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Large droughts are not large small droughts: hydro-meteorological drought generation processes vary with streamflow drought size in the Alpine region

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Abstract. Streamflow droughts can be caused by a range of processes which can show strong heterogeneity from basin to basin. In contrast to local droughts, spatially extensive droughts seem to have more spatially homogeneous driving processes. However, the underlying mechanisms that cause this difference in the generation processes of small vs. large droughts are not well understood. This study presents an observation-based analysis that bridges this scale gap between large and small streamflow droughts. We assess how drought generation processes vary with drought size by classifying droughts into different types using streamflow drought observations and different hydro-meteorological variables. We find that: (1) most large drought events are characterized by one or two drought types even in hydro-climatically complex regions such as the Alps; (2) each drought type has its own spatial footprint and only specific drought types can lead to large droughts; and (3) in recent years, large droughts have increasingly been characterized by a mix of drought types. Our results highlight that the most common drought type in a catchment might not always lead to large droughts, which can be important for water management.

1 Introduction

Streamflow droughts result from the interplay of several hydro-meteorological processes. The root cause of these droughts can often be found in strong meteorological anomalies, as illustrated by the precipitation deficits and heatwaves that led to the large droughts in Europe in 2015 (Ionita et al., 2017; Laaha et al., 2017; Van Lanen et al., 2016), 2018 (Bakke et al., 2020) or 2022 (Bevacqua et al., 2024). Still, the propagation of precipitation deficits to streamflow drought is not straightforward as land surface processes further shape drought development (Brunner and Chartier-Rescan, 2024). Snow storage (Chartier-Rescan et al., 2025; Avanzi et al., 2024; Han et al., 2025), glaciermelt (Van Tiel et al., 2023), evapotranspiration (Bruno et al., 2025; Vicente-Serrano et al., 2020; Bevacqua et al., 2024), groundwater or storage processes (Berghuijs et al., 2025; Hughes et al., 2012; Hellwig et al., 2022), and human water regulation (Brunner, 2021; Schilstra et al., 2024; Van Loon et al., 2022) all

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influence whether, where, and how meteorological anomalies translate to streamflow drought. Streamflow drought occurrence and characteristics can therefore vary depending on the hydro-meteorological processes that generate them.

To facilitate the systematic study of streamflow droughts and their generation processes, Van Loon and Van Lanen (2012) developed a qualitative drought typology, which identifies different streamflow drought types based on their hydro-meteorological generation processes. Van Loon et al. (2015) extended this typology by including additional melt-related drought types, making it more suitable for catchments in colder climates. They identified eight different drought types. *Rainfall deficit droughts* are caused by a lack of rainfall only. Sometimes these droughts can continue into the snow (*rain to snow season droughts*) or into the dry season (*wet to dry season droughts*). Other droughts are linked to the meteorological conditions in the snow season: *cold snow season droughts* are caused by cold conditions leading to an early start or a late end of the snow season or a lack of storage recharge due to snow accumulation. In contrast, *warm snow season droughts* are linked to high above zero temperatures in the snow season, which lead to early or complete melting of snow which causes less streamflow later in the season. When there is a lack of snowmelt or glaciermelt, droughts are classified as *snowmelt deficit droughts* or *glaciermelt deficit droughts*, respectively. Lastly, *composite droughts* result from the combination of several drought generation mechanisms.

Subsequent research has translated these qualitative definitions into an automated classification scheme (Brunner et al., 2022, 2023). This classification scheme identifies drought types based on preceding rainfall or snow deficits and the event's season of occurrence. Applications of this classification scheme have shown that the dominant hydrological drought types vary with hydro-climate, leading to a high variability of dominant drought types in regions with strong heterogeneity in local conditions (Brunner et al., 2022, 2023). However, these applications have also shown that the dominant drought types might not always be the type that leads to the most severe droughts in terms of streamflow deficit. In a single catchment, moderate and severe droughts can have different generation processes and these processes can also vary with the season (Brunner et al., 2022).

Aside from severity, another factor that can worsen societal drought impacts is a drought's spatial extent. Water transfers between different basins – an often-used tool for water managers to combat drought impacts – are less effective when neighboring basins in a region are simultaneously under drought (Patterson et al., 2013; Murgatroyd and Hall, 2020). Similarly, reduced upstream water availability due to water use can worsen downstream water stress (Munia et al., 2016). Earlier studies on drought types have not explicitly accounted for this spatial dimension of streamflow droughts, even though they hypothesized that precipitation-driven droughts might be more synchronous than other drought types (Van Loon and Van Lanen, 2012). Recent model-based research in the Alps do indeed suggest that large streamflow droughts are mostly associated with rainfall deficits (Janzing et al., 2026), even in the hydro-climatically-complex Alpine region, where other generation processes such as snowfall or snowmelt are important locally (Brunner et al., 2023). Furthermore, recent spatially extensive streamflow droughts over Europe have been associated with widespread and thus relatively homogeneous meteorological conditions (Ionita et al., 2017; Laaha et al., 2017; Van Lanen et al., 2016; Bakke et al., 2020; Bevacqua et al., 2024).

While there is some first evidence for differences in the driving processes of large vs. small droughts, these have not yet been systematically investigated across large spatial domains. Furthermore, it also remains mechanistically unclear how locally less common generation processes of streamflow droughts can become the dominant generation processes of large droughts. These

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questions are particularly pressing as there is increasing evidence that both drought generation processes and drought spatial extent are changing: snowmelt-deficit-related streamflow droughts have become more common around the Alps (Brunner et al., 2023) and increased evapotranspiration has led to decreases in streamflow in Germany (Bruno et al., 2025). Such local changes likely play a role in explaining observed changes in streamflow drought size (Brunner et al., 2021; Lorenzo-Lacruz et al., 2013; Sharma and Mujumdar, 2024), and there is evidence that temperature is an increasingly important control on drought spatial extent (Brunner et al., 2021).

Investigating the variation of drought generation processes with drought size requires bringing together the large scale perspective, as e.g. used in model-based studies (Janzing et al., 2026), with the local drought typology perspective as used in observation-based studies (Brunner et al., 2022, 2023). What is thus needed is an observation-based study that can bridge the local and large-scale perspectives on drought generation processes, that is, a study that quantifies the difference between the generation processes of large vs. small streamflow droughts. Here, we address this research gap by studying how differences in hydro-meteorological processes vary with the spatial extent of streamflow droughts. We address the following questions:

- Which hydro-meteorological generation processes are most important for the development of the largest streamflow drought events?
- Why do some drought types lead to large streamflow droughts, while others do not?
- How have the drought types of large droughts changed over time?

2 Methods

2.1 Study region and dataset

We focus on the larger Alpine region, which covers diverse hydro-climates and streamflow drought generation processes (for elevation ranges and the Alps, see Figure S1 in the Supporting Information). We aim to explicitly make the connection from the generation processes of local to those of spatially-extensive, that is large droughts. To do so, we rely on the dataset and the methodological choices from a previous study on local streamflow drought generation processes in the Alps (Brunner et al., 2023). The dataset contains observed daily streamflow records, derived from local government agencies in the countries surrounding the Alps (see Brunner et al. (2023) for a detailed overview of data sources) and daily time series of precipitation, temperature, snow water equivalent, and snowmelt derived from ERA5-Land (Copernicus Climate Change Service, 2019; Hersbach et al., 2020). We limit the analysis to the period 1970 – 2017 and to discharge stations with observations covering this entire period ($\leq$5% missing observations).

2.2 Drought definition and classification

We follow the drought definition and classification from Brunner et al. (2023) to identify drought events and classify them into different drought types. Streamflow droughts are defined as seasonal flow anomalies using the commonly-used variable

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threshold approach (e.g. Van Loon and Laaha, 2015; Brunner et al., 2022, 2023). For each calendar day, we pool the data from the 15 days before and after the day of interest over all years and calculate the 20th streamflow percentile as a threshold. The 20th percentile has been commonly used as a drought threshold in previous drought studies (e.g. Wanders and Van Lanen, 2015; Brunner et al., 2023; Götte and Brunner, 2024; Janzing et al., 2026). Then, we smooth the streamflow time series over 30 days to pool dependent droughts events (Fleig et al., 2006). We apply the threshold to the smoothed time series and define streamflow drought events as periods where the smoothed streamflow is below the threshold. We only include events that last for at least 30 days, as we consider such events to be most impactful. Precipitation and snowmelt deficits are identified following an analogous procedure (30 day moving window, 20th percentile threshold and minimum duration of 30 or 5 days for precipitation and snowmelt, respectively; Brunner et al. (2023)). We select only the catchments that experienced more than 20 streamflow droughts over the study period, as we need a sufficient sample size of droughts to compare a set of large events against a set of small events (see Section 2.3). The remaining catchments have a median of 36 streamflow droughts per catchment.

The drought events identified are then classified into eight types following the classification scheme of Brunner et al. (2022) and Brunner et al. (2023). This scheme first separates between proximally rainfall-driven and snowfall-driven drought types based on the presence of a rainfall deficit occurring shortly (30 days) before or during the drought (until the middle of the event). Next, based on drought seasonality and the potential for snow accumulation, rainfall-driven droughts are further divided into i) rain-to-snow season, ii) wet-to-dry season, or iii) general rainfall deficit droughts. The snow-driven droughts are further separated using information about drought seasonality, snow availability and glacier cover into iv) cold snow season droughts, v) warm snow season droughts, vi) snowmelt deficit droughts, vii) composite droughts, or viii) glaciermelt deficit droughts. For a more detailed description of the classification method, we refer the reader to Brunner et al. (2022) and Brunner et al. (2023).

2.3 Analysis

We study the relationship between drought type and size using two perspectives: (1) a location perspective, which focuses on the size of droughts that affect a specific catchment, and (2) an event perspective, which focuses on the total number of catchments under drought during a large drought event, irrespective of the location of the affected catchments.

From the location perspective, we determine drought size and dominant drought types, as well as drought frequency and synchrony. First, we calculate a drought's size as the maximum fraction of all catchments under drought over the duration during which this catchment is under a specific drought (see Figure 1A). We distinguish between *total drought size*, that is the fraction of catchments under drought irrespective of the drought type, and *type-specific drought size*, i.e. the fraction of catchments affected by the same drought type observed in the catchment under consideration. Using total drought size, we also determine dominant types. We identify the dominant *local* drought type, considering all events identified in the catchment, and the dominant *regional* drought type, considering only the 10 largest events (see Figure 1B). In case two or more drought types have the same number of occurrences, we define the dominant type as the one with the largest average total drought size across the identified events. Lastly, we calculate metrics to study the general spatial behaviour of drought types. We calculate the local

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frequency of each drought type (i.e. how many events of this type occur) and the local *synchrony* of each drought type, which is calculated as the average *type-specific* size of a drought type in a catchment.

For the event perspective, we consider a daily time series of the fraction of catchments under drought and define large drought events (see Figure 1C). We identify an *event* as a time interval when at least 50% of catchments in the domain are under drought simultaneously. For each event, we quantify its maximum extent and look at the distribution of drought types observed in the catchments affected by drought at this point in time. We consider each drought type's *contribution* to the total event as the number of catchments under this drought type divided by the total number of catchments under drought. Last, we study whether the specific drought types that lead to large events have changed over time. Therefore, we compare the contributions from event to event and between two periods (1970-1993 versus 1994-2017, same periods as used by Brunner et al. (2023)). To test for the significance of changes between the two time periods, we apply a t-test at a significance level of 0.05.

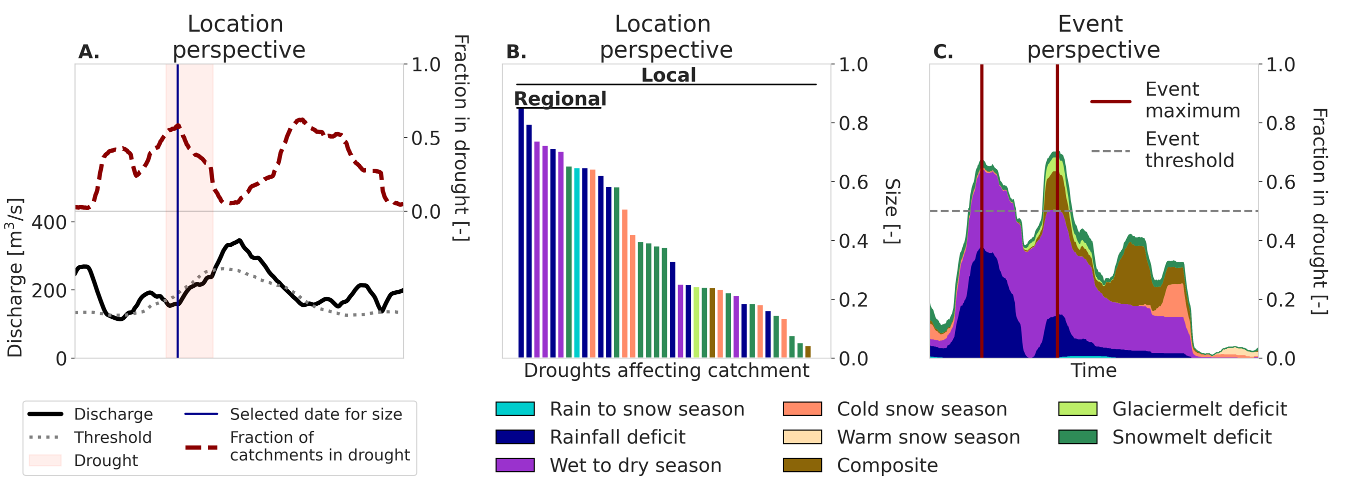

Figure 1. Schematic overview of the methods and definitions used. A. Determining the (total or type-specific) size of a drought from the location perspective: when the catchment is under streamflow drought, we consider the maximum fraction of catchments that is under drought over the duration of this event. B. Each drought event in a catchment has its own size (defined as in A., i.e. the maximum fraction of catchments under drought during the local drought). The most common drought type overall is the dominant local drought type, whereas the dominant regional drought type is the most common drought type among the 10 largest droughts. C. Using the event perspective, we define a drought event when more than 50 % of catchments are under drought. On the day of maximum extent, we study how many catchments are affected by each individual drought type.

3 Results

The location perspective shows that the main drought types of regional droughts are more homogeneous in space than the dominant drought types of local droughts (see Figure 2). Although rainfall deficit droughts were already the most common driver of local droughts (in 57% of the catchments, see Figure 2A and C), they are even more common for the regional droughts

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in the study region (dominant driver in 79% of catchments, see Figure 2B and D). Other drought types such as composite droughts, cold snow season droughts and snowmelt deficit droughts are less common for regional droughts than for local droughts. Aside from rainfall deficit droughts, wet to dry season droughts are dominant in more catchments for regional (8.3% of catchments) than for local droughts (0% of catchments). This is also the case for rain to snow season droughts (regional: 2% of catchments, local: 0% of catchments). These results remain largely similar when the analysis is performed over a subset of unnested catchments only, suggesting that these findings are not dependent on the upstream-downstream linkage between catchments (see Figure S3 in the Supporting Information). The general direction of change (i.e. which drought types are more and less dominant for regional droughts than in local droughts) is also robust against different thresholds for regional droughts (i.e. the largest 5 or 15 events; see Figure S2 in the Supporting Information) and against the choice of time period (though the dominance of rainfall deficit droughts for regional droughts is much weaker in 1994-2017 than in 1970-1993; see Figure S4 in the Supporting Information; see also Figure 6).

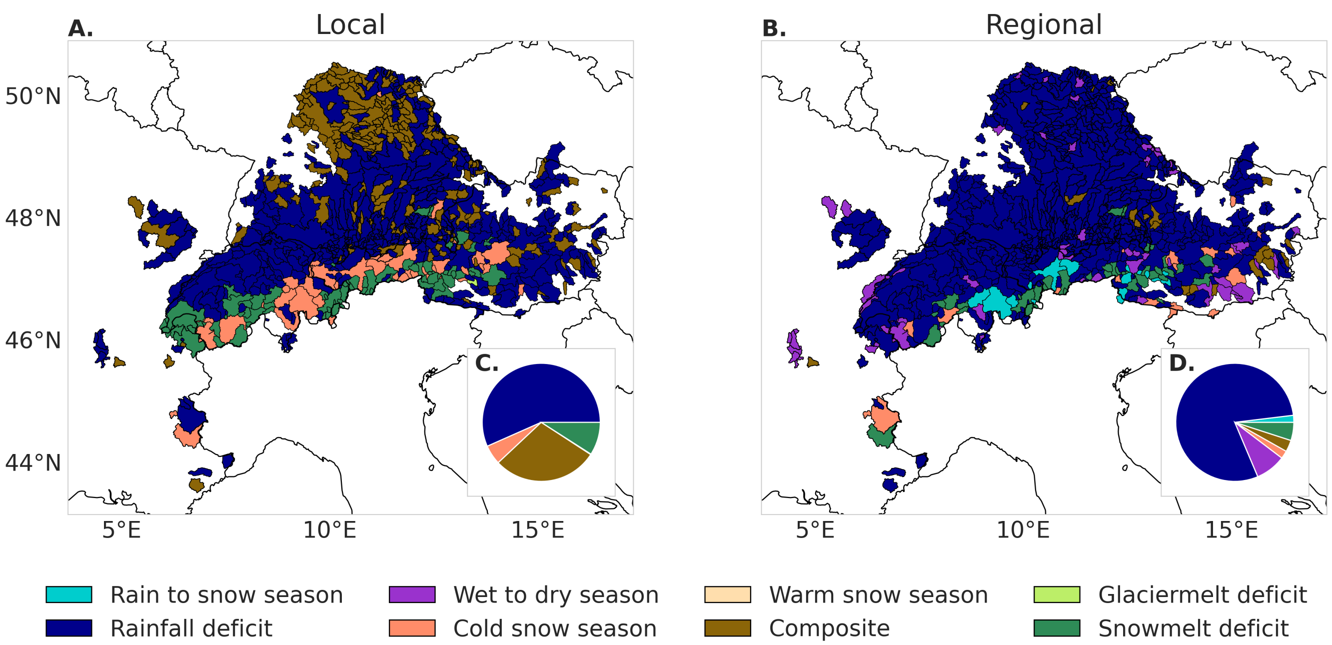

Figure 2. A. Most common drought type for local droughts in each catchment. B. Most common drought type for the 10 largest (i.e. regional) droughts in each catchment. Catchments are sorted by size, with smaller catchments plotted over larger catchments. The pie charts in the bottom right corners of the plots show the proportion of catchments with a specific most common drought type for all droughts (C) and for the 10 largest droughts in each catchment (D).

We now move to the event perspective and consider the contribution of different drought types to large drought events (see Figure 3). For many events (8 out of the 10 largest events), a single drought type contributes more than half of the catchments under drought. Rainfall deficits are the main contributing drought type in 5 out of the 10 largest events, wet to dry season droughts in 3 events, and snowmelt deficit and composite droughts in one event each. Over all events (i.e. not only the 10

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largest), we find that in 58% of events a single drought type contributed half or more of the catchments under drought, and two drought types contribute half or more of the affected catchments in 100% of events (see Figure S5 in the Supporting Information). Rainfall deficit droughts are the largest contributor in 63% of all events.

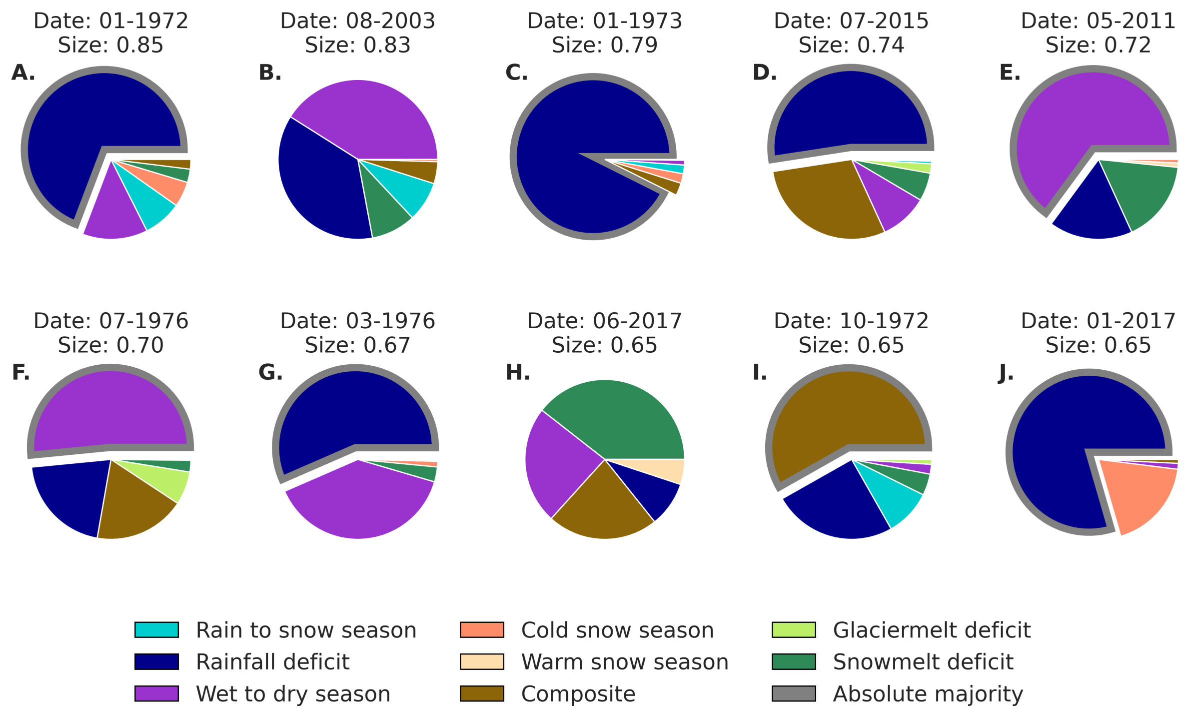

Figure 3. The contribution of different drought types to the largest 10 events in the study period. Size is here defined as the total fraction of catchments under drought on the given date. The events are sorted by size.

Next, we consider the synchrony of each drought type, i.e. the average type-specific drought size when considering only a single drought type (see Figure 4). Rainfall deficit droughts show the highest synchrony on average (0.30) and their synchrony is highest north of the Alps. Other drought types with relatively high synchrony include wet to dry season droughts (0.25), cold snow season droughts (0.19), and composite droughts (0.15). Snowmelt droughts (0.09), warm snow season droughts (0.10), and rain to snow season droughts (0.08) show more moderate synchrony, whereas glaciermelt droughts (0.02) show relatively weak synchrony.

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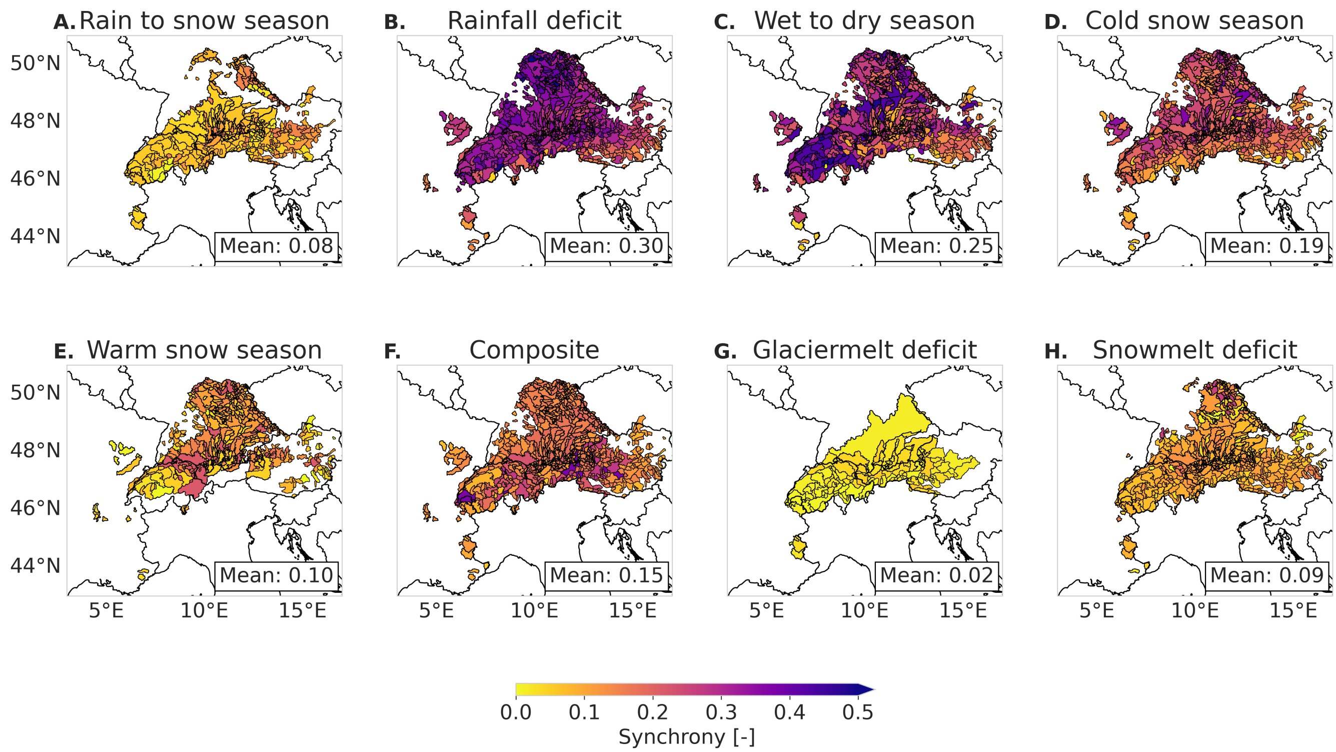

Figure 4. Synchrony of different drought types. For each drought type, synchrony is the type-specific size (i.e. the size when considering only droughts from this drought type) averaged over all events of this type in a catchment. The subplots show A. rain to snow season droughts, B. rainfall deficit droughts, C. wet to dry season droughts, D. cold snow season droughts, E. warm snow season droughts, F. composite droughts, G. glaciermelt deficit droughts and H. snowmelt deficit droughts. The mean indicates the average synchrony over all catchments.

In a next step, we compare drought synchrony with drought type frequency over the entire study period (see Figure 5). Rainfall deficit droughts have the highest average frequency over the catchments where they occur (11.33), but their frequencies are lower in the Alps that are located in the south. Composite droughts also occur frequently, particularly north of the Alps (9.32). Cold snow season droughts (6.14) and snowmelt deficit droughts (4.83) occur at a medium frequency, with snowmelt deficit droughts reaching higher frequencies over the Alps in the south than in the lower areas in the north. Wet to dry season droughts occur at a low frequency (2.90), despite their high synchrony. Similarly, glaciermelt deficit (2.86), warm snow season (2.22), and rain to snow season droughts (1.64) only rarely occur. These latter drought types also only affect specific parts of the domain, with glaciermelt deficit and rain to snow season droughts focused around the Alps and warm snow season droughts only occurring in the northern part of the study region.

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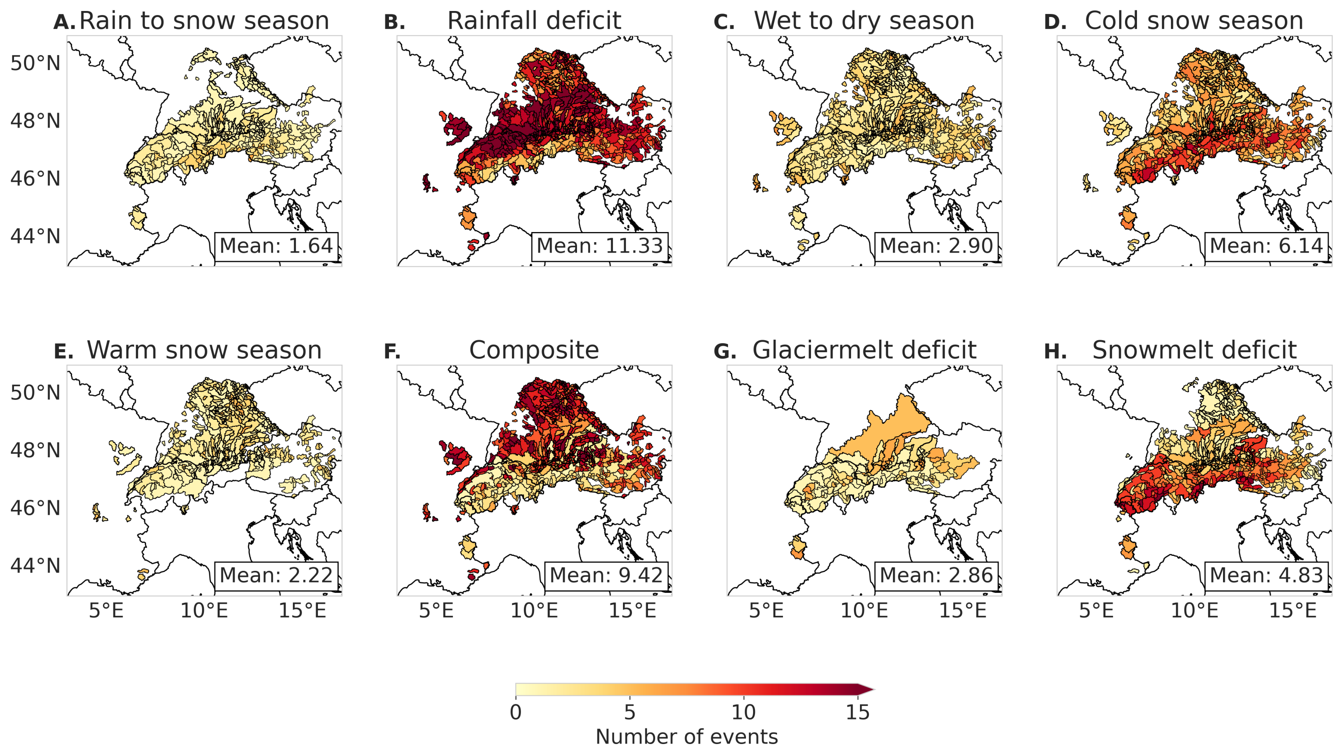

Figure 5. The frequency of occurrence of different drought types. The subplots show A. rain to snow season droughts, B. rainfall deficit droughts, C. wet to dry season droughts, D. cold snow season droughts, E. warm snow season droughts, F. composite droughts, G. glaciermelt deficit droughts, and H. snowmelt deficit droughts. The mean indicates the average frequency over all catchments where this drought type occurs.

Last, we look at changes in the contribution of different drought types to large drought events, i.e. those that affect more than 50% of the studied catchments. Over time, the number of large events with a single drought type affecting half of the catchments under drought has decreased from 77% before 1993 to 36% after 1993 (see Figure 6). At the same time, the average size of the events has only slightly increased (from 62% to 64% of catchments) and the number of larger events has slightly decreased (from 13 to 11). Rainfall deficit droughts have become less important, but have still retained their role as the most dominant contributor to large drought events after 1993 (see Figure 6B). Rain-to-snow season droughts have also become less important over time (see Figure 6A). In contrast, the contribution of cold snow season droughts, warm snow season droughts, and snowmelt deficit droughts has increased over time (see Figure 6D, E, and H). The contribution of other drought types has remained largely constant. Note that only the decrease in rainfall deficit and the increase in snowmelt deficit drought contribution are significant at the 5% significance level.

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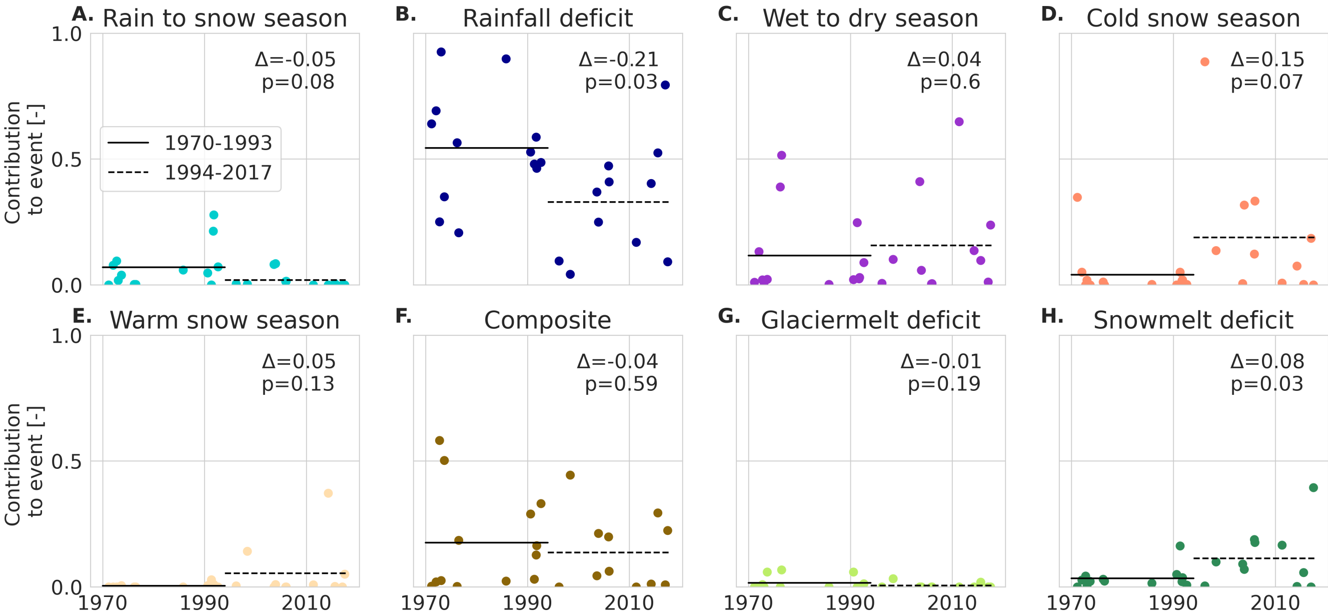

Figure 6. The contribution of each drought type to large events over time. We compare 1970-1993 with 1994-2017. The subplots show A. rain to snow season droughts, B. rainfall deficit droughts, C. wet to dry season droughts, D. cold snow season droughts, E. warm snow season droughts, F. composite droughts, G. glaciermelt deficit droughts and H. snowmelt deficit droughts. Δ indicates the difference in average contribution (new (1994-2017) minus old (1970-1993)), whereas p indicates the p-value of this change based on a t-test.

4 Discussion

Large droughts have different and more spatially homogeneous generation processes than small droughts, even in hydroclimatically complex and heterogeneous regions like the mountainous Alps (see Figure 2). Given that large droughts can have more severe impacts than localized ones, this finding highlights that the most dominant local drought generation process might not always be the most impactful one (Brunner et al., 2022).

Streamflow drought events with a large spatial extent often consist of just one or only two drought types (see Figure 3). Drought size is thus mostly controlled by the spatial footprint of the occurring drought types, which differs significantly across drought types (see Figure 4). These conditions lead to other generation processes being dominant for large than for small droughts. Let us consider the example catchment in Figure 1B: this catchment experiences droughts that can be attributed to a variety of different drought types. Snowmelt deficit droughts represent the drought type occurring most frequently and are therefore locally dominant, however, the droughts belonging to this type remain limited in size. In contrast, when a wet to dry season or a rainfall deficit drought occurs in this catchment, many other catchments are also in drought because such rainfall-driven events are relatively synchronized in space (see Figure 4B).

Only four types of droughts have the ability to reach large spatial extents by themselves: rainfall deficit, wet to dry season, cold snow season, and composite droughts (see Figure 3 and Figure 4B, C, D, and F). These findings support the hypothesis

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by Van Loon and Van Lanen (2012) that spatial synchrony is especially high for rainfall-driven drought types. Among these, rainfall deficit droughts occur more frequently than other drought types, while wet to dry season droughts are rare (compare Figure 5B and C). Therefore, rainfall deficit droughts are the dominant driver of large droughts. Why would exactly these drought types lead to large-scale drought patterns? For a large scale drought to occur, all catchments must to some extent be influenced by similar hydro-meteorological conditions. In heterogeneous regions such as the Alps, only some drought generation processes can i.) span across hydro-climates and ii.) cause droughts in each hydro-climate at the same time. An example of such a process not bound to a specific hydro-climate is rainfall deficits: rainfall deficits can affect large regions simultaneously (e.g. Haslinger et al., 2019; Haslinger and Blöschl, 2017) and they can lead to streamflow droughts – i.e. rainfall deficit droughts – in most seasons and in most catchments. In contrast, many drought types are restricted to specific hydro-climates or time periods: glaciermelt deficit droughts require the presence of glaciers and snowmelt deficit droughts are generally restricted to regions and seasons in which snow is important for streamflow generation. Snowmelt droughts are therefore rare in non-snow-dominated rivers (see Figure 5H). Still, examples such as the 2022 Po river drought show that snowmelt-driven streamflow droughts can grow well beyond mountain chains (Colombo et al., 2023; Avanzi et al., 2024). These droughts grow along upstream-downstream connections in the river network (whereas our analysis focuses on any spatial relationship between catchments) and sometimes require additional compounding factors such as the precipitation deficits and high summer temperatures present in 2022 (Avanzi et al., 2024). However, even drought generation processes that do affect multiple hydro-climates might not always lead to simultaneous and therefore large droughts. Instead, the exact timing of drought occurrence might depend on the hydro-climate of each catchment. (Sub-)surface processes can cause heterogeneity or influence the transmission of the drought signal to the river (e.g. Hellwig et al., 2022), and the time in the year when the local air temperature reaches a specific temperature threshold (e.g. the melt temperature) can also be location and elevation dependent (Van Loon and Van Lanen, 2012). Regional and elevation-dependent temperature differences can cause spatial variations in the start of the snowfall or snowmelt seasons (Klein et al., 2016), which play a role for rain to snow season or cold snow season droughts. The resulting relative time shifts between catchments could lead to asynchrony in drought onset and could potentially limit the spatial extent of drought types associated with these temperature thresholds (Van Loon and Van Lanen, 2012).

The identified dominant patterns of the driving processes leading to large droughts likely depend on the specific set of streamflow stations selected for this analysis. While we used a wide range of stations that are representative for the larger region and the results are largely robust when using unnested catchments only (see Figure S3 in the Supporting Information), we acknowledge that low-elevation catchments are better represented than high-elevation catchments. As rainfall deficit droughts are particularly common in the lower elevation catchments in the north of the study domain (see Figure 2 and 5B), this over-representation of low-elevation catchments might slightly skew the results. Still, we argue that streamflow droughts in the Alps should be seen in the context of the surrounding region when studying large droughts. The largest and most impactful droughts in the Alpine region – such as those in 2003 and 2015 (Stephan et al., 2021) – did not remain restricted to the Alpine region. Instead, they co-occurred with hydrological drought over large parts of the European continent (Laaha et al., 2017). Our identified driver patterns are thus representative of larger droughts in this region. Nevertheless, in a study region where snowmelt-dominated rivers are in the majority, snow-driven droughts would likely be the dominant driver of larger droughts.

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However, the same general mechanisms as those identified in our study would hold: the processes that affect a majority of catchments simultaneously will lead to the largest droughts, even if other processes occur more frequently locally.

Earlier research has indicated that historic changes in hydro-climate have affected drought size (Brunner et al., 2021; Sharma and Mujumdar, 2024; Lorenzo-Lacruz et al., 2013) and dominant drought types (Brunner et al., 2023). Our results additionally show that the drought types that contribute to large droughts are changing (see Figure 6). In particular, we find that rainfall deficit droughts contributed less to large droughts at the end of the study period than at the beginning. Other processes show an increased contribution in recent years (i.e. cold snow season droughts, warm snow season droughts and snowmelt deficit droughts; see Figure 6). Brunner et al. (2023) found a similar change pattern for local droughts and have shown that the relative frequency of certain drought types has increased over time. Specifically, they have shown that drought events driven by snowmelt deficits have become relatively more frequent because of reductions in the Alpine snow cover (Matiu et al., 2021). The number of events dominated by a single drought type has decreased in recent decades (see Figure 6), suggesting that larger droughts are increasingly related to a mix of drought types. Sometimes, the co-occurring drought types could still be causally linked: one type of meteorological anomaly can cause multiple drought types when catchments have different surface conditions or absolute temperatures due to elevation differences (Van Loon and Van Lanen, 2012). For example, a rainfall deficit could lead to rainfall deficit droughts in temperate catchments and rain-to-snow season droughts in colder catchments. Anomalously warm temperatures, in contrast, can lead to both snowmelt deficit droughts and warm snow season droughts. As the climate is warming (Auer et al., 2007), we find that both snowmelt deficit droughts and warm snow season droughts show increased contributions to larger drought events over time (see Figure 6E and H). The increase in the contribution of these temperature-driven event types to large drought events supports findings of previous studies which have shown that temperature plays an increasingly important role in explaining drought spatial extent (Brunner et al., 2021). In contrast, the increasing contribution of cold snow season droughts to larger droughts seems in contradiction with the general warming trend. Without increases in cold winter frequency, the increase in contributions from this drought type could be related to a higher sensitivity of catchments to this drought type. For example, attenuation by sub-surface storage can sometimes prevent the development of streamflow droughts (Van Loon and Van Lanen, 2012). Reduced pre-event catchment storage (for example due to increased evapotranspiration in the preceding summer; Bruno et al. (2025)) could thus be a cause of the increased frequency of cold snow season droughts (Brunner et al., 2023). Such increased sensitivity to droughts could also lead to a spatial synchronization of droughts and thus larger cold snow season droughts. Still, this example illustrates the limitation of the classification scheme applied here, which cannot clearly distinguish between different causes of a frequency increase in a specific drought type.

Our results show that each drought type is associated with its own typical drought size, which can have important implications for water management. Not all drought types are equally impactful locally, and not all regions experience all drought types. As an illustration, hydropower production in catchments with limited storage and glacier cover is vulnerable to hot and dry weather, whereas hydropower production in glacierized catchments can be sustained by the influx of glaciermelt (Otero et al., 2023). The droughts that lead to impacts on hydropower might therefore be large in non-glacierized catchments (e.g. rainfall deficit drought, wet to dry season drought), but much smaller in glacierized catchments (e.g. glaciermelt deficit droughts;

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compare Figure 4B and C with G). Furthermore, hydropower plants in such hydroclimatologically different catchments might rarely be affected by drought at the same time. By explicitly considering such differences in typical drought sizes between different spatial drought patterns in the planning of an economic sector, the likelihood that the entire sector is affected by drought at any given time can be decreased. For example, hydropower production in the Western United States is relatively stable over time, as the variability in climatic conditions that affect the hydropower plants in this region make it unlikely that all plants are affected by drought at the same time (Turner et al., 2022). Lastly, we have identified trends in the drought types that contribute to large droughts: the contribution of rainfall deficit droughts has decreased, whereas the contribution of other drought types such as snowmelt deficit droughts has increased over time (see Figure 6). We also find that each drought type is associated with its own spatial footprint (see Figure 4). If we understand how the relative frequency of different drought types is expected to change in future, knowledge on each type's typical spatial pattern could be used to project drought sizes into the future.

5 Conclusions

Our study provides new observational evidence confirming that large droughts are mostly driven by spatially-homogeneous rainfall deficits, even in catchments where local droughts are dominated by other processes such as snowmelt or snowfall. We show that large drought events often consist of one or two drought types that affect the majority of the catchments affected. We also find that only some drought types (i.e. rainfall deficit, wet to dry season drought, cold snow season and composite droughts) can actually result in large droughts, whereas other drought types generally remain small in extent. Last, we show that the contribution of different drought types to large drought events has changed over time: in recent decades, rainfall deficit droughts have become less dominant over other processes, so that generation processes of larger droughts are more heterogeneous than before. These insights can help water management to focus their resources on the most impactful droughts (in terms of spatial extent) instead of the most common drought event type occurring in a catchment.

Data availability. The streamflow time series, catchment characteristics and time series of generation processes derived from ERA5 are available through Hydroshare from http://www.hydroshare.org/resource/f1c12fa6c5be4c61a5ec617fa62e13d6 (Schlemper et al., 2024).

Author contributions. JJ and MIB both worked on the conceptualization of the study and on software and data curation. JJ performed the formal analyses and visualizations. JJ wrote the original paper draft and MIB and JJ reviewed and edited the draft. MIB acquired the funding for and supervised this project.

Competing interests. Manuela Brunner is an editor with HESS. The authors declare no further competing interests.

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