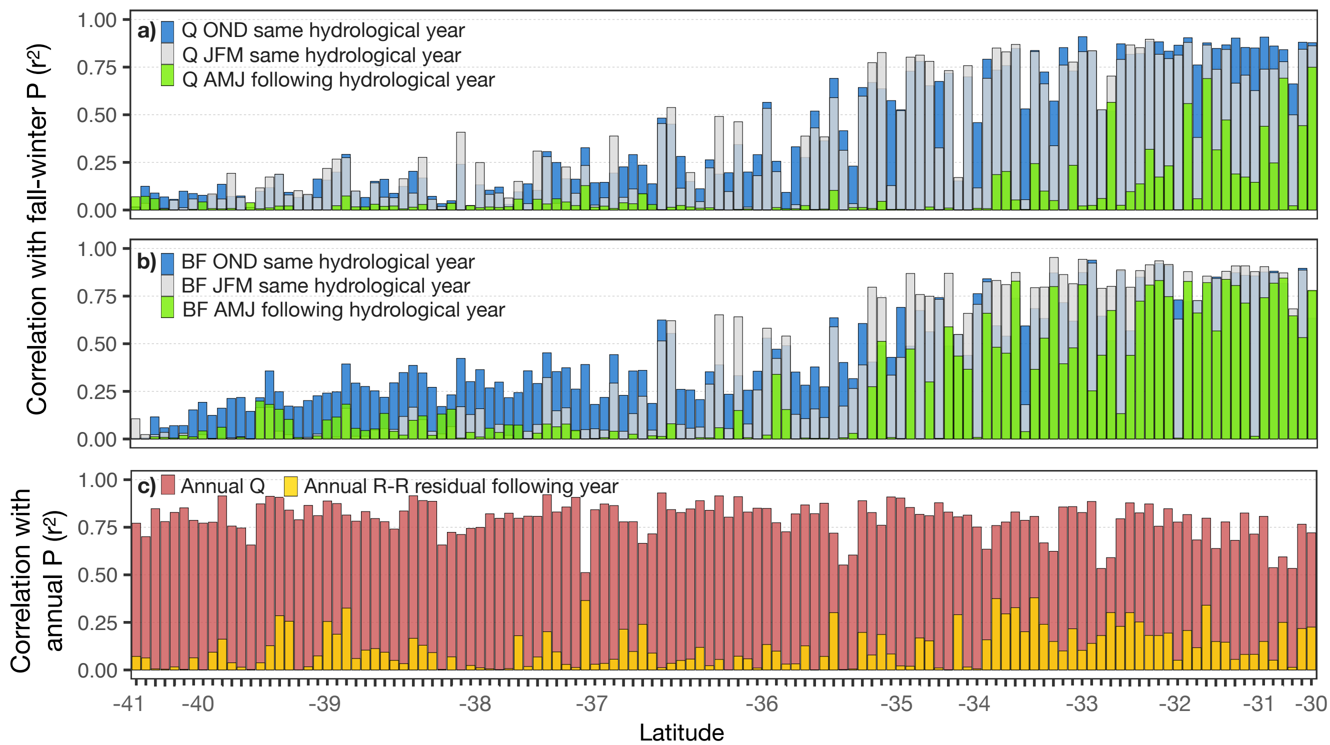

Figure 7: Catchment memory represented by the variance in seasonal runoff (panel a) and seasonal baseflow (BF, panel b) explained by fall-winter precipitation (P). Panel c shows the r^2 between annual precipitation and annual streamflow (r^2 of R-R regressions), and the variance of the R-R residuals explained by the precipitation from the preceding year.

In semi-arid catchments, hydrological memory beyond one hydrological year (April to March) is represented by the correlation between fall-winter precipitation and the streamflow in the fall season of the following year (green bars in Fig. 7a and 7b). The high r^2 values (up to 0.75 in some northern catchments) indicate that fall-winter precipitation is contributing to the following year runoff as baseflow, since snowmelt process is mostly finished by January (Fig. 5a).

For the temperate catchments, there is some memory effect beyond one hydrological year, represented by the correlation between fall-winter precipitation and seasonal baseflow of the following year (Fig. 7b). The relatively low r^2 values (below

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0.25 in most basins) are due to fall-winter precipitation of the current year explaining most of the generated streamflow (these are mostly pluvial catchments), which overshadows the dependency with previous seasons. To remove the effect of the precipitation of the current year, we computed the dependency of the R-R regression residuals from Sect. 4.2 (i.e., annual streamflow not explained by the current precipitation) to the precipitation from the previous year. The R-R residuals r^2 values in Fig. 7c (corresponding to positive correlation coefficients, not shown here) are also an indicator of hydrological memory since they show that the precipitation explains a part of the annual streamflow from the previous year. Interestingly, although the residual r^2 is larger in semi-arid catchments (mostly snow-dominated), there are also significant values in the most humid and pluvial basins southward, suggesting that baseflow in pluvial catchments may also contribute to more extended catchment memory.

The relationship between hydrological memory and groundwater dynamics was further explored in Fig. 6c and Fig. 6d. These plots show that larger BFI values are associated with stronger longer-than-a-year hydrological memory, represented by larger increments in r^2 from Fig. 7c, and larger r^2 values between winter precipitation and baseflow from the following year (green bars in Fig. 7b). In the next section we provide a more detailed analysis of the relationship between hydrological memory and drought propagation.

4.4 Extreme versus persistent droughts

Figure 8 presents drought propagation for 25 years with negative anomalies over the last four decades (see Fig. 2). Drought propagation is represented by the difference between runoff and precipitation deficits (red markers in Fig. 8). In the semi-arid basins, the difference increases 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 end of a hydrological drought after a meteorological drought has ceased (Yang et al., 2017). While 2016 had above-average precipitation in semi-arid 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. 4.3) and the 7-year (2009 to 2015) precipitation deficits prior 2016, which probably prevented 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 (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 temperate catchments (Fig. 8b), prior to 2010, drought propagation has been around 10% (i.e., streamflow deficits are, on average, 10% larger than precipitation deficits), 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

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years (2012 and 2016) where drought propagation was intensified (red markers below 20%). These larger streamflow deficits during the MD may be due to different factors, including the hydrological memory of these basins (Sect. 4.3) and the large ET in 2012 and 2016 (positive anomalies, and z-scores above 1.5, as can be seen in Fig. S1) combined with large precipitation deficits. Since R-R relationships do not explicitly account for variations in ET, the anomaly values of ET during the MD might explain the R-R shifts identified in some temperate catchments (Fig. 4). Furthermore, towards the south of the study region, basins move from water-limited to energy-limited (Alvarez-Garreton et al., 2018). Therefore, ET in temperate catchments is modulated by both the available water and the available energy.

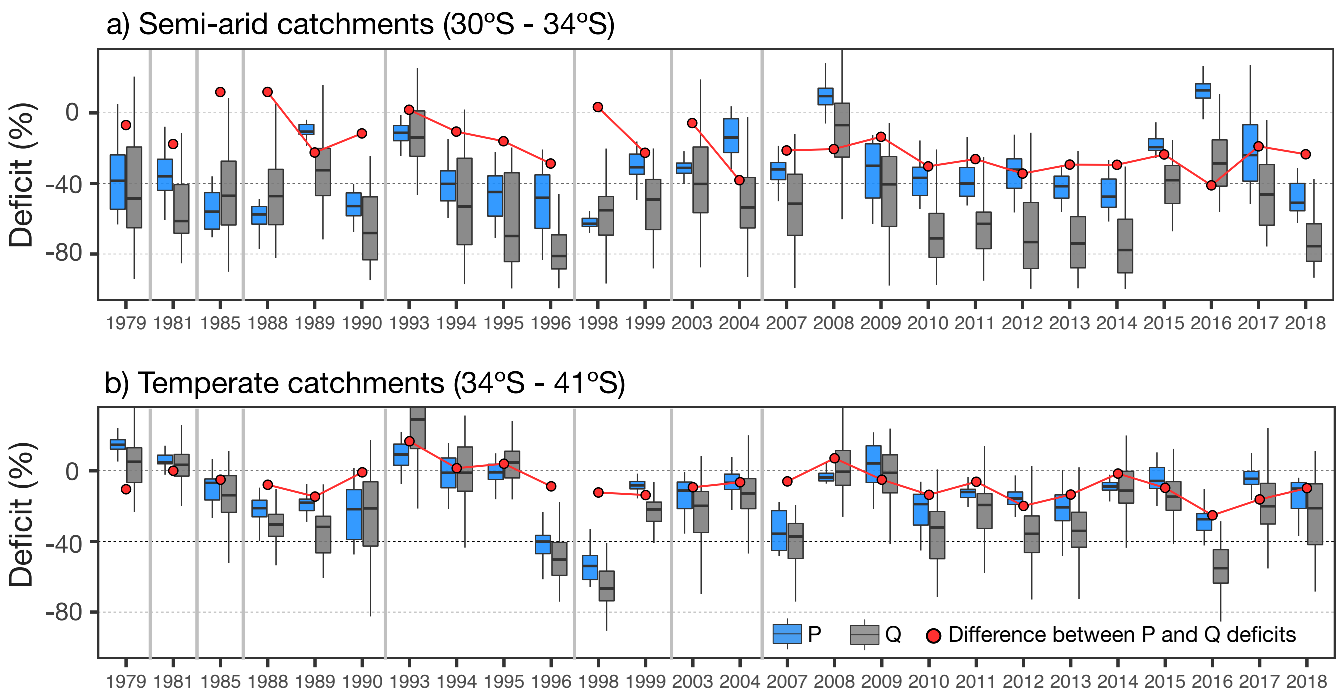

Figure 8: Precipitation and runoff deficits for dry years for northern semi-arid catchments (panel a) and southern temperate catchments (panel b). The difference between runoff and precipitation deficits are represented by red points and consecutive years are connected with red lines.

Finally, to analyse catchment responses during short extreme droughts and persistent moderate droughts, Fig. 9 presents drought propagation for three cases: i) single-year extreme droughts (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); ii) single-year extreme droughts preceded by a dry year (mean precipitation below average); iii) persistent years with precipitation anomalies below -5%.

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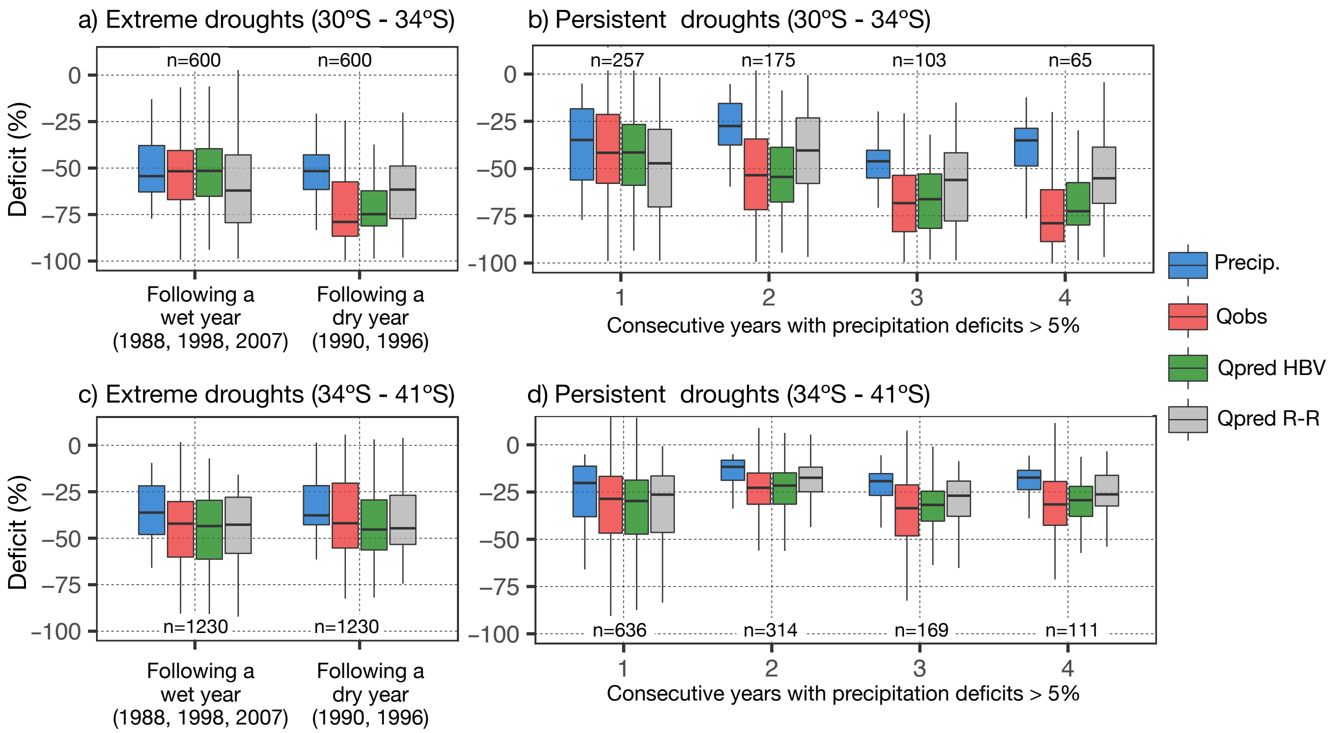

Figure 9: Observed and simulated annual drought propagation for consecutive dry years. Panel a presents the results for semi-arid catchments, and panel b for humid catchments. The number of cases is presented for each set of boxplots.

5 Discussion

Longer-than-a-year hydrological memory is related to slow groundwater and subsurface flow which is responding to precipitation from previous seasons (Fig. 7b). In catchments where snow processes contribute significantly to runoff generation, the importance of low-flow contribution to runoff is positively correlated with snow accumulation (Fig. 6a).

A higher baseflow in basins with higher proportion of solid precipitation can be interpreted by analysing the groundwater recharge mechanisms when the snow melts. Snowmelt infiltrates in situ, where ET is low compared to precipitation, the soil storage is shallow and there is a low permeability bedrock underneath (Carroll et al., 2019). 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 the 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). The large snowmelt infiltration rates at high elevations during snowmelt season, combined with the absence of precipitation events (precipitation is concentrated in winter season)

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would explain the higher BFI in snow-dominated basins and is consistent with the positive correlation between BFI and per cent of precipitation falling as snow reported in Upper Colorado River Basin (Rumsey et al., 2015).

Further, high snow fraction ratios 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, which may support groundwater recharge from interflow. The role of snow in hydrological memory and its relation to water provision during droughts reveal the need to understand seasonal characteristics of drought propagation further. 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 expected (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).

In addition to the climatic characteristics (e.g., the ratio between solid and liquid precipitation), groundwater contribution to runoff depends on physical factors (e.g., geology, topography, soil properties, soil drainage density), which are not explored in this paper, and which may explain the large scatter in Fig. 6a.

Our results also indicate that hydrological memory is related to the intensification of drought propagation during multi-year droughts. This can be seen in Fig. 6b, where catchments with longer hydrological memory (represented by higher BFI, as shown in Fig. 6c and Fig. 6d) present larger shifts in R-R relationships. This is consistent with the conceptualisation proposed by Carey et al., (2010), who classified basins that can store water over long time periods (i.e., long hydrological memory) as catchments with higher resistance, and showed that such catchments featured lower resilience, defined as a lower capacity to keep their normal functioning (translating inputs to outputs) under changing inputs.

When we analyse isolated extreme droughts, and consistently with the large hydrological memory in semi-arid 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 condition of groundwater reservoirs. This is also observed in persistent but moderate droughts, where under similar precipitation deficits, the surface water supply in semi-arid regions consistently decreases after one year with below-average conditions. This result also 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.

Wetter and more rainfed basins in the study region generally show a weaker longer-than-a-year hydrological memory than semi-arid catchments, which may be explained by their pluvial or mixed hydrologic regimes, and their lower groundwater contribution to runoff. The weaker hydrological memory leads to a more similar behaviour under extreme meteorological droughts occurring after a wet and a dry year (Fig. 9c), which is in line with the concept of resilient catchment proposed by Carey et al., (2010). However, even when these basins are largely controlled by precipitation during the same year, there is some over-one-year memory (Fig. 7c), which is reflected by a decrease in streamflow generation after one year of consecutive precipitation deficits (Fig. 9d). This effect is well captured by the HBV model, while the annual R-R

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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

6 Conclusions

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 semi-arid catchments compared to temperate catchments. However, observing such large deficits at a single year in the northern region is not unusual given its highly variable rainfall regime. The precipitation anomalies experienced in the southern region, on the other hand, were highly unusual considering the last four decades. When we aggregated the entire 8-year MD period, precipitation and streamflow anomalies are shown to be extremely unusual across the complete domain.

The persistent precipitation deficits have led to larger than expected water deficits in 68.5% of the study catchments when compared to their historical (1979-2009) streamflow response to precipitation (R-R relationship). This indicates that there has been an intensification in drought propagation over the last decade. We argue that this intensification during multi-year droughts reflects the hydrological memory within a catchment. Hydrological memory is directly related to groundwater storages, which respond to liquid and solid precipitation of the previous seasons. Within this study region, catchments are more snow-dominated towards the north due to the higher elevation of the Andes in central Chile, and present a larger contribution of groundwater to runoff.

Catchments with more extended hydrological memory showed larger shifts in R-R relationships, which is related to the intensification of drought propagation during multi-year droughts. Water deficits during a meteorological drought in basins with longer hydrological memory are closely tied to previous meteorological conditions. For semi-arid catchments (30ºS-34ºS), after one year of precipitation deficits, the surface water supply –under equivalent precipitation deficits– significantly decreases. That is, the basins progressively generate less water for a given precipitation amount, compared with the historical behaviour. Catchments in the southern part of the study region (34ºS-41ºS) generally feature a shorter memory, since they have a more pluvial regime, with less predominant groundwater contribution to streamflow. In these catchments, the annual streamflow is mostly explained by the precipitation of the current year, and this is reflected by a slighter decrease in water supply after consecutive years of precipitation deficits, compared to semi-arid catchments.

Our results also reveal the limitations of predicting annual streamflow based only on precipitation (R-R relationship). Explicitly accounting for other processes and fluxes (ET, snow, soil moisture and groundwater dynamics), in particular those representing hydrological memory, improves the predictability of water deficits, and this becomes particularly relevant under persistent climate anomalies, such as the MD.

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 semi-arid regions of Chile, catchments strongly depend on both the current and previous precipitation seasons. Soil water levels can be slowly (more than a year) and rapidly (during the same year) depleted, both cases leading to large water deficits. The worst scenario would be an extreme meteorological drought following consecutive years of below average precipitation, as occurred in 2019 (not analysed in this paper). In more pluvial regimes, initial conditions and hydrologic memory are still important factors to represent catchment response fully. However, 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.

This work provides new evidence and knowledge about drought propagation. We argue that hydrological memory plays a key role in catchments response to persistent droughts, and show that extreme and persistent droughts impact water supply in different ways depending on catchment characteristics. Since the propagation of persistent droughts is modulated by catchment memory, which in turn is related to snow dynamics, future work should focus on seasonal characteristics of drought propagation.

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. However, snow and baseflow dynamics also lengthen hydrological memory of a basin and therefore makes them prone to intensify the propagation of persistent droughts. For adaptation strategies, we recommend focusing future work on linking drought propagation and hydrological memory to water scarcity, which requires to incorporate human activities and the long-term use of water resources.

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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