Water Resources Research

RESEARCH ARTICLE
10.1029/2022WR032871

Moderate and Severe Hydrological Droughts in Europe Differ in Their Hydrometeorological Drivers

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Key Points:

- We develop a standardized and objective classification scheme for streamflow droughts using hydroclimatic information
- The most severe drought events are governed by other processes than moderate events
- Moderate droughts are dominated by rainfall deficits and severe droughts by snowmelt deficits or prolonged rainfall deficit droughts

Supporting Information:

Supporting Information may be found in the online version of this article.

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Citation:

Brunner, M. I., Van Loon, A. F., & Stahl, K. (2022). Moderate and severe hydrological droughts in Europe differ in their hydrometeorological drivers. *Water Resources Research*, *58*, e2022WR032871. https://doi.org/10.1029/2022WR032871

Received 27 JUN 2022
Accepted 16 SEP 2022

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Abstract Hydrological extreme events are generated by different sequences of hydrometeorological drivers, the importance of which may vary within the sample of drought events. Here, we investigate how the importance of different hydrometeorological driver sequences varies by event magnitude using a large sample of catchments in Europe. To do so, we develop an automated classification scheme for streamflow drought events. The classification scheme standardizes a previous qualitative drought typology and assigns events to one of eight drought event types—each characterized by a set of single or compounding drivers—using information about seasonality, precipitation deficits, and snow availability. The objective event classification reveals how drought drivers vary not just in space and by season, but also with event magnitude. Specifically, we show that (a) rainfall deficit droughts and cold snow season droughts are the dominant drought event type in Western Europe and Eastern and Northern Europe, respectively; (b) rainfall deficit and cold snow season droughts are important from autumn to spring while snowmelt and wet-to-dry season droughts are important in summer; and (c) moderate droughts are mainly driven by rainfall deficits while severe events are mainly driven by snowmelt deficits in colder climates and by streamflow deficits transitioning from the wet to the dry season in warmer climates. These differences in sequences of drought generation mechanisms for severe and moderate events suggest that future changes in hydrometeorological drivers may affect moderate and severe events differently.

1. Introduction

Streamflow droughts can be generated and influenced by a variety of processes including rainfall deficits, limited snow availability, or high evapotranspiration. For example, the 2018 drought, which affected wide parts of Europe, was mainly caused by rainfall deficits modulated by high temperatures (Bakke et al., 2020). In contrast, the multiyear California drought from 2013 to 2016 was mainly caused by rainfall deficits modulated by a lack of snow accumulation during winter leading to below-average snowmelt contributions (Luo et al., 2017). There is some evidence that the importance of different drought drivers such as precipitation or snowmelt deficits varies in space. For example, it has been shown that drought generation processes are related to climate (Van Loon & Van Lanen, 2012; Van Loon et al., 2015) and that the relative importance of precipitation and potential evapotranspiration for drought onset varies by region (Markonis et al., 2021). Furthermore, it has been demonstrated that the drought statistics of a catchment, for example, the number of drought events, mean drought duration, maximum drought intensity, the drought propagation behavior from meteorological to hydrological drought, and drought termination are related to climatic characteristics, soil properties, catchment storage state, and other physiographic catchment characteristics (Apurv & Cai, 2020; Barker et al., 2016; Ganguli et al., 2022; Konapala & Mishra, 2020; Parry et al., 2016; Tijdeman et al., 2022; Van Loon & Laaha, 2015). While these existing studies indicate that drought drivers vary regionally, we here assume that they also vary by event, that is, that different drought events in a catchment can be driven by different hydrometeorological drivers or a set of drivers.

As a result of such temporal variations in drought drivers, we may expect variations with event magnitude. That is, moderate droughts may be driven by different processes than severe droughts. Existing studies based on small sets of catchments suggest such varying drought driver-magnitude relationships by showing that events with high drought deficits are likely to develop in catchments where snow processes play an important role (Van Loon & Van Lanen, 2012). In addition, such varying relationships have been revealed for floods where severe events have been shown to have different drivers than moderate events (B. Merz et al., 2021; R. Merz & Blöschl, 2003; Tarasova et al., 2020). We here hypothesize that such dichotomous behavior may also exist in the case of hydrological droughts if moderate and severe droughts are caused by different sequences of hydrometeorological drivers. However, the relationship of compounding hydroclimatic drought drivers with respect to drought magnitude remains relatively unexplored. Therefore, we here ask how hydrometeorological drought-driver combinations vary in a catchment's drought sample and with event magnitude.

To study the relationship between event magnitude and driver sequences, we use event classification, which has been extensively used in the flood community to study a variety of flood drivers (Brunner et al., 2017; R. Merz & Blöschl, 2003; Sikorska et al., 2015; Stein et al., 2019; Tarasova et al., 2019). While a variety of different flood typologies exists, only few attempts have been made to develop classification schemes for streamflow droughts which separate events according to their dominant hydrometeorological driver sequences. Van Loon and Van Lanen (2012) proposed a qualitative hydrological drought typology based on drought-generating processes consisting of six drought event types, which they later extended by two further drought event types to describe droughts in cold climates (Van Loon et al., 2015). Hydrological drought event types include rainfall deficit droughts, which are exclusively caused by a prolonged lack of rainfall and possibly aggravated by high evapotranspiration; rain-to-snow season droughts, caused by a rainfall deficit in the rain season continuing into the snow season; wet-to-dry season droughts caused by a rainfall deficit in the rain season that continues into the dry season, potentially enhanced by evapotranspiration (Massari et al., 2022; Mastrotheodoros et al., 2020; Teuling et al., 2013); cold snow season droughts, caused by abnormally low temperatures in the snow season; warm-snow-season droughts, caused by abnormally high temperatures in the snow season; snowmelt droughts, caused by a lack of snowmelt discharge in snow-influenced basins; glaciermelt droughts, caused by a lack of glaciermelt; and composite droughts, caused by a number of drought generation mechanisms. While this drought typology is comprehensive and has been successfully applied in individual catchments, it is not readily applicable to a large set of catchments because of a lack of standardized classification rules. Such rules enable the attribution of specific events to specific drought event types, but have so far been limited to a small set of drought event types (Van Loon et al., 2014) or been derived using unsupervised learning (Markonis et al., 2021).

We here standardize and automate the classification scheme by Van Loon et al. (2015) to classify drought events in temperate and cold regions according to their hydrometeorological drivers into one out of eight drought event types. The scheme is applicable to large samples of catchments because it uses globally available data, that is, observed streamflow from the Global Runoff Database (GRDC, 2019) and hydrometeorological time series from the ERA5-Land reanalysis including temperature, precipitation, and snow-water-equivalent (SWE). We use this standardized classification scheme on a large sample of catchments in Europe to better understand (a) the spatio-temporal variability of physical drought drivers over Europe and (b) differences in the drivers of severe and moderate drought events in streamflow time series.

To assess how hydrological drought event types vary by event magnitude, that is, whether the most severe events in streamflow time series are governed by different sequences of drought generation processes than moderate drought events, we look at the relative importance of different drought event types for events with a moderate versus severe deficit and duration. This event-based perspective is distinct from the more general catchment-based perspective taken in catchment-similarity studies which summarizes a catchment's drought behavior in terms of one or several drought statistics (Apurv & Cai, 2020; Konapala & Mishra, 2020; Van Loon & Laaha, 2015). These previous studies established relationships between drought characteristics such as mean drought duration or maximum drought intensity using various types of analyses including correlation analyses or linear and nonlinear regression models. That is, they show that catchments with on average more severe droughts have different characteristics than catchments with on average less severe droughts. In contrast to this catchment-based perspective, the event-based perspective allows us to look at the differences between severe and moderate drought events within a catchment's drought sample (rather than across catchments). That means that contrary to past catchment-similarity studies, we are able to identify differences between the governing processes of severe and moderate drought events in a catchment's streamflow time series rather than differences between the characteristics of catchments with different drought properties.

2. Methods and Materials

2.1. Data and Study Region

To study variations in the hydrometeorological drivers of droughts in a given catchment and by event magnitude, we selected 817 catchments in Central Europe that do not reflect heavily regulated flow conditions from the Global Runoff Database (GRDC, 2019) (Figure 1). The catchments have streamflow observations for the period

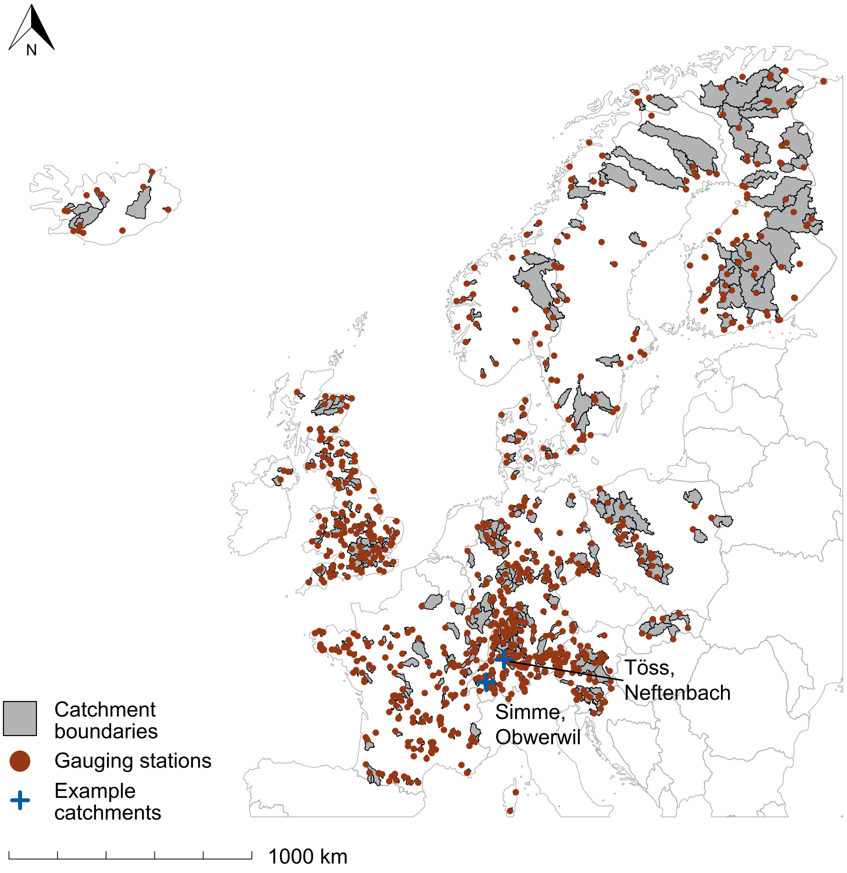

Figure 1. Map of 817 nearly natural catchments contained in the GRDC runoff database used to analyze hydrological drought event types in Europe and locations of two example catchments in different regions and hydroclimates: Simme, Obwerwil: snow dominated and Töss, Neftenbach: rainfall dominated.

1981–2012 (France no longer available from 2013) and streamflow is unaltered by dams according to the Global Streamflow Indices and Metadata Archive (GSIM) (Do et al., 2018). Our focus is on natural flow conditions because we are interested in studying natural drought generation processes and their variability over Europe. Catchment areas of the selected catchments range from a lower quartile of 114 km^2 over a median of 276 km^2 to an upper quartile of 820 km^2 and mean elevations from a lower quartile of 55 m above sea level (m.a.s.l.) over a median of 166 m.a.s.l. to an upper quartile of 401 m.a.s.l.

For each of these catchments, we derive a set of hydroclimatic time series using gridded ERA5-Land reanalysis data (ECMWF, 2019; Muñoz-Sabater et al., 2021) downloaded from the Copernicus data store and catchment boundaries extracted from the GSIM. ERA5-Land provides hourly time series for a number of variables describing the water and energy cycles over land at a spatial resolution of 9 km for the period 1981–2020. We compute areal sums for precipitation (P) and snow-water-equivalent (SWE) and areal averages of temperature (T) for the period 1981–2012 overlapping with the period for which streamflow data is available. Compared to other potential data sources that only provide a subset of these variables at equal or finer spatial resolution, ERA5-Land allows us to consistently compute time series across all variables needed for hydrological drought classification. In addition to these hydroclimatic variables, we derive the glacier cover percentage for each catchment using glacier cover outlines derived from the Randolph Glacier Inventory version 6.0 (RGI Consortium, 2017).

2.2. Deficit and Anomaly Definitions

For each catchment, we derive time series of droughts defined as streamflow anomalies and anomalies in the different hydrometeorological drivers. We define droughts as negative streamflow anomalies using a variable threshold-level approach suitable for catchments with a seasonal streamflow regime (Van Loon & Laaha, 2015).

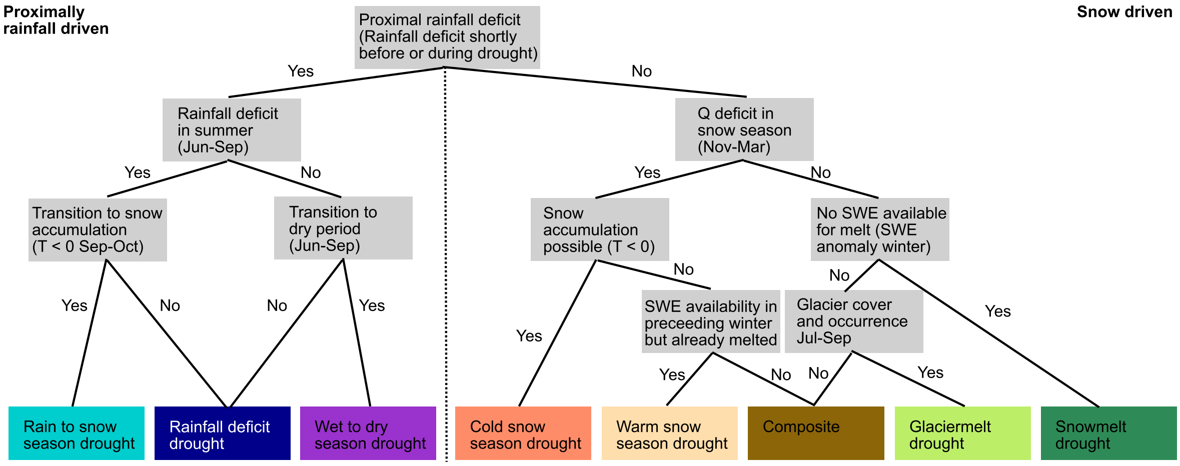

Figure 2. Illustration of standardized drought classification scheme compiled based on the drought type descriptions provided in Van Loon and Van Lanen (2012) and Van Loon et al. (2015). Distinction between proximally rainfall-driven drought types including rain-to-snow season, rainfall deficit, and wet-to-dry season droughts and snow driven types including cold snow season, warm snow season, composite, glaciermelt, and snowmelt droughts using specific classification rules (gray boxes).

Prior to event extraction, the daily time series are smoothed over a time window of 30 days to minimize the number of dependent events (Fleig et al., 2006). The variable threshold is computed using the 20th flow percentile for each day of the year derived within a moving window ±15 days before and after the day of interest (Brunner, Slater, et al., 2021; Brunner, Swain, et al., 2021). We only retain drought events lasting at least 30 days to limit the selection to important events. This event identification procedure resulted in a median number of 25 extracted events per catchments (first quartile: 20 events, third quartile: 29 events). For each event, we determined its duration (days) and deficit (mm/event). Precipitation anomalies are defined using the same procedure as for streamflow, that is, by applying a variable threshold at the 20th percentile, using a moving window of 30 days, and applying a minimum event duration of 30 days. In addition to precipitation anomalies, we define months with SWE anomalies as months where monthly SWE falls below the long-term monthly 20th percentile of SWE. In addition to these anomalies, the classification relies on the timing of drought occurrence and on temperature with negative temperatures indicating the potential for snow accumulation.

2.3. Streamflow Drought Classification

We propose a standardized classification scheme for streamflow droughts in temperate and cold regions that enables assigning specific drought events to one of eight hydrological drought event types (hereafter also simply referred to as drought types) using hydroclimatic information including rainfall deficits, snow availability, or temperature during the months and seasons leading up to drought occurrence (Figure 2). The hydrological drought types considered have initially been proposed by Van Loon and Van Lanen (2012) and Van Loon et al. (2015) and include proximally rainfall-driven drought types such as rain-to-snow season droughts, rainfall deficit droughts, and wet-to-dry season droughts as well as snow-driven drought types such as cold snow season droughts, warm snow season droughts, snowmelt droughts, glaciermelt droughts, or composite droughts, that is, droughts with multiple drivers.

The classification tree in a first step separates proximally rainfall-driven events (Figure 2), that is, events that are caused by rainfall deficits shortly before or during drought, from snow-driven events which are more temperature driven or when precipitation deficits occurred during the preceding winter. An event is assigned to the proximally rainfall-driven branch if a precipitation deficit was detected in a time window spanning 30 days before the start of the streamflow drought and the middle of the streamflow drought. If an event is assigned to the proximally rainfall-driven branch, three rules are applied to assign an event to one out of three drought types. If the rainfall deficit occurred in summer (June to September), we test whether the drought persisted into autumn because of snow accumulation (drought also affected September or October and temperature is below 0°C). If so, we assign the event to the class of rain-to-snow season droughts. If not, the event is assigned to the class of rainfall deficit droughts. If the rainfall deficit occurred outside summer, we test whether the drought persisted into the dry period, when evapotranspiration is an important water balance component (June–September) and can potentially

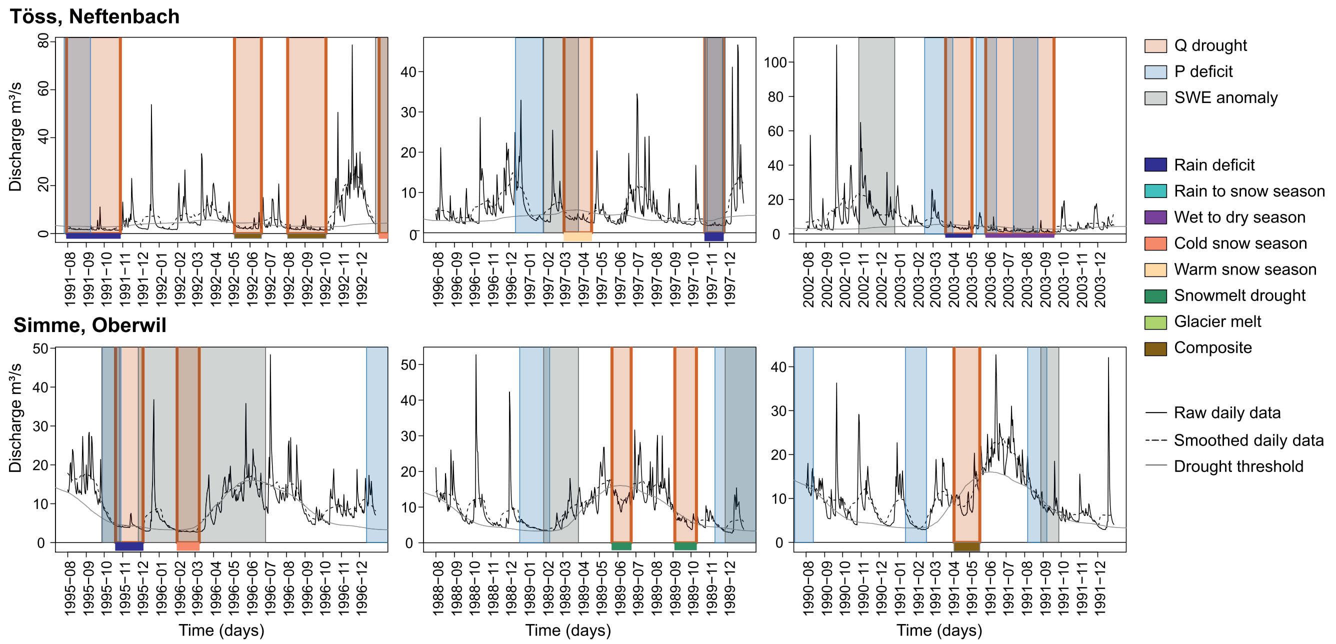

Figure 3. Three drought development examples for two example catchments Töss, Neftenbach (rainfall dominated, upper panel) and Simme, Oberwil (snow dominated, lower panel). Driver deficits are indicated by colored rectangles and drought types by colored vertical bars.

enhance the streamflow deficit (Apurv et al., 2017; Massari et al., 2022; Mastrotheodoros et al., 2020; Teuling et al., 2013). We assign the event to the wet-to-dry season drought class if it did persist into the dry period or to the rainfall deficit drought class if it did not. That is, we are using season of occurrence as a proxy for the importance of evapotranspiration as a drought driver to ensure that only events in the season when evapotranspiration is a relevant water balance component are classified as wet-to-dry season droughts.

We now move to the snow-driven branch, which is activated if the drought event does not fall into the proximally rainfall driven branch, and define the rules applied to assign snow-driven events to one out of five drought types. First, we look at streamflow drought seasonality and determine whether the streamflow deficit happened during the snow season (November–March). If the streamflow deficit occurred during the snow season, we test whether snow accumulation was possible (temperature $< 0°$C). If so, the event is classified as a cold season drought. If no snow accumulation was possible, we check whether snow was available sometime in winter but has already melted (SWE in winter > 0). If so, we assign the event to the class of warm snow season droughts, if not, to the class of composite droughts. If the streamflow deficit did occur outside of the snow season, we test whether insufficient SWE was available for melt (SWE anomaly winter). If yes, the drought event is assigned to the snowmelt drought class. If sufficient SWE was available, we test whether the catchment does have glaciers and the drought event occurred during the glaciermelt season (July–September). If yes, the event is defined as a glaciermelt drought and if not as a composite drought. Implementing these standardized classification rules allows us to assign any drought event to one of eight drought classes (for two examples see Figure 3).

We apply the standardized classification procedure to all streamflow drought events identified in the 871 catchments. There is no benchmark drought data set that might be used to validate this new standardized scheme. However, we based the classification scheme on drought type descriptions, which are based on hydrological processes, provided in existing studies (Quesada-Montano et al., 2021; Van Loon & Van Lanen, 2012; Van Loon et al., 2015) and checked the plausibility of assigned classes for a few well described events such as the event in 2003. We compared the drought type distributions of two severe drought events affecting wide parts of Europe, that is, the 2003 and 2015 events, which were importantly driven by precipitation deficits (Hanel et al., 2018). While both events were characterized by precipitation deficits, they differed in terms of snow availability in the higher-elevation catchments. The year 2015 was characterized by a precipitation deficit already in the preceding winter season while the winter 2003 was rather wet (Laaha et al., 2017). That is, one would expect more snow-related droughts in 2015 compared to 2003. Our classification scheme recognizes that both events were

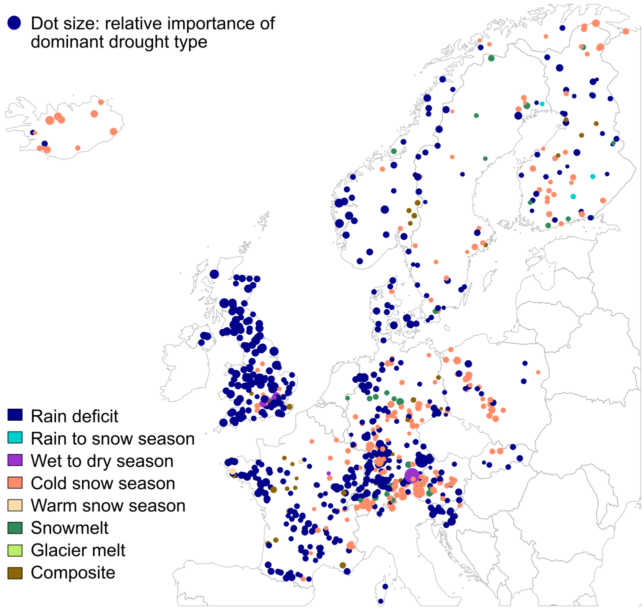

Figure 4. Dominant (i.e., most frequent) drought type per catchment. The size of the dot indicates the relative importance of the dominant drought type within a catchment (the larger the dot is, the larger is the share of the dominant drought type).

importantly influenced by rainfall-driven droughts types and that snowmelt droughts were substantially more important in 2015 than in 2003, while the importance of all other drought types was similar for both events (Figures S1 and S2 in Supporting Information S1). For each catchment in our data set, we determine its dominant drought type, that is, the most frequent drought type per catchment, and the relative importance of each drought type, that is, the relative frequency of each drought type.

2.4. Frequency Analysis

To address the question of whether and how the importance of different drought driver combinations varies by event magnitude, we divide the observed streamflow droughts into "moderate" and "severe" events by applying a return period threshold of 10 years, that is, we define moderate and severe events as events with return periods <10 and >10 years, respectively. The return period of each event in terms of deficit and duration is defined by performing a frequency analysis on deficits and durations separately. For this analysis, we fit a generalized extreme value (GEV) distribution to the deficit and duration sample separately using L-moments (because of the small sample size, this is a more suitable alternative estimation method than maximum likelihood estimation (Hosking et al., 1985)). Both the Anderson–Darling and Kolmogorov–Smirnov tests do not reject the GEV at a level of significance of 0.05 in 98% of the catchments and we therefore consider the distribution a suitable choice for our drought frequency analysis. All parameters of the GEV are considered stationary as the nonparametric Mann–Kendall test rejects H0 of no trend in only 5% of the catchments at $\alpha = 0.05$. The fitted distributions are used to determine the probability p of each observed drought event both in terms of deficit and duration. Then, the corresponding return period T is assigned using the relationship

$$p = 1 - (\mu/T), \tag{1}$$

where μ is the mean inter-arrival time between events. Subsequently, severe drought events are defined as those with a return period longer than 10 years.

3. Results

3.1. Drought Type Variation in Space and Time

The dominant drought type, that is, the most frequent drought type per catchment, varies spatially with rainfall deficit droughts dominating in Western Europe and cold snow season droughts dominating in the Alps, continental regions in Central Europe and parts of Scandinavia (Figure 4). With some exceptions in the Alps and Scandinavia, which are dominated by snowmelt droughts, very few catchments show other dominant drought types than rainfall and cold snow season droughts.

The dominant drought type per catchment also varies in time, that is, by season (Figure 5). From fall to spring, rainfall deficit droughts dominate in Western Europe and cold snow season droughts in the Alps, Eastern and Northern Europe. In summer, Western Europe droughts are proximally rainfall driven (rain deficit or wet-to-dry season) while continental, high-latitude and -altitude catchments are snowmelt drought dominated.

Although it is useful to look at spatial patterns in drought types, the dominant drought type only provides a partial picture of the catchment-specific drought type distribution. More than 85% of the catchments are affected by five or six different drought types and only a handful by less than four different types. That is, the diversity of drought types within a catchment is substantial. Each catchment shows a particular drought type distribution or mix, that is, changing importance of different drought types relative to each other (Figure 6). This drought type distribution changes as we move from warmer to colder catchments or from low-elevation and -latitude catchments to high-elevation and -latitude catchments. Warmer catchments are importantly influenced by proximally

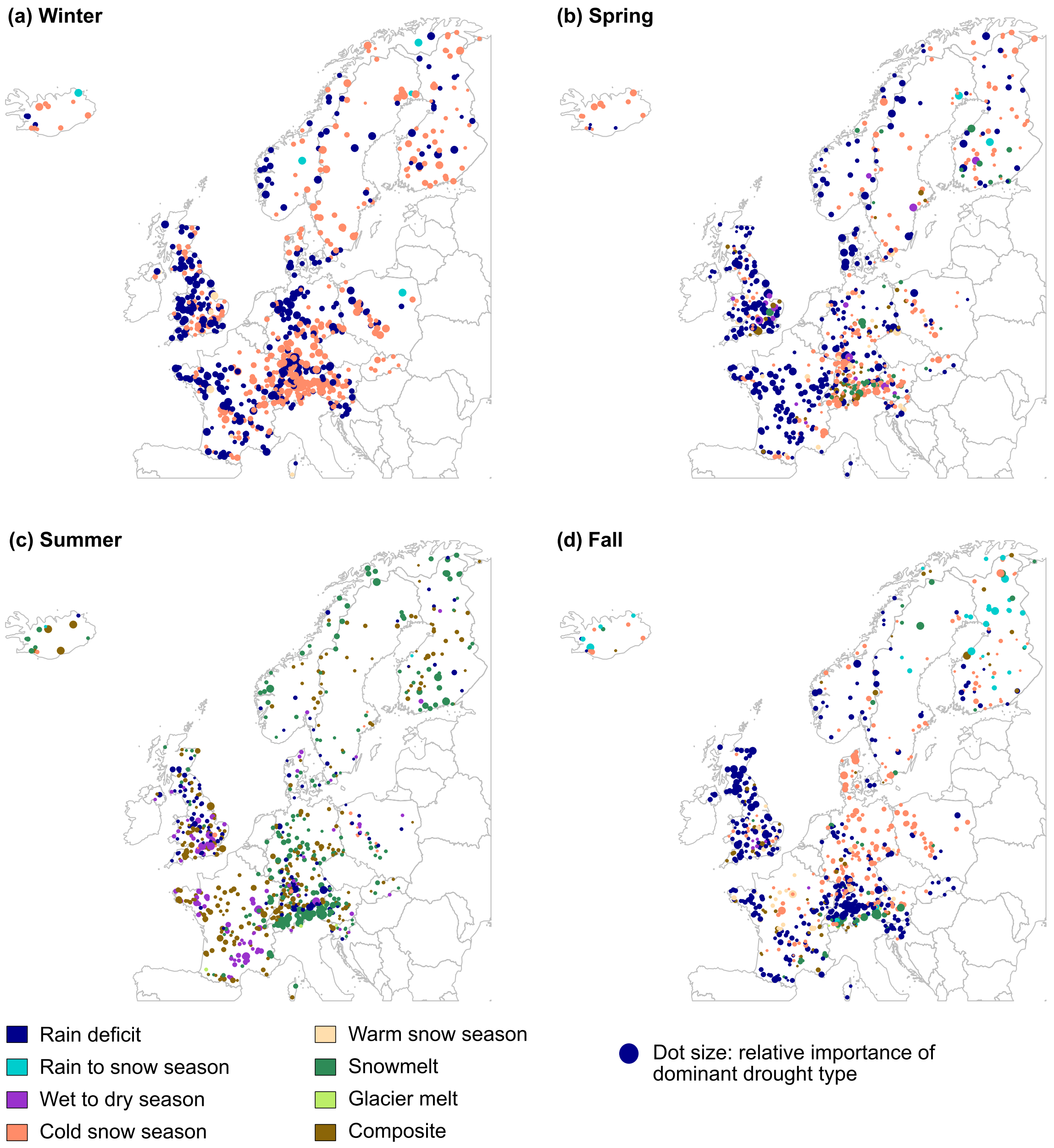

Figure 5. Seasonally dominant drought types over Europe: (a) winter (December–February), (b) spring (March–May), (c) summer (June–August), and (d) fall (September–November). The size of the dot indicates the relative importance of the dominant drought type within a catchment (the larger the dot is, the larger is the share of the dominant drought type).

rainfall-driven events including rainfall deficit and wet-to-dry season droughts, in addition, they experience warm snow season and cold snow season droughts as well as composite droughts. As we move toward colder, that is, high-elevation and -latitude catchments, drought type diversity increases and snow-influenced drought types become more important (i.e., snowmelt droughts, rain-to-snow season droughts, and cold snow season droughts) while proximally rainfall-driven events become less important.

3.2. Drought Type Variation With Event Magnitude

Drought types differ in their drought characteristics, that is, some have longer/shorter durations, larger/smaller deficits or higher/lower intensities (Figure S3 in Supporting Information S1). Rain-to-snow season droughts and wet-to-dry season droughts are the most severe drought types both in terms of duration and deficit while glacier

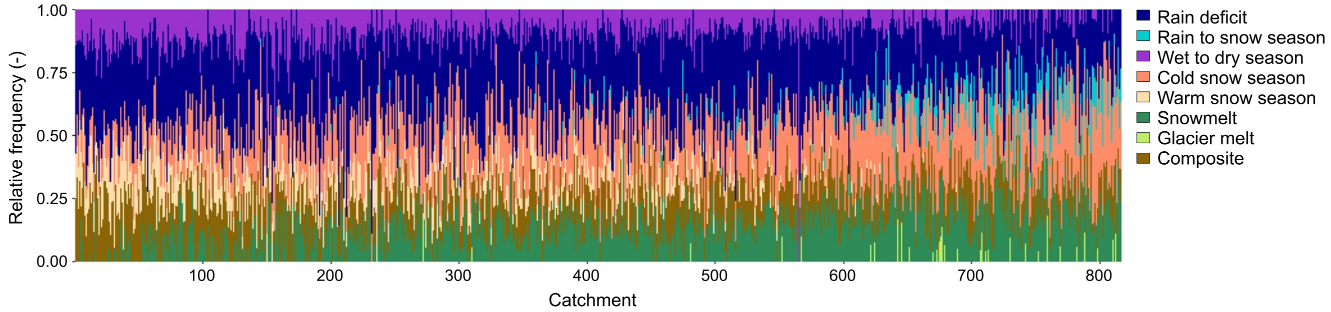

Figure 6. Drought type frequency distribution per catchment (one bar = one catchment). Catchments are ordered by mean temperature from warmer on the left to colder on the right.

melt droughts show the highest intensities but are relatively short (Figure S3 in Supporting Information S1). These differences in characteristics are reflected in the drought frequency curves of two example catchments (Figure 7) where certain drought types appear to be more likely to be associated with severe droughts both in terms of deficit (left column) and duration (right column). For example, in the Töss catchment, the most severe droughts are all proximally rainfall driven while the less severe droughts are driven by a mix of processes. Similarly, the Simme catchment mostly experiences snow-related droughts but the most severe event on record is a wet-to-dry season drought and proximally rainfall driven.

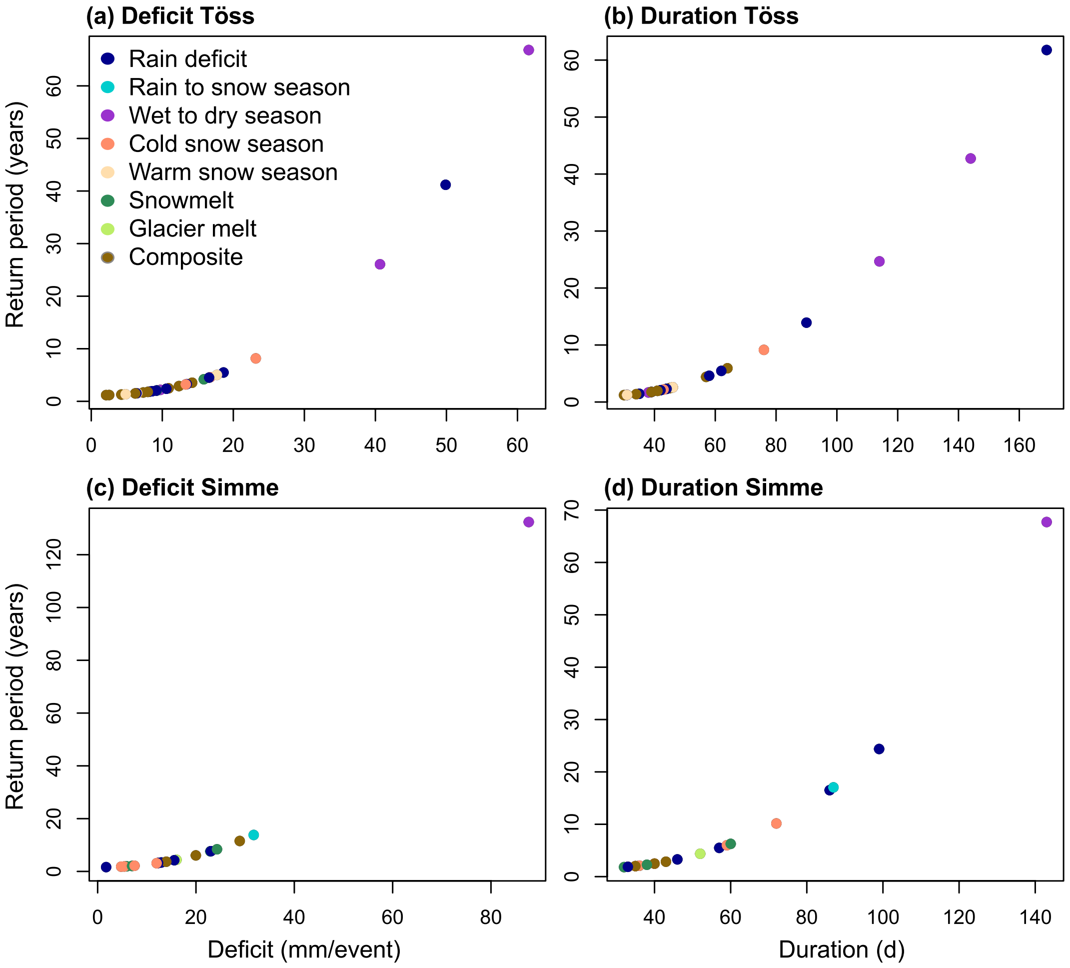

Figure 7. Drought frequency curves for two example catchments—Töss and Simme—with return period estimates in terms of deficit (a and c) and duration (b and d) colored according to drought type.

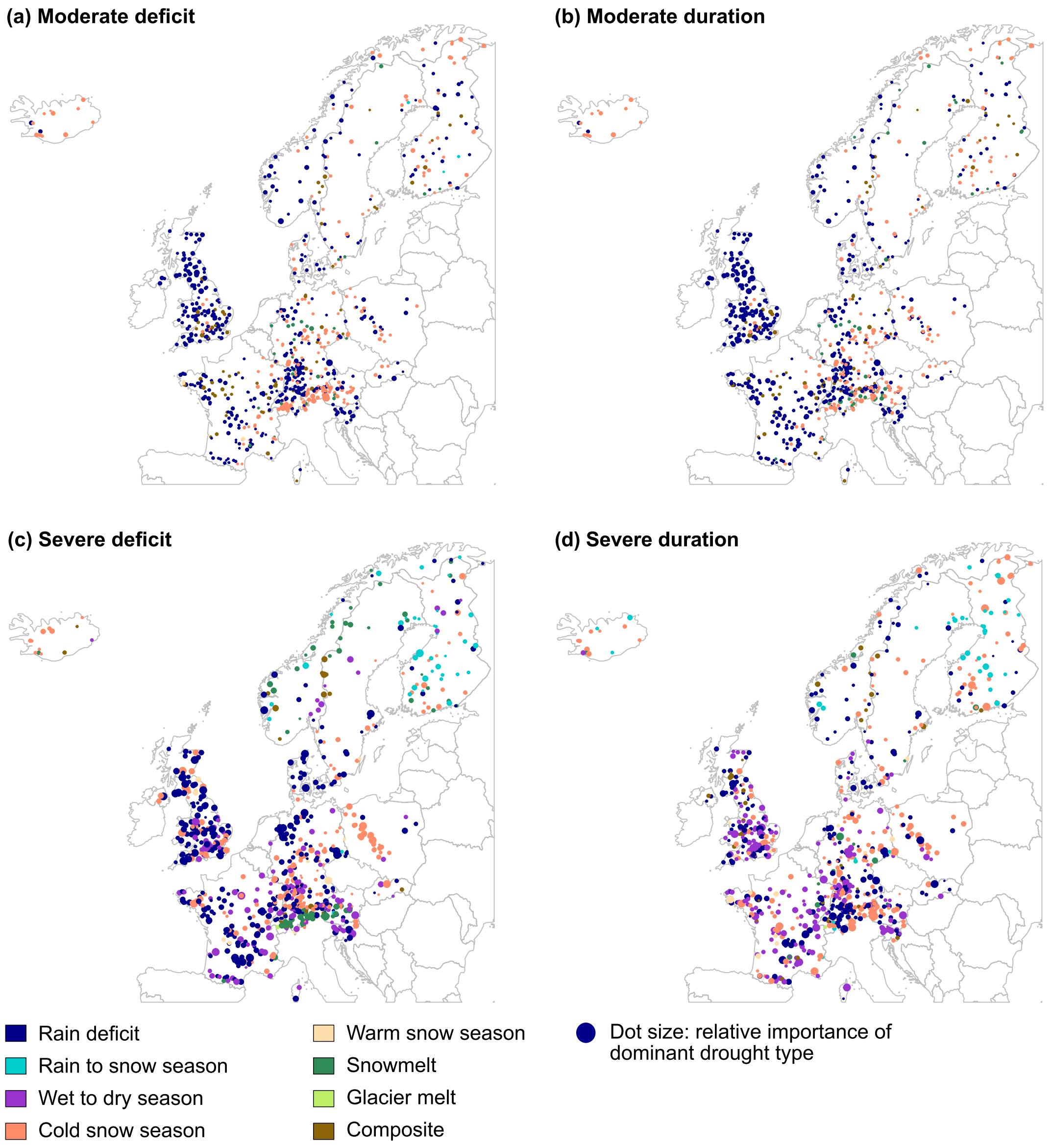

Figure 8. Map of dominant drought types related to (a) moderate events in terms of deficit (return periods < 10 years), (b) moderate events in terms of duration, (c) severe events in terms of deficit (return periods > 10 years), and (d) severe events in terms of duration. The size of the dot indicates the relative importance of the dominant drought type within a catchment (the larger the dot is, the larger is the share of the dominant drought type).

This impression that severe droughts might have different generating mechanisms than moderate droughts is confirmed when we look at the dominant type of moderate (i.e., those with return periods < 10 years) versus severe droughts (i.e., those with return periods > 10 years) (Figure 8). The dominant drought type of the most severe droughts in Western and Central Europe are rainfall deficit droughts and those in Northern Europe rain-to-snow season droughts independent of whether we are looking at severe events in terms of deficit or duration (Figures 8c and 8d). In the Alps, the severe deficit droughts are caused by a lack of snowmelt because the snowmelt period is the period of largest flows and even a small deviation will cause a large deficit. Compared to the moderate events (Figures 8a and 8b), snowmelt droughts are less important for severe droughts in catchments with warmer climates and more important in catchments with colder climates.

In low-elevation and -latitude catchments (i.e., those with warmer climates), the severe droughts in terms of deficit are mostly proximally rainfall driven, sometimes related to cold snow season droughts and hardly ever snowmelt driven (Figure 9). In contrast, in catchments in colder climates, severe droughts are often associated

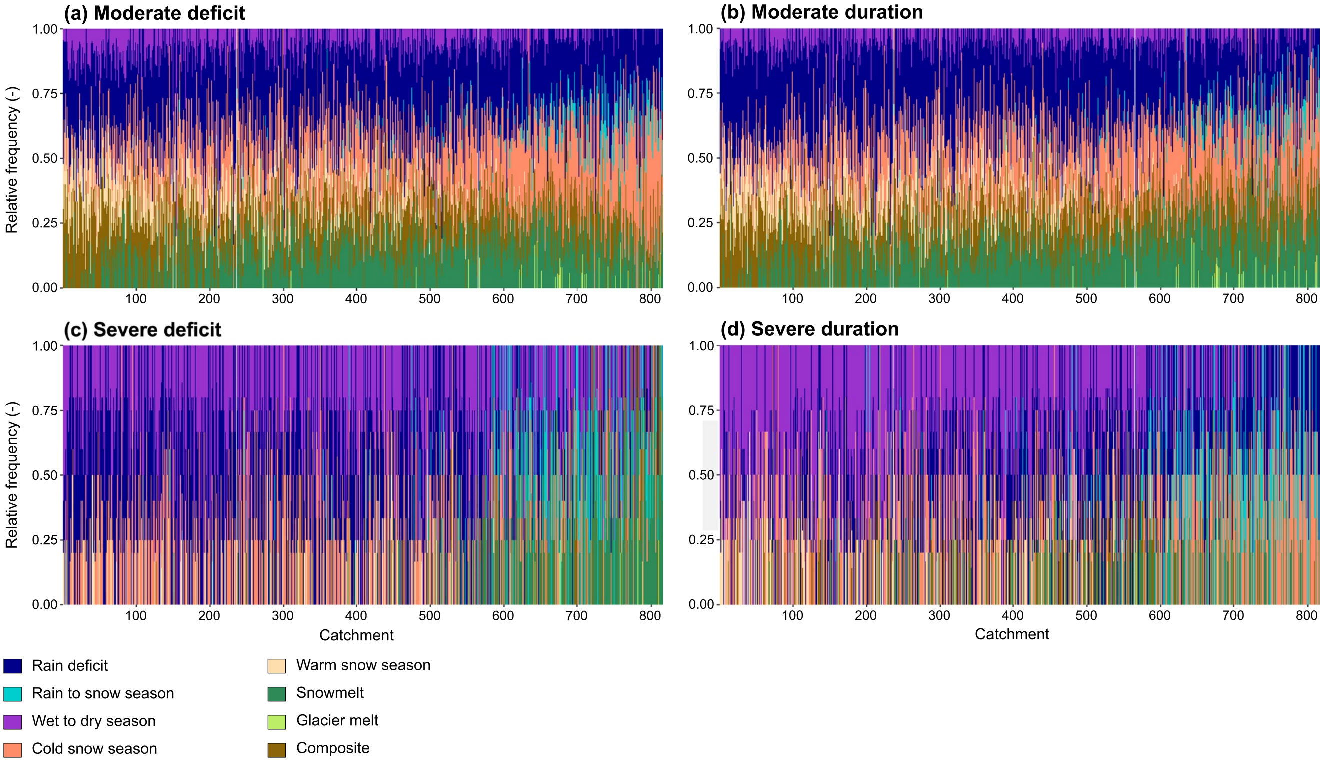

Figure 9. Drought type distribution over (a) moderate deficit droughts, (b) moderate duration droughts, (c) severe deficit droughts, and (d) severe duration droughts. Catchments in each panel are sorted from high (left) to low mean temperature (right).

with snowmelt droughts or rain-to-snow season droughts. The picture looks similar when we consider severe droughts in terms of duration, with the exception that snowmelt droughts are hardly ever associated with extreme durations even in cold catchments.

4. Discussion

Because Europe spans temperate and cold climate zones, the standardized classification scheme proposed here, distinguishes between proximally rainfall driven and snow-driven drought types. While such a subdivision is sensible in the European context, drought type analyses in other climate zones, for example, semi-arid or tropical regions, may require adaptations of the classification scheme. For example, an application in semi-arid regions, may require a focus on ET-rather than snow-driven drought types (Quesada-Montano et al., 2021). Our classification scheme considers droughts caused by precipitation deficits and potentially enhanced by ET anomalies during the dry season (i.e., wet-to-dry season droughts), however, it does not explicitly consider droughts solely caused by positive ET anomalies. While we are unaware of documented events caused by positive ET anomalies in the absence of low precipitation or snowmelt deficits, this phenomenon may potentially be observed in a warmer climate where actual ET further increases in regions where it is currently energy-limited (Condon et al., 2020; Konapala et al., 2020). Consequently, one may want to add a third additional branch to the classification tree defining an ET-driven drought type. Furthermore, future classification scheme development could consider changes in land use or vegetation cover as potential drought drivers (Tietjen et al., 2017; Zipper et al., 2019).

Our results show that the dominant drought type and drought type distributions in Europe vary both in space and time. Proximally rainfall-driven droughts, particularly rainfall deficit droughts, are frequent in the Atlantic region while snow-influenced drought types such as cold snow season droughts and snowmelt droughts become frequent as we move to more continental catchments at higher altitudes characterized by colder temperatures and also in summer compared to the other seasons. Snow-influenced drought types may also be observed in larger streams (which were not part of our sample) as we move away from the cold headwater catchments because large streams integrate upstream (snow-driven) and downstream (precipitation-driven) signals. The finding that rainfall deficit droughts dominate in a large part of the catchments corroborates findings by Van Loon and Van Lanen (2012) and Van Loon et al. (2015) who identified rainfall deficit droughts as the dominant drought type for five catchments in different parts of Europe and for 23 catchments in Austria and Norway, respectively. While rainfall deficit droughts are an important drought type over all seasons and events, our findings also show that rainfall deficit droughts are less dominant in summer than during the remaining seasons because snowmelt droughts become important in regions with snowmelt influences. Snowmelt is an important flow contributor in late spring and early summer in snow-influenced catchments and a lack thereof may lead to drought development. Rainfall deficit droughts are also less relevant for severe than moderate events. These severe events are rather dominated by wet-to-dry season droughts or rain-to-snow season droughts, that is, event types where rainfall deficits either persist into the dry summer season or the cold snow season which is consistent with findings by Van Loon and Van Lanen (2012). In addition to these proximally rainfall-driven event types, some snow-driven event types are related to severe droughts—cold snow season droughts in low-elevation and -latitude catchments and snowmelt droughts in high-elevation and -latitude catchments. That is, while a lack of rainfall is also an important driver of severe droughts in low-elevation catchments, snow-related factors become important drivers of severe droughts in high-elevation catchments.

The current drought type distribution for both moderate and severe droughts may be changing in a warming climate together with drought magnitudes (Stahl et al., 2018). Such changes might be particularly pronounced in high-elevation and -latitude catchments where events are snow influenced and therefore directly linked to temperature (Blahušiaková et al., 2020). They may furthermore be pronounced for wet-to-dry season droughts, which persist into the dry and substantially evapotranspiration influenced season, as an increase in evapotranspiration may lead to an extension of rainfall deficit droughts to wet-to-dry season droughts. The association of severe droughts with the wet-to-dry season drought type in low-elevation and -latitude catchments and the snowmelt drought type in high-elevation and -latitude catchments suggests a potential increase in the number of severe droughts caused by these types of events as a result of increasing temperatures. Such an increase of evapotranspiration-influenced drought events has already been demonstrated for different regions in Europe (Markonis et al., 2021). How exactly drought type distributions are going to change as a result of climate change needs to be evaluated in targeted simulation studies assessing the effect of both temperature and precipitation changes on drought types in different elevation zones.

The drought classification scheme proposed here requires certain methodological and threshold choices that to some degree influence the drought classes assigned. These include the choice of event definition, search windows, season definitions, or SWE thresholds. Our analysis used a variable threshold approach to identify drought events. Such a definition focuses on streamflow anomalies. That means that our event selection can include events with small deficits in the high flow season, which may be irrelevant from an operational perspective and when compared to actual water uses and needs. Our classification scheme may be applied to drought samples identified using alternative definitions, for example, a fixed drought threshold if one is interested in low flow events, or to water scarcity events identified by considering water demands in addition to water supply (Stahl et al., 2020). Our sensitivity analysis comparing search windows for precipitation deficits prior to streamflow drought occurrence of 15, 30, and 60 days shows that the dominant drought type distribution across all catchments does not substantially change when changing the length of the search window. Increasing the search window leads to an increase of catchments with rainfall deficit droughts as their dominant drought type at the cost of cold snow season and snowmelt droughts. Other threshold choices such as the temperature threshold distinguishing snow accumulation from non-snow accumulation conditions are physically based and changing them is not sensible. Adjustments of the season definitions become necessary if one desires to apply this classification scheme on the southern hemisphere or in different climate zones than the temperate to cold climate zone considered here. Evaluating or validating the classification scheme is challenging because drought types are not an observed quantity. Therefore, we based the classification scheme on drought type descriptions, which are based on hydrological processes, provided in existing studies (Quesada-Montano et al., 2021; Van Loon & Van Lanen, 2012; Van Loon et al., 2015). In addition, we checked the plausibility of assigned classes for the relatively well studied drought events 2003 and 2015. The classification scheme correctly recognizes that rainfall-driven events were important in both years and that snowmelt droughts were more important in 2015 than in 2003.

Here, we have solely focused on climate-induced drought types, neglecting the fact that droughts can also be human-induced or human-modified (AghaKouchak et al., 2021; Van Loon, Gleeson, et al., 2016; Van Loon, Stahl, et al., 2016), for example, that droughts can be either alleviated or aggravated by reservoir regulation

(Brunner, 2021; He et al., 2017; Wan et al., 2017), water consumption (Wada et al., 2013), or groundwater abstractions (Tijdeman et al., 2018). A natural extension of the climate-induced classification scheme presented here, is to include additional human-induced drought types and to separate solely climate-driven events from human-modified ones. However, such extension requires detailed data on human water regulation, use and abstraction, which is difficult to obtain, particularly at regional scales (Brunner, Slater, et al., 2021). Other potential extensions of the classification scheme include flexible season definitions independent of calendar months which would make the scheme applicable in a wide variety of geographical and climatic contexts. Such extension would be possible thanks to the use of globally available input data (i.e., GRDC streamflow, ERA5-Land climate time series, and RGI glacier outlines).

Potential applications of the classification scheme are not limited to studies focusing on process understanding and change assessments but extend to more practical applications such as frequency analysis. As extensively discussed in the flood literature, conducting frequency analysis on the whole event sample violates the homogeneity assumption (Brunner et al., 2017; Fischer, 2018; Klemes, 2000). To overcome this problem, frequency analysis approaches that perform frequency analysis on different event subsamples, for example, by season (Fischer, 2018) or event type (Brunner et al., 2017) have been proposed. Such approaches could also be applied in drought frequency analysis to derive event-type specific drought frequency and magnitude estimates or to construct event-type-specific severity-area-duration curves (Andreadis et al., 2005). Other potential applications include model evaluation studies trying to learn from varying model performance for different drought types or climate impact assessments quantifying differences in magnitude and frequency changes for different drought types.

5. Conclusions

We developed and applied a standardized classification scheme to a large sample of catchments in Europe to assess how drought generation processes vary in a given catchment and by event magnitude. Our analyses allowed us to quantify how both the dominant drought type and the drought type distribution vary by region, season, and event magnitude. Rainfall deficit droughts dominate in Western Europe from fall to spring, cold snow season droughts in Eastern and Northern Europe from fall to spring, and snowmelt droughts in summer in high-elevation and -latitude catchments. Both dominant drought type and distribution differ for moderate and severe events. Severe droughts are often wet-to-dry season droughts (i.e., events where evapotranspiration is a relevant drought driver) in the west, rain-to-snow season droughts in the north, and snowmelt droughts in the Alps. This high importance of snow-influenced and evapotranspiration-influenced droughts (i.e., wet-to-dry season droughts) for severe events suggests that these potentially high-impact events might undergo the strongest changes in a warming climate because of their close relationship to temperature.

Data Availability Statement

Streamflow observations can be downloaded from the GRDC: https://www.bafg.de/GRDC/EN/02_srvcs/21_tmsrs/riverdischarge_node.html, catchment characteristics from the GSIM: https://doi.pangaea.de/10.1594/PANGAEA.887470, and hydroclimatic time series (ERA5Land) from the Copernicus data store: https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-land?tab=overview. The extracted drought events and the extracted anomalies needed for drought classification are provided together with the R-implementation of the classification procedure through HydroShare: http://www.hydroshare.org/resource/77114d4dfdfd4dd39e0e1d99165f27b3.

Acknowledgments
The authors thank the German Research Foundation (2100371301 granted to Manuela Brunner) and the European Research Council (ERC-2020-StG 948601 granted to Anne Van Loon) for funding this project. Open Access funding enabled and organized by Projekt DEAL.

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