Evaporation enhancement drives the European water-budget deficit during multi-year droughts

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Abstract. In a warming climate, periods with below-than-average precipitation will increase in frequency and intensity. During such periods, known as meteorological droughts, the decline in annual runoff may be proportionally larger than the corresponding decline in precipitation. Reasons behind this exacerbation of runoff deficit during dry periods remain largely unknown, and this challenges the predictability of when this exacerbation will occur in the future and how intense it will be. In this work, we tested the hypothesis that runoff-deficit exacerbation during droughts is a common feature across climates, driven by evaporation enhancement. We relied on multidecadal records of streamflow and precipitation for more than 200 catchments across various European climates, which distinctively show the emergence of similar periods of exacerbated runoff deficit identified in previous studies, i.e., runoff deficit on the order of -20% to -40% less than what expected from precipitation deficit. The magnitude of this exacerbation is two to three times larger for basins located in dry regions than for basins in wet regions, and is qualitatively correlated with an increase in annual evaporation during droughts, on the order of +11% and +33% over basins characterized by energy- and water-limited evaporation regimes, respectively. Thus, enhanced atmospheric and vegetation demand for moisture during dry periods induces a nonlinear precipitation-runoff relationship for low-flow regimes, which results in an unexpectedly large decrease in runoff during periods of already low water availability. Forecasting onset, magnitude, and duration of these drops in runoff availability have paramount societal and ecological implications, especially in a warming climate, given their supporting role for water, food, and energy security. The outcome that water basins are prone to this exacerbation of runoff deficit for various climates and evaporation regimes makes further understanding of its patterns of predictability an urgent priority for water-resource planning and management in a warming and drier climate.

1 Introduction

Timing and seasonality of runoff (Q) from a river basin are dictated by the interaction across incoming precipitation (P), atmospheric and vegetation water use (evaporation, ET), and the variation in water stored in the basin (ΔS): $Q = P - ET - \Delta S$ (Bales et al., 2018). While changes in precipitation will ultimately affect runoff, processes driving the precipitation-runoff relationship (Saft et al., 2016) are complicated by the nonlinear and often delayed response of ET and ΔS (Bales et al., 2018; Avanzi et al., 2020). Depending on the direction of precipitation change, evaporation-precipitation feedback mechanisms may comprise vegetation expansion and/or mortality (Senf et al., 2020; Choat et al., 2018) and *vice versa* (Gouveia et al., 2017; Biederman et al., 2014), wildfires (Bowd et al., 2019), a shift in the composition of vegetation according to species-specific water-use strategies (i.e., isohydric to anisohydric prevalent species), and depletion of regolith water storage and rock moisture (McDowell, 2018; Domec and Johnson, 2012; Gentilesca et al., 2017). For instance, weathered bedrock and rock moisture are significant water sources for plant transpiration in addition to soil water in Mediterranean climates (Goulden and Bales, 2019; Hahm et al., 2019; Rungee et al., 2019; Klos et al., 2018). If access to the whole of the regolith is not possible, or regolith moisture has already been depleted as a consequence of a long deficit in precipitation, plant mortality occurs, further decreasing basin-scale transpiration (Karban and Pezzola, 2017; Senf et al., 2020). The rate and distribution of regolith-storage recharge and drainage also depends on precipitation, for example in terms of enhanced soil hydrophobicity during periods with low precipitation and the related disconnection between soil and groundwater storage (Rye and Smettem, 2017). These processes are intertwined with changes in other climatic factors, such as air temperature, making water basins to profoundly co-evolve with climate (Troch et al., 2015).

The fact that runoff deficit is not only dictated by atmospheric demand but other factors play a role like access of plants from deep water storage and specific vegetation response to water stress (often not well represented in Earth system models, e.g., (Fowler et al., 2020; De Kauwe et al., 2015)) is especially true when prolonged precipitation deficits occur such as those experienced during multi-year drought periods. While for a single dry year catchment storage may sustain a higher than usual evaporation rate (Orth and Destouni, 2018), this might not happen during multi-year droughts. During multi-year droughts, precipitation deficit and pre-existing catchment conditions (e.g., storage) modulate the response of evaporation to temperature anomaly in ways that are only partially quantified and predictable and that have direct consequences on runoff volumes. These aspects make multi-year droughts essentially different from individual and shorter dry years and motivate specific research on this topic. Note that we are not excluding here that runoff deficit exacerbation can also manifest during single severe drought years as the one impacted Europe in 2018 (see the article collection: https://royalsocietypublishing.org/toc/rstb/2020/375/1810). However, here we will focus on multiyear drought periods as it is our interest to understand mechanisms leading to hydrological drought during long and sustained precipitation deficit periods, as already done by (Avanzi et al., 2020; Saft et al., 2016, 2015).

The relevance of ET and storage during droughts has been recognized for a long time (Teuling et al., 2013; Miralles et al., 2019), but the runoff implications of their response to precipitation changes are still poorly understood (Goulden and Bales, 2019). For instance, Orth and Destouni (2018) found that runoff decreases account for 65–80% of the precipitation deficits, while ET reductions are small and only notable in dry climates, accounting for 0–20% of the precipitation deficits. In other words, they found that the decline in runoff during droughts is faster and stronger than that in evaporation. While Orth and Destouni (2018) provided pieces of evidence of the importance of soil moisture and evaporation in the propagation of the meteorological drought into hydrological droughts, they did not focus specifically on multi-year drought periods, nor they quantified explicitly the further aggravation of runoff deficit with respect to precipitation deficit. In this regard, previous studies have shown that prolonged meteorological droughts may indeed result in a larger-than-expected decrease in runoff (Saft et al., 2015; Avanzi et al., 2020; Tian et al., 2018; Mastrotheodoros et al., 2020; Tian et al., 2020; Alvarez-Garreton et al., 2021). This observation not only shows that precipitation deficit is an insufficient predictor for fully characterizing droughts, but also proofs that the coevolution of water basins with climate (in the form of ET and ΔS) may play a non-negligible role in driving meteorological to hydrological droughts, as during these periods plants adapt differently to water stress (McDowell et al., 2008) and might access water even from very deep water pools (Fan et al., 2017; Klos et al., 2018; Goulden and Bales, 2019; Hahm et al., 2019; Carrière et al., 2020) thus subtracting water from storages potentially destinated to runoff.

The ultimate cause behind this observed exacerbation of runoff deficit is still unknown, with previous works providing contrasting and not conclusive results related either to the buffered response time of evaporation to precipitation deficit (Avanzi et al., 2020) or to streamflow memory (Alvarez-Garreton et al., 2021). It is also unclear whether this exacerbation takes place only in specific climates , such as Mediterranean regions where precipitation distribution is skewed toward winter and summer is normally dry (Feng et al., 2019), or whether exacerbation of runoff deficit during meteorological droughts is a common feature of water basins across climates. In this regard, previous works in non-Mediterranean regions of Europe showed the evaporation amplifies the impact of summer droughts, but these studies mostly focused on storage rather than on runoff exacerbation (Teuling et al., 2013). Large-scale assessments spanning a variety of climates are still needed to gain further understanding of the runoff implications of meteorological droughts. Assessing the validity and the large-scale occurrence of this behavior especially over a variety of basins with different climate and hydrological characteristics has important implications for defining sustainable water management strategies and understanding potential ecological traits and is becoming more and more urgent due to the increasing frequency and magnitude of drought events (Roudier et al., 2016; Sheffield and Wood, 2008; Samaniego et al., 2018; Wehner et al., 2011; Haile et al., 2020).

In this work, we answered the following research questions:

i. do multiyear droughts in Europe correspond to an exacerbation of runoff deficit compared to precipitation deficit?
ii. If so, how severe is this exacerbation and how much is related to a coupled increase in water allocated to evaporation?
iii. Finally, what are the potential drivers of this exacerbation?

To answer the above defined research questions, we used long-term observations from 210 basins across different European climates (area from 200 to 50,000 km2). We calculated if basins show a runoff deficit comparatively larger than expected (i.e., a shift in the water balance), by fitting a multivariate regression across annual cumulative streamflow, basin-averaged cumulative annual precipitation, and a categorical variable denoting drought and non-drought years. The basins analysed, located from −10◦ to +25◦E and from +35 to +70 ◦N, experienced at least one multi-year drought episode over the period 1979-2016.

2 Data and methods

2.1 Study area

The study area was initially composed of 1,043 basins, with an area ranging in size from 200 to 50,000 km². Basins are scattered across Europe, over a longitude varying from 10W to 25E and a latitude from 35 to 70°N (see Figure 1). The considered region is characterized by a complex topography, with the Alpine and Pyrenees Mountain chains crossing the continent from west to east. Hilly plateaus gently slope towards the Great European Plain, a low, flat region extending from the Atlantic coast of France to the Urals, crossed by many rivers and with densely populated cities. The climate is humid continental in central and eastern Europe (with cold summers) and Mediterranean in southern Europe (with dry summers and humid winters). Mean annual precipitation across Europe ranges from about 300 to 4000 mm yr^{-1}, depending on the location. The north Atlantic coast of Spain, the Alps and Balkan countries generally receive higher precipitation amounts. Flood occurrence ranges from spring to summer, moving from northeastern Europe towards the Alps, whereas the Mediterranean region and western Europe are mainly subject to winter floods (Berghuijs et al., 2014).

2.2 Precipitation, temperature, evaporation, and soil data

The present analysis relies on two high-quality precipitation data sets: one having a comparatively high spatial resolution (i.e., 0.25°) and using ground-observations (the European Climate Assessment & dataset project E-OBS, (Haylock et al., 2008), and a reanalysis dataset (ERA5, Hersbach et al., 2020), spatial resolution 36 km see below). The gridded-precipitation dataset E-OBS is derived through interpolation of the ECA&D (European Climate Assessment & Data) station data. The station dataset comprises a network of 2,316 stations, with the highest density of station in northern and central Europe and lower density in the Mediterranean, northern Scandinavia and eastern Europe. E-OBS was used to analyse the precipitation-runoff relationship for each basin, while ERA5 was used for the drought characterization. The motivations of the use of two different precipitation data sets are further explained in Section 2.5.

From ERA5 we also extracted actual and potential evaporation. ERA5 is the latest climate reanalysis produced by the European Centre for Medium-Range Weather Forecasts (ECMWF), providing hourly data on many atmospheric, land-surface and sea-state parameters together with estimates of uncertainty. Actual evaporation from ERA5 reanalysis was used because its relatively high quality (Martens et al., 2020) over its predecessor ERA-Interim which already showed relatively good performance in comparison to other evaporation products and in closing the water balance of many catchments worldwide (Miralles et al., 2016). In particular, the good performance is expected over especially over Europe where a substantially large volume of observations is ingested within ERA5. The latter is expected to provide an improvement of the accuracy in the simulation of latent heat fluxes determined by vegetation and land cover change. On the other hand, attempts to implement more complex land cover and vegetation changes in the ECMWF model's land cover characterization (by leveraging on state-of-the-art earth observations) showed mostly neutral impacts on the simulated surface latent and sensible heat fluxes when compared against 51 FLUXNET stations over 1996–2014 over Europe (Nogueira et al., 2021).

Precipitation, actual and potential evaporation as well as air temperature variables used in this study are characterized by a spatial resolution of 36 km and monthly temporal resolution. ERA5 data were downloaded from the Copernicus Climate Change service (last access: 24 April 2020, see data availability section below).

Both precipitation and evaporation data were extracted for each basin by selecting pixels falling within the catchment boundaries and then averaged to provide basin-averaged annual precipitation and evaporation time series since 1979. E-OBS and ERA5 precipitation and evaporation variables were accumulated over the yearly time scale, while monthly temperature data were average out to obtain mean yearly temperature.

Catchment-average soil properties (rooting depth and total available water content) were obtained from the European Soil Database Derived Data product (Hiederer and Hiederer, 2013) for each basin.

The climate of the specific basin was defined based on the aridity index which we calculated as the ratio between long-term average annual potential evaporation and precipitation (both from ERA5) (Unesco, 1979). Note that this is index was used for the mere climate classification while departures from it during multi-year drought periods and its impact on the precipitation-runoff relationship are beyond the scope of the study.

2.3 Runoff data

Daily streamflow records for the 1980-2015 period over Europe were obtained by merging the Global Runoff Data Base (GRDC); the European Water Archive (EWA); the Italian ISPRA HIS national database; the Portuguese national database; and the Spanish national database (see data availability note for more information). Most of these streamflow records mainly derived from near natural catchments were also used in previous studies as for instance by (Stahl et al., 2010) and Orth and Destouni (2018) and, according to the authors, are characterized by relatively small human influence.

However, an additional severe screening was carried out to avoid the influence of human regulations by considering the following processing steps:

1. From an initial number of more than 3,900 stations, 1,043 stations were retained by excluding (via visual inspection) those with evident dubious patterns due to human regulations (such as constant flows), inhomogeneity, problems in low flow range, missing values for a long period of time (> 2 year) (as suggested in (Kundzewicz and Robson, 2004), or an observation period below 20 years.
2. Gauged stations for catchments with an area larger than 50,000 km^2 were excluded by the analysis because human disturbance is unavoidable at that scale (Piniewski et al., 2018).
3. Discharge time series were partially gap-filled via linear interpolation for a maximum time window of 5 days.
4. Only years where the number of observations were available for more than 350 days were retained.

Although care was taken in identifying these issues, some human-induced alterations are likely to be still present in these time-series. Nevertheless, a certain degree of disturbance can be tolerated (Murphy et al., 2013), considering also the annual granularity of our analyses. To avoid influence of the catchment area and to be coherent with the units of precipitation and evaporation streamflow measurements have been expressed in terms of runoff (i.e., we have considered the catchment area to transform m^3/s to mm/year).

2.4 Multi-year drought definition

Multi-year droughts were identified based on the precipitation deficit. The reason for using precipitation to characterize the multi-year drought period is that we are interested in analyzing the runoff response, therefore it was not used to define the drought (Saft et al., 2016). In particular, we used the indications of (Saft et al., 2016) to define a multi-year drought period, using precipitation anomalies (i.e., the departures from the mean divided by the standard deviation). The following procedure was adopted:

1. Calculation of the precipitation anomalies. The latter were calculated both on the mean annual precipitation and on precipitation smoothed with a three-year moving window. Smoothing was applied to avoid single wet years to interrupt a long and significantly dry period and was only used to set the beginning of the multi-year-drought period.
2. To reduce the blurring effect of the moving window, the exact end date of the dry period was determined through analysis of the unsmoothed anomalies data from the last negative three-year anomaly. The end year was set as the last year of this three-year period unless: i) there was a year with a positive anomaly larger than 0.15, in which case the end year was set to the year prior to that year; or ii) if the last two years had slightly positive anomalies (but each less than 0.15), the end year was set to the first year of positive anomaly;
3. The first year of the drought remained the start of the first three-year negative anomaly. To ensure that the dry periods were sufficiently long and severe, we only used dry periods with the following characteristics: i) length over three years; ii) mean dry period anomaly < -0.8.
4. By defining drought in this way, we ended up with 210 basins out of 1043 having experienced at least one multi-year drought episode over the available period of record.

Although relaxing the procedure for the multi-year drought definition would have brought to a larger sample of basins, we preferred to maintain this approach to have consistent results with previous studies (Saft et al., 2016) and because doing so guaranteed that the period analysed coincided with a period of a severe precipitation deficit. The above procedure resulted in a satisfactory multi-year drought definition (see Figure 2) that was validated with data found in the literature (Spinoni et al., 2015 see result section) with a minimum of three years to a maximum value of eight years for few basins (median duration of four years). Note that we also:

1. tested different thresholds (i.e., larger than 3 years), without noticing any significant difference in the results;
2. cross validated our drought definition (i.e., based on yearly precipitation anomalies divided by the standard deviation) technique with the use of a classical SPI-12 based on monthly data (not shown) and found almost identical patterns

between the two. However, given that our analysis focus on annual water balance we preferred to maintain the use of the precipitation anomalies.

2.5 Shift in the precipitation-runoff relationship

We detected shifts in the precipitation-runoff relationship by fitting a multivariate regression across annual cumulative streamflow (target variable), basin-averaged annual precipitation, and a categorical variable denoting drought and non-drought years (Avanzi et al., 2020; Peterson et al., 2021)

$$Q_{BC} = b_0 + b_1 I + b_2 P + \epsilon \tag{1}$$

where I is a categorical drought variable (1 for years characterized by multi-drought and 0 otherwise, b_0 , b_1 , and b_2 are regression coefficients, ϵ is noise, and Q_{BC} is annual streamflow transformed according to a Box-Cox transformation following the arguments in (Avanzi et al., 2020):

$$Q_{BC} = \frac{Q^{\lambda} - 1}{\lambda} \tag{2}$$

where λ has been estimated from data to ensure linearity and heteroscedasticity (i.e., the λ that maximizes the log-likelihood function, (Box and Cox, 1964). A parameter b_1 different from zero (p-value <0.05) indicates a shift of the precipitation-runoff relationship during multi-year droughts. Following Avanzi et al., (2020) the statistical significance of coefficient b_1 during droughts was assessed based on whether the signs of the confidence bounds agreed (significance level α=5%, (Kottegoda and Rosso, 2008).

The relative magnitude of the shift in precipitation vs. runoff (M_Q) for each basin was calculated by using the approach suggested in Saft et al. (2016):

$$M_Q = \frac{Q_{dry,P_I} - Q_{dry,P}}{Q_{dry,P}} \tag{3}$$

where Q_{dry,P_I} is the (predicted annual) runoff for a representative precipitation during dry periods according to the shifted precipitation - runoff relationship (I = 1 in Eq. 1), while $Q_{dry,P}$ is the full-natural flow for the same precipitation according to the non-shifted relationship (I = 0 in Eq. 1). We assumed as representative annual precipitation the mean between average and minimum annual precipitation across the entire period of record.

In this study, I in Eq. (1) was defined based on ERA5 precipitation (I=1 during multi-year drought and I=0 for the other years), while the annual precipitation P was calculated based on E-OBS precipitation dataset. We used two different precipitation datasets because we wanted to rely upon observed-only higher spatial resolution precipitation (i.e., E-OBS) for the definition of the precipitation-runoff relationship to reduce water balance issues. On the contrary, for the drought definition we relied on ERA5 because we wanted to have consistent ERA5-based drought definition evaporation anomalies (both coming from the same dataset). On the other hand, both ERA5 and E-OBS precipitation are characterized by a relatively high accuracy (Massari et al., 2020) and high similarities over Europe (Pearson annual correlation close to 0.9 during the 1980-2016 period not shown) and interchanging them guaranteed very similar results (not shown here).

3 Results and discussion

3.1 Multi-year droughts in Europe and water budget-deficit exacerbation

During the last five decades, Europe has experienced various multi-year drought episodes (Parry et al., 2012; Spinoni et al., 2015; Hanel et al., 2018), which have been perhaps less studied but are as relevant as those that have impacted other world's regions, such as Australia, California, or South America (Dijk et al., 2013; Griffin and Anchukaitis, 2014; Garreaud et al., 2017). For instance, the 1995-1997 multi-year drought impacted almost all Central and North Europe, but unlike episodes prior to 1979 (which were not taken into consideration here), it had a limited initial spatial extent and coherence on a regional basis, with a late exacerbation in terms of severity and extent by 1997 (Parry et al., 2012). The 1989-1991 drought impacted Belgium, France, Luxembourg, The Netherlands, as well as Balkan countries, the Mediterranean (Spinoni et al., 2015) and also UK (Marsh et al., 1994, Peters et al., 2006). The period from 1992 to 1995 was one of the driest in the century for the Iberian Peninsula, and especially for Spain (Sheffield and Wood, 2011; Domínguez-Castro et al., 2019). The 2000-2005 period was also impacted by a severe drought in Northern Italy and Italian Alps (Fink et al., 2004) and Scandinavia (https://www.geo.uio.no/edc/droughtdb/edr/DroughtEvents/2003_Event.php last access: 07-01-2022). The drought characterization we included in this work, based on precipitation anomalies (Saft et al., 2016, see section 2.4 for details and motivation of this choice), provided consistent results with the above-mentioned studies (see Figure 2). In particular, the 1989-1991 in UK and France and the severe drought that peaked in 1992 in Central Europe (see Table 4 of Spinoni et al. 2015) were identified by our procedure. The same holds for the long drought which hit Spain during 1990-1995 also mentioned by of Sheffield and Wood and the 2000-2005 drought over the Alps and Scandinavia.

During these periods of severe precipitation deficit, 69 out of the considered 210 basins with at least one multi-year drought (i.e., 33%) showed a statistically significant shift in the water balance (i.e., a negative shift in the precipitation-runoff relationship, see Figure 3). This means that these 69/210 basins experienced statistically significant less runoff than would be expected based solely on the historical functional dependency of runoff on precipitation. This so-called negative shift is in contrast with experiencing no shift or a positive shift, where the runoff deficit during droughts would be equal to or smaller than that expected based on the precipitation deficit, respectively. By way of examples, a shift in the precipitation-runoff relationship of -30% during one year belonging to a multi-year meteorological drought with mean annual precipitation equal to the long-term 10^{th} percentile (which corresponds to a Standardized Precipitation Index of about -1.6 and thus to a severe drought, see McKee et al., 1993) means that a basin of 1400 km^2 (75th percentile of the areas of the considered basins) will experience an additional reduction in runoff volume of 43 Mm^3 compared to what one would predict solely based on precipitation deficit. This reduction in runoff is equivalent to the annual renewable freshwater resource for 10k people, considering that that the annual renewable freshwater resources averaged over the total European population for the period 1990-2017 reached 4,560 m^3 per person (https://www.eea.europa.eu/data-and-maps/indicators/use-of-freshwater-resources-3/assessment-4 last access: 25/10/2021). On the other hand, even if 30-40% of runoff reduction can result in small absolute reduction for drier basins, this reduction can lead to important changes in hydrological connectivity and shifts in streamflow regimes from perennial to intermittent (Fovet et al., 2021) with serious implications for water quality (Armstrong et al., 2012; Addy et al., 2019), river ecosystems and fish survival (Lennox et al., 2019) freshwater biodiversity (Datry et al., 2016) and the quality and diversity of ecosystem services they provide especially over Southern Europe (Vicente-Serrano et al., 2014; García-Ruiz et al., 2011).

Although this exacerbation could also take place during shorter dry periods, we focused here on multi-year droughts because of their relevance from a water-management standpoint. Also, we expect precipitation deficit to be particularly intense, sustained, and prolonged during multi-year droughts, which facilitates the quantification of any shift in the precipitation-runoff relationship and so the testing of our research hypothesis.

The shift magnitude ranges from about -85% to -12% (-28% in median, see Figure 3b), consistent and even larger than what found in previous works (Saft et al., 2015; Avanzi et al., 2020; Tian et al., 2018, 2020). Only two basins showed a statistically significant positive shift (i.e., 3% of the sample). A similar result was also found by Saft et al. (2016) and no clear explanation was provided. The reasons behind it could be due to the quality of the data used, the screening process, the uncertainty in the multiyear drought definition and in the fitting of the precipitation-runoff relationship.

3.2 Evaporation enhancement, catchment aridity, and water budget-deficit exacerbation

The distribution of basins with a statistically significant shift shows no obvious pattern of variability with the aridity index (see Figure 3c). Note that we assume the aridity index to be a proxy of climate (Unesco, 1979). The only exception is that no shift was observed at very high latitudes (>65 °N), where winters are comparatively cold and the evaporation regime is strongly energy-limited.

The magnitude of runoff-deficit exacerbation during droughts is strongly related to mean annual runoff, being larger for drier basins (Figure 4). This outcome qualitatively agrees with earlier findings related to the pre-drought aridity index being an important predictor of shifts in the precipitation-runoff relationship in Australia (Saft et al., 2016b). Runoff exacerbation occurs in both rainfall- and cryosphere-dominated basins as defined by the month of maximum daily discharge (see again Figure 4). Exacerbation occurs both in energy- and water-limited regimes, as delimited by aridity index (Budyko and Miller, 1974; Maurer et al., 2021) (Figure 4b). This demonstrates that catchments may experience a shift in the precipitation-runoff relationship and so an exacerbation of runoff deficit during droughts regardless of the predominant local climate. Indeed, we found a statistically significant shift for 25% of the basins within the water-limited domain and for 35% of the basins in the energy-limited one (Figure 4b), including snow-dominated basins characterized by annual runoff peak during late spring and summer. Nonetheless, drier catchments experience a larger runoff reduction during multi-year droughts than wetter catchments: shift magnitude asymptotically tends to -20% for wet catchments, while drier basins reach shift magnitudes as large as -80% (Figure 4).

Given the annual water balance ($Q = P - ET - \Delta S$), we explain this relationship between shift magnitude and aridity with the potentially enhanced contribution of evaporation to the annual water budget, particularly for water-limited regimes during droughts. In basins located over water-limited regimes, atmospheric demand for moisture is generally well above the available water storage needed to support evaporation, so that the latter will have a significant impact on already low runoff, especially at the beginning of a multi-year drought when water storage is comparatively large. In energy-limited environments, instead, evaporation is mainly controlled by the available energy and may play a minor role in the annual allocation of incoming precipitation.

The distribution of actual-evaporation anomalies does show enhanced evaporation during multi-year droughts compared to the remainder of the years, for both catchments located over energy- and water-limited regimes (Figure 5). Basins located in a water-limited regime show a larger increase compared to those located in the energy-limited one (33 % vs 12%). A two-sample Kolmogorov-Smirnov test carried out between the distributions of evaporation anomalies during droughts vs. during non-drought years confirms that the anomaly during droughts is statistically different ($p<0.01$) from that during non-drought years. This anomaly is generally larger for basins with the largest shifts (in absolute values, see Figure S2 in the supplementary material). Note that in Figure S2 we divided basins between those located above and those located below 50N, because we did not observe basins with a positive anomaly in evaporation below than 30% in the water-limited domain (we assumed that northern basins are mainly energy-limited).

This regime of enhanced evaporation during droughts was previously suggested by Teuling et al. (2013) and points to generally warmer conditions during droughts leading to additional demand for moisture, as also suggested by Orth and Destouni, (2018) and Mastrotheodoros et al., (2020). Here, we further expanded these findings by showing that evaporation anomaly exacerbates runoff deficit in the form of shifts in the precipitation-runoff relationship beyond Alpine regions and across various climates. A similar result (not shown) was also found by calculating evaporation as $ET = P - Q$ and thus neglecting the contribution of the change in storage, as in Teuling et al. (2013).

The distribution of evaporation anomalies in Figure 5 shows a larger spread during droughts than during non-drought years. We attributed this increased variability in evaporation during droughts to the regulation operated by energy (that is, vapor pressure deficit) and available water (that is, storage) during these water-scarce periods. Figure 6a and b shows two such examples, which also iterate how a positive actual evaporation anomaly is intimately coupled with runoff exacerbation (precipitation-runoff relationships for these two basins are shown in Figure S1). Figure 6a shows a multi-year drought period in the northern Europe (1989-1994); this drought was characterized by both negative precipitation anomalies (-77 mm/year on average) and a positive anomaly in potential evaporation (+47 mm/year on average). The result of this dry and warm period was a positive actual evaporation anomaly (+8 mm/year on average) and a markedly negative runoff anomaly (-44 mm/year on average). This situation significantly differs from 1996, a single dry year with i) much less precipitation than observed during many of the multi-year-drought years (e.g., 1990, 537 mm/y vs 368 mm/y) and, importantly, ii) a substantially lower potential evaporation anomaly (-75mm/year) denoting a much colder year with respect to 1989-1994. This cold-dry 1996 resulted in a negative actual evaporation anomaly (-72 mm/y), which translated into a much smaller runoff deficit than the multi-year drought (-33 mm/y as opposed to -49 mm/y in 1990). This demonstrated that in such energy-limited environments, the emergence of an enhanced evaporation regime during droughts is regulated by the available energy: if this is not sufficient, then actual evaporation will not increase.

Similar conclusions can be drawn for the basins located in Southern Europe (Figure 6b), with some notable differences in this water-limited region. The multi-year drought period 1991-1995 in this area was characterized by a close-to-zero anomaly in potential evaporation (-1.94 mm/y on average) and a below-than-average precipitation (-98 mm/y). This dry-mild period significantly differs from another single-dry and warm year, i.e., 2012 (+229 mm/y of potential evaporation and -98 mm/y precipitation). Despite the much warmer and drier 2012, we observed a relatively larger runoff deficit during the multi-year drought period (-35mm/y on average equal to 25.9 mm/year) than in 2012 (-16 mm/year, equal to 46 mm/year) with an increase of actual evaporation equal to +27 mm/y on average during the multi-year drought. Differently from the basin located in northern Europe (i.e., in an energy-limited region), the emergence of an enhanced evaporation regime in a water-limited region is much more complex and regulated by both energy and available water storage (Seneviratne et al., 2010) (that can even result from carryover from previous years). Here, demand for moisture may also trigger plant-stomata closure thus reducing transpiration. Therefore, in water-limited regimes the year-to-year comparison of runoff deficit and evaporation anomaly is not straightforward and can be further complicated by the precipitation variability typical of Mediterranean regions (Seager et al., 2019). In any case, if storage is not sufficient, and/or other feedback mechanisms like stomata closure occur, then actual evaporation will not increase and runoff may be substantially higher than in relatively wetter periods.

As basin storage (i.e., ΔS) plays an important, but frequently neglected role in modulating runoff deficit via sustaining evaporation during multi-year droughts (Van Loon and Laaha, 2015), we compared the average rooting depth and the total available water content (TAWC) distribution for basins characterized by significant versus non-significant shifts (see Figure 7). Results highlight that the basins showing a significant shift in the precipitation-runoff relation are characterized by a different distribution of rooting depth and TAWC from basins showing no-significant shifts (two-sample Kolmogorov-Smirnov test with p-value<0.05). Because basins with a statistically significant shift show both a slightly deeper rooting depth and a larger TAWC, these findings tally with the enhanced ET anomaly for shifting basins in Figure 5, because a deeper rooting depth may provide access to deeper storage during water stress and so sustain evaporation even during dry periods. Nonetheless, these findings are only of qualitative nature, given that distributions in Figure 7 tend to overlap.

4 Concluding remarks and study limitations

In a warming climate, different regions of the world will experience an increase in frequency and intensity of meteorological droughts. In this regard, this work provides evidence that:

1. Runoff-deficit exacerbation compared to precipitation deficit during droughts is a common feature of basins across Europe;
2. runoff-deficit exacerbation occurs irrespective of local climate. In other words, we found such exacerbation in both water- and energy-limited environments. Moreover, basins prone to shift in the precipitation-runoff relationship are characterized by vegetation cover featuring a comparatively larger rooting depth and by soils with greater total available water content compared to basins that do not show shifts in the precipitation-runoff relationship. This suggests the important role of storage in sustaining basin-scale evaporation.

3. Runoff exacerbation is related to an increase in evaporation occurring under two defined and concurrent preconditions: 1) water storage can support ET during the drought period, and 2) there is a sufficient vapor-pressure deficit (mainly driven by the temperature increase) to generate evaporation. When both circumstances are verified, then the catchment water balance shifts toward a new regime in which ET proportionally weights more than during wet periods. The macroscopic, bulk effect of this regime change is the shift in precipitation-runoff relationship as observed in previous works (Avanzi et al., 2020). This shift is more pronounced in drier catchments, because evaporation tends to be proportionally higher as long as enough water is available to sustain atmospheric and vegetation demand for moisture. It is noteworthy that these drier catchments are areas of the world where water planners and ecosystem services are already challenged by limited water resources.

These results were obtained from an empirical, strictly data-based analysis, but are in line with earlier findings (Saft et al., 2015; Avanzi et al., 2020), as well with those inferred from blending data with mechanistic modelling across the European Alps (Mastrotheodoros et al., 2020). The key role of evaporation was also addressed in Europe by Orth and Destouni (2018) and points to the vegetation as a potential driver (Vicente-Serrano et al. 2014, Peña-Gallardo et al. 2016, Peña-Angulo et al. 2021) caused by enhanced evaporative demand during drought. Despite this was not clearly demonstrated in this work, the cited literature and Figure 6b suggest that this likely the case. In other words, our findings suggest that the increase in actual evaporation can be sustained also for long dry periods (i.e., multi-year droughts) and in typically water-limited environments (while for example Orth and Destouni (2018) highlighted this behavior predominantly in energy limited regions). A potential explanation to this can be given by the capacity of deep-rooted trees to access water from weathered highly porous saprock or rock moisture (Rempe and Dietrich, 2018; Hahm et al., 2019; Carrière et al., 2020; Amin et al., 2020) which can go up to 20-30 m beneath the surface (Klos et al., 2018). These mechanisms, which are vital to support the ecosystem during extended drought periods especially over water limited regions, by bringing large volumes of subsurface water into the atmosphere, might subtract water to runoff potentially determining an aggravation of the hydrological drought (Amin et al., 2020; Carrière et al., 2020; Barbeta and Peñuelas, 2017). Thus, during long and sustained dry periods like those that have impacted the European continent, not only runoff is reduced faster than evaporation (Orth and Destouni, 2018), but it is also reduced stronger than expected.

The understanding of the propagation of meteorological drought into hydrological drought for long and sustained dry periods is challenging because the overall catchment storage is expected to play a major role in driving runoff deficit. However, understanding the role played by storage is complicated by the difficulty to measure and estimate it (apart from large scale satellite-derived measurements like GRACE (Rodell et al., 2009)) which is seldom addressed at catchment scale (McNamara et al., 2011). This is mainly due to the fact that storage is characterized by marked spatial heterogeneity, which is difficult to measure at the point scale and so extrapolate to the catchment scale (Spence, 2010). We have addressed this by plotting the root depth distribution and TAWC for basins experiencing a significant shift in the precipitation-runoff relationship finding that the latter are characterized by slightly larger values of these two variables. Nonetheless, further evidences are needed to corroborate this finding.

On top of this, the tested hypothesis of the drop in predictive skill in ET during drought found by Avanzi et al. (2020) and the fact that ET seems to be less coupled with soil moisture than models can generally predict (Dong et al., 2020; Qiu et al., 2020) may undermine the comprehension of the response of ET to drought in Earth system models, especially over water-limited environments for long dry periods where, the "shallow" moisture storage, simulated by the latter can be already completely depleted leading to the paradox of null evaporation (Fowler et al., 2020). The suboptimal representation of ET by Earth system models is not rare. For example, many models do not include stomatal response to dry periods, hydrologic regulation of plant rooting depth (De Kauwe et al., 2015; Fan et al., 2017), correct representation of the plant hydraulics (Li et al., 2021; Kennedy et al., 2019) as well as coevolution mechanisms such as vegetation mortality and expansion (Goulden and Bales, 2019). These coevolution mechanisms affect the so-called climate elasticity of evaporation (Avanzi et al., 2020), that is, the capability of ET (and indirectly runoff) to respond and adapt to changes in climate. This is specifically true for conceptual rainfall-runoff models which are still widely used in operational practice, as well as for many scientific purposes like climate-change studies due to their parsimony and computationally efficient model structure (Pagano et al., 2014). These models may be inadequate tools during periods of runoff exacerbation like those we found here across Europe especially if one considers that their calibration remains inevitable (Beven and Freer, 2001; Fowler et al., 2016).

The findings of our study highlight the need to gain a better knowledge about the propagation of meteorological to hydrological anomalies across different climatic regions (Lorenzo-Lacruz et al., 2013) as well as the identification of meteorological drought indices that best reflect streamflow anomalies as suggested by (Tijdeman et al., 2018). This would provide an important basis for large-scale drought monitoring and early warning information. This is true especially over data scarce regions due to the observed decline of stream gauge observations (Crochemore et al., 2020) where meteorological-based drought indices are normally used to monitor and predict hydrological droughts.

Given the projected warming climate and aridity, and the role of ET in driving the exacerbation of runoff during droughts, improving understanding of this elasticity appears an urgent task for future work and attempts to do this are still ongoing (Fowler et al., 2020; Hughes et al., 2021). The large-scale experiment we carried out provides useful insights about the influence of climate on and catchment characteristics on the propagation of the meteorological to the hydrological drought. Although the study catchments were limited to Europe, the diversity of physiographic and aridity settings, as well as the number of catchments used suggest that storage and evaporation are important factors involved in shifting the water balance of other regions of the world. On the other hand, further research is needed in this direction also considering that:

1. in the study we did not consider the potential impact of trends in temperature and the associated long-term coevolutionary mechanisms of the catchments. In this respect there can be potential reflections of coevolution mechanisms on the runoff reduction for which a simple fitting of the precipitation-runoff relationship might be inadequate.
2. Despite we have carried out a high controlled experiment employing as much as possible near natural catchments by screening out basins potentially characterized by human regulations and used some of the best available precipitation and evaporation products, we cannot exclude that the observed runoff deficit exacerbation might have been driven by

other factors related to the climate/land cover changes/water regulation interactions than the simple increase of actual evaporation (Vicente-Serrano et al., 2019; Teuling et al., 2019; Teuling and Hoek van Dijke, 2020) which might also not well be represented in the used actual evaporation dataset.

3. Our analysis was based on annual time scale. However, intra-annual variations of the water balance components could exert an important role to explain hydrological drought response to precipitation deficits. Despite this, the study might lack details in resolution (for instance it can reveals periods where the runoff deficit is larger and the impact of the climate of the seasons on the runoff aggravation) but it still valid in terms of water balance perspective.
4. The processes underlying the aggravation of the runoff deficit due to increased evaporation for individual catchments may be related to differences in water storage dynamics, flow paths, and evaporation due to changes in the infiltration capacity of soils, the duration of infiltration periods, the timing of infiltration periods, the soil moisture regime, the human water use amongst other factors. Given the diversity of catchments in our dataset, each with its own internal heterogeneity, the mechanisms connecting precipitation deficit to runoff deficit are likely to result from combinations of factors and may vary from site to site, as well as depending on human influences and topography of the catchment. Further work is needed to clarify which hydrological processes are the main contributors to the findings we have presented.
5. Despite we selected some of the best possible climate datasets of evaporation and precipitation some uncertainty is unavoidable which is also related to the their relatively coarse spatial resolution with respect to the size of the analysed basins.

Despite these limitations, the findings of this study have significant implications for water resource ecological management of river basins. Given the projected global temperature rise is expected to lead to significant increase in drought frequency and intensity in many regions of the world our results indicate possible larger-than-expected decrease in mean streamflow across different climates in the world.

Data availability. Data from E-OBS were obtained via (Dijk et al., 2013; Griffin and Anchukaitis, 2014; Garreaud et al., 2017) ERA5 data were downloaded from the https://climate.copernicus.eu/climate-reanalysis, runoff data and basin areas were downloaded from the Global Runoff Data Base (GRDC); the European Water Archive (EWA); the Italian ISPRA HIS national database (http://www.hiscentral.isprambiente.gov.it/ 360 hiscentral/default.aspx); the Portuguese national database (http://snirh.pt/); and the Spanish national database (http://ceh-95flumen64.cedex.
es/anuarioaforos/default.asp).

Code and data availability. All codes are available by request.

Author contributions. Christian Massari and Francesco Avanzi designed, coordinated the study and made the analyses. Giulia Bruno helped in the data analysis and interpretation, Daniele Penna, Simone Gabellani helped in the result interpretation, Stefania Camici helped in the result interpretation and in the data collection. All authors contributed to the editing of the manuscript.

Competing interests. The authors declare no competing interests

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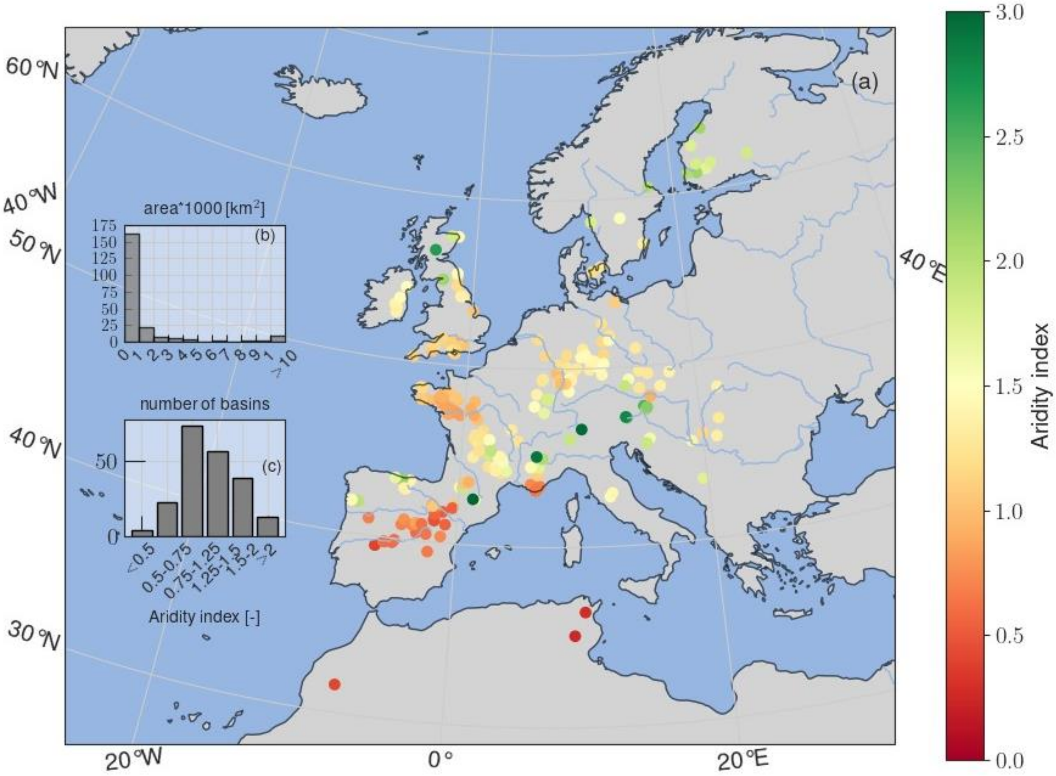


Figure 1. (a) Aridity index (P/PET) distribution of the basins of the study area. (b) frequency distribution of the area of the basins. (c) frequency distribution of the aridity index of the basins of the study area.

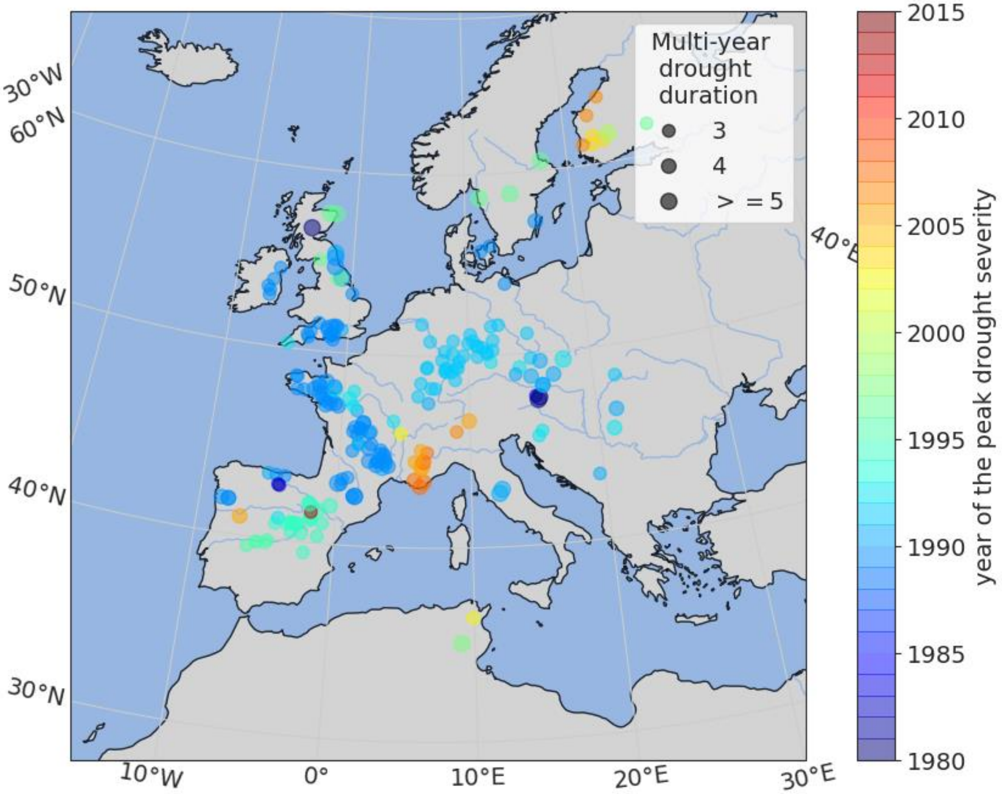


Figure 2: Year of the most intense drought (the most negative precipitation anomalies) within the multi-year drought period identified as well as its duration for each basin. Note that other years might have shown more severe droughts but they were shorter than the 3 years period we have defined."

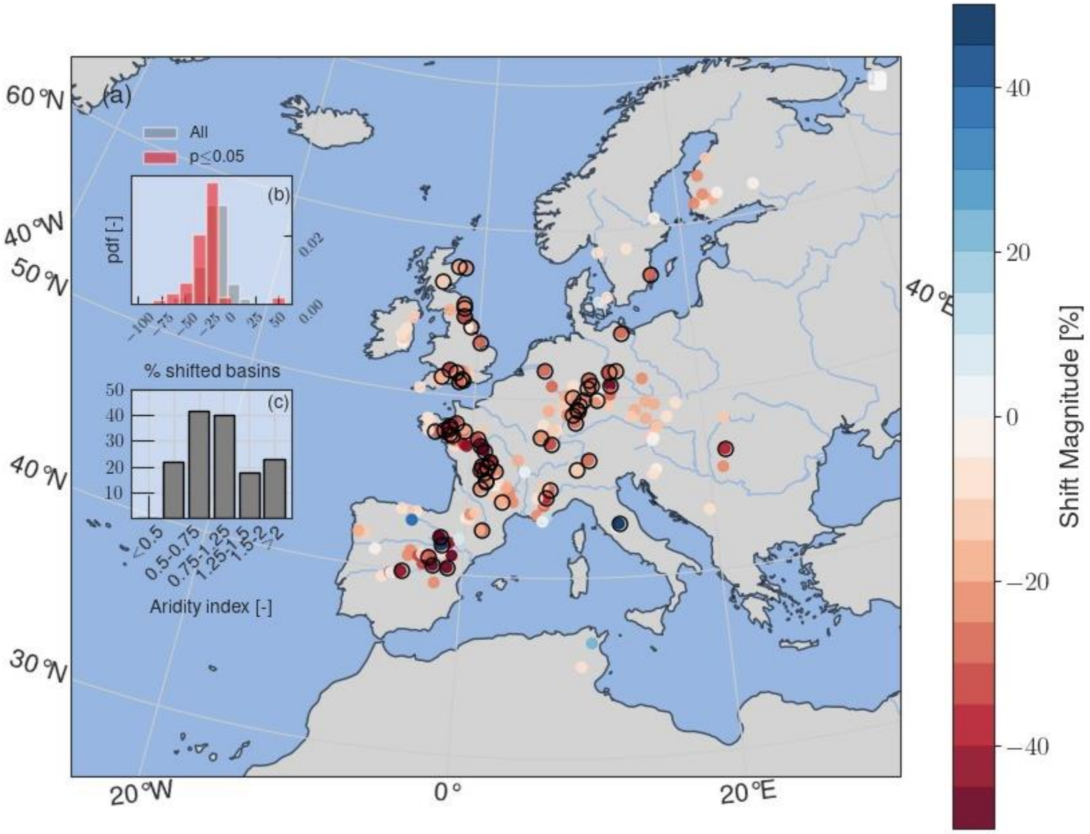


Figure 3. Spatial distribution of the magnitude of the shift in the precipitation-runoff relationship (a). The shift in the precipitation-runoff relationship was calculated by fitting a multivariate regression across annual cumulative streamflow (target variable), basin-averaged annual precipitation, and a categorical variable denoting drought and non- drought years. Each dot refers to the position of the river gauge station. The basins where the shift was found statistically significant with p-value<0.05 plotted with a black edge. Darker red dots refer to catchments where a larger exacerbation of runoff deficit during multi-year drought periods was observed. (b) Probability density function (pdf) of the magnitude of shift found for the basins in the study area. (c) percentage of the basins showing statistically significant shift (p<0.05) as a function of the aridity index calculated as the ratio between ERA5 precipitation and potential evaporation. The percentage has been calculated by stratifying basins for each aridity index class.

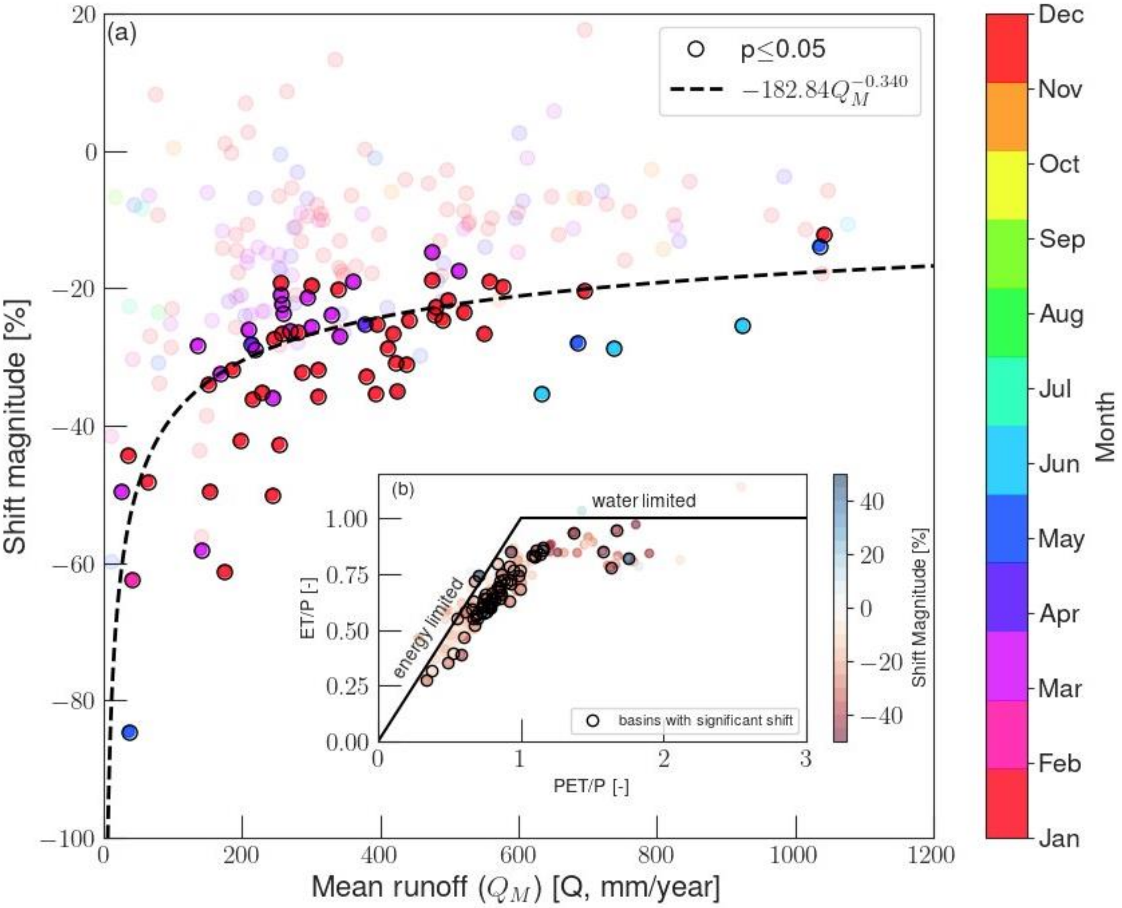


Figure 4. (a) Shift magnitude versus mean discharge grouped for maximum daily monthly discharge for all basins and for basins showing a shift (p-value<0.05 are shown with darker color and a black edge). The black dashed line curve was obtained by fitting mean runoff vs. shift magnitude of basins showing a statistically significant shift. (b) Energy- and water-limited domain of the basins of the study area as a function of the shift magnitude. Dots with black edge indicate basins showing statistically significant shift at p<0.05. PET, P and ET indicate ERA5 potential evaporation, precipitation and actual evaporation, respectively.

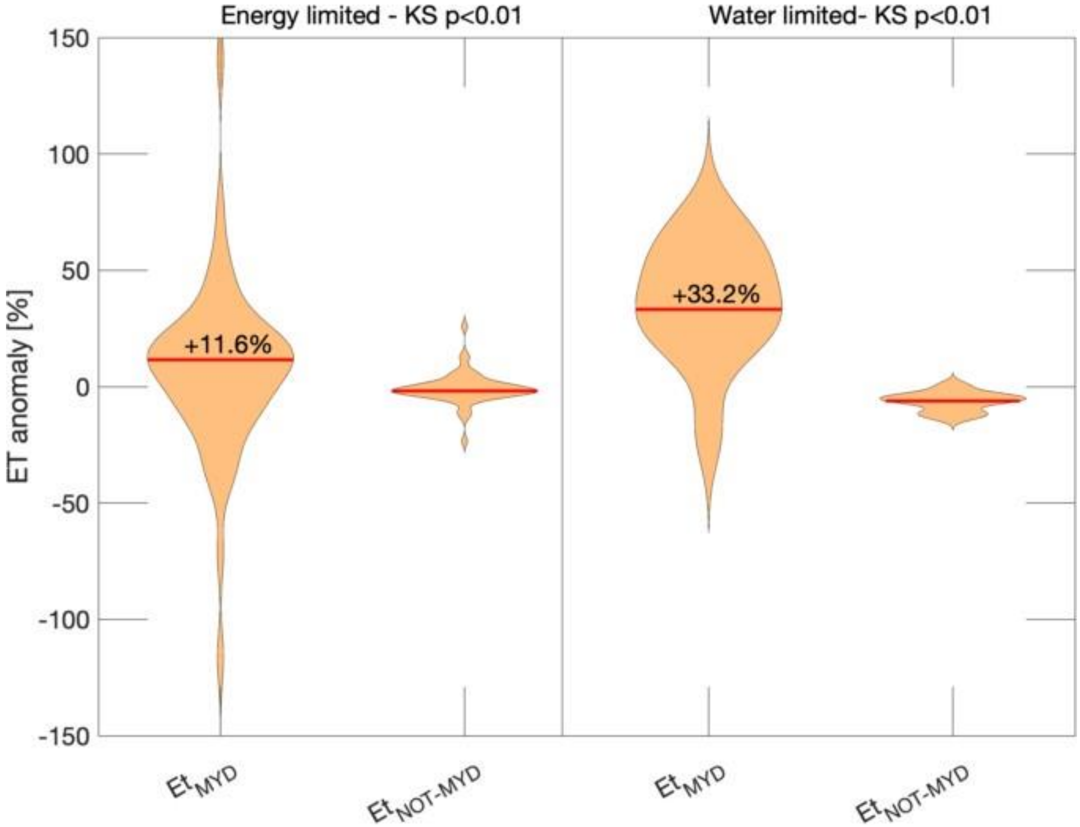
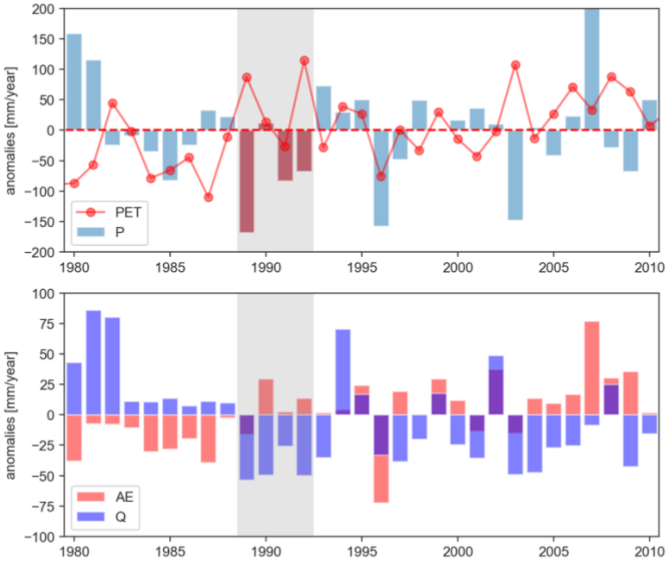
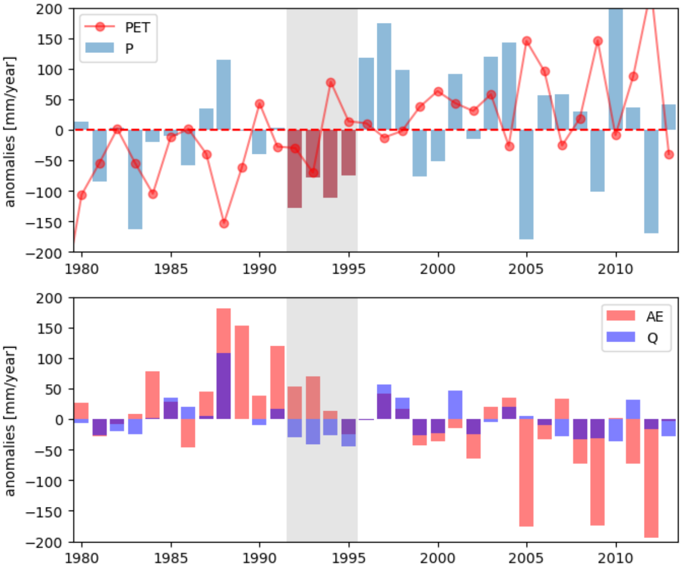


Figure 5. ERA5 evaporation anomalies distribution for multi-year drought period (ET_{MYD}) versus non-multi-year drought periods ($ET_{NOT-MYD}$) for basins showing statistically significant shift ($p<0.05$) and characterized by an energy-limited regime (left) and for basins in the water-limited regime (right). KS refer to the two- sample Kolmogorov-Smirnov test between the distribution of evaporation anomalies of ET_{MYD} and $ET_{NOT-MYD}$. The red line in the violin plots refers to the median value. The anomalies are calculated as the ratio between the deviation with respect to the long-term mean and the absolute long-term standard deviation on the catchments showing statistically significant shift.



(a) - North Europe



(b) South Europe

Figure 6. a) Precipitation and potential evaporation long-term mean anomalies (top), actual evaporation and runoff anomalies (bottom) for a basin located in northern Europe (6.8°O, 53.6°N) characterized by a energy limited regime according to Figure 4b. (b): same as (a) but for southern Europe (5.4°O, 39.8°N) characterized by a water- limited-regime. Gray areas represent the identified multi-year drought periods.

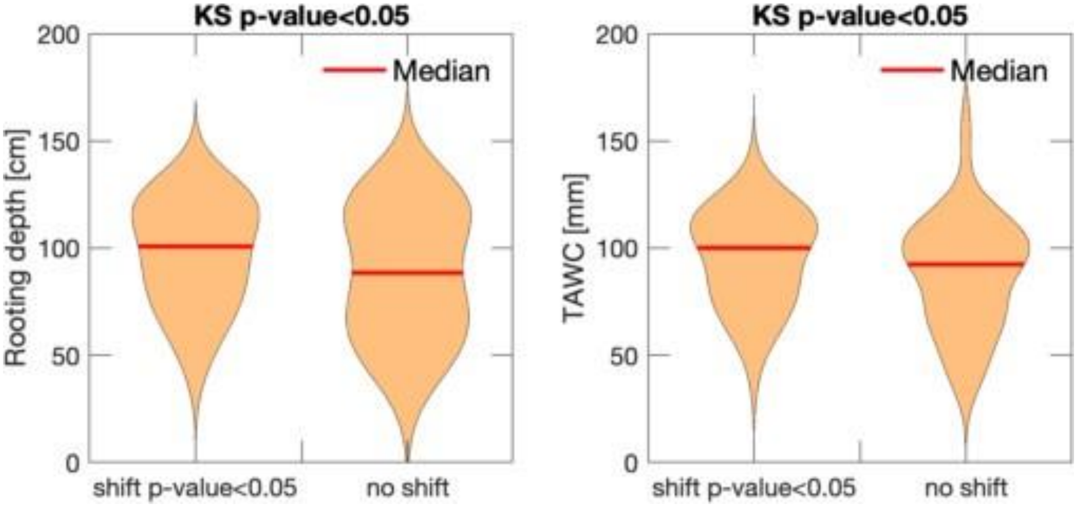


Figure 7. Average rooting depth and total available water (TAWC) content for basins characterized by a significant shift in the precipitation-runoff relationship and those where shift was not significant. KS refer to the two- sample Kolmogorov-Smirnov test between the distribution of basins with shift (p-value<0.05) and basin showing not statistically significant shift.