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Climate Driven Trends in Historical Extreme Low Streamflows on Four Continents

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Key Points:

- Temporal trends in occurrence rates of extreme low-flow events computed: analysis based on pooling stations by low-flow regimes
- For 1976–2015, low flow events become more frequent in some warm regimes (related to Pacific Decadal Oscillation), and less frequent in some cold regimes
- For 1946–2015, low flow events become less frequent across multiple warm and cold regimes

Supporting Information:

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

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Abstract Understanding temporal trends in low streamflows is important for water management and ecosystems. This work focuses on trends in the occurrence rate of extreme low-flow events (5- to 100-year return periods) for pooled groups of stations. We use data from 1,184 minimally altered catchments in Europe, North and South America, and Australia to discern historical climate-driven trends in extreme low flows (1976–2015 and 1946–2015). The understanding of low streamflows is complicated by different hydrological regimes in cold, transitional, and warm regions. We use a novel classification to define low-flow regimes using air temperature and monthly low-flow frequency. Trends in the annual occurrence rate of extreme low-flow events (proportion of pooled stations each year) were assessed for each regime. Most regimes on multiple continents did not have significant ($p < 0.05$) trends in the occurrence rate of extreme low streamflows from 1976 to 2015; however, occurrence rates for the cold-season low-flow regime in North America were found to be significantly decreasing for low return-period events. In contrast, there were statistically significant increases for this period in warm regions of NA which were associated with the variation in the Pacific Decadal Oscillation. Significant decreases in extreme low-flow occurrence rates were dominant from 1946 to 2015 in Europe and NA for both cold- and warm-season low-flow regimes; there were also some non-significant trends. The difference in the results between the shorter (40-year) and longer (70-year) records and between low-flow regimes highlights the complexities of low-flow response to changing climatic conditions.

1. Introduction

Low streamflows affect water supply, water quality, and aquatic habitats, particularly during extreme low-flow events (Detenbeck, 2018; Hisdal et al., 2001). Low-flow seasonality and climatic drivers differ among streamflow regimes and it is important to consider them separately (Section 1.1). It is also important to separate the effects of climate from human-caused catchment alterations (Burn et al., 2012; Whitfield et al., 2012). This can be done using reference hydrometric networks (RHNs) that contain long high-quality streamflow records from catchments minimally affected by reservoir regulation and land-use change (Section 1.2). Understanding historical changes in climate-driven seasonal low flows will help better anticipate future changes. Much research has documented changes in typical annual low flows (Section 1.3) but little work has focused on the most extreme low flows. The combined consideration of all these aspects and our multi-continental study area makes our article unique, as further explained in Section 1.4.

1.1. Low-Flow Regimes and Processes

Periods with low streamflow can be caused by different processes, including (a) a deficit in precipitation, possibly combined with increased evapotranspiration, and (b) prolonged periods with temperature below the freezing point. As such, low-flow seasonality differs among streamflow regimes and with aridity (Burn et al., 2008; Fleig

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et al., 2006; Floriancic et al., 2021; Laaha & Blöschl, 2007; McMahon & Finlayson, 2003; Pournasiri Poshtiri et al., 2019). Different regimes are characterized by precipitation being dominated by either rainfall, snowfall, or a mix (Wade et al., 2001). In arid and semi-arid areas, the amount and timing of precipitation in a region can determine the seasonality or lack of seasonality of low flows.

While both pluvial and nival regimes typically have only one low-flow season, mixed regimes may have two, one in the warm season and one in the cold season (Fiala et al., 2010; Hisdal et al., 2001; Kohn et al., 2019; Stahl et al., 2010; Vlach et al., 2020; Wade et al., 2001). Arctic and subarctic areas regularly have their lowest flows of the year in the cold season (Burn et al., 2008). Tropical, subtropical, and many temperate areas typically have their lowest flows in the warm season. Tropical basins often have two warm low flow seasons as the sun crosses back and forth over the equator. Mountainous and high-latitude temperate areas can have their lowest flows in the cold season or have a mix of warm- and cold-season low flows.

Warm- and cold-season low flows are affected by different processes (Birsan et al., 2005; Burn et al., 2008; Dierauer et al., 2018; Fleig et al., 2006; Floriancic et al., 2021; Kohn et al., 2019; Pournasiri Poshtiri et al., 2019; Smakhtin, 2001; Whitfield et al., 2003). The variability of warm-season low flows can be related to precipitation in the winter and spring prior to the warm season (Burn et al., 2008; Cooper et al., 2018; Dierauer et al., 2018) or to warm-season precipitation (Hodgkins et al., 2005; Kormos et al., 2016; Kumar et al., 2009; Laaha & Blöschl, 2006b). Warm-season low flows can be affected by evapotranspiration; these processes are influenced by air temperatures (Floriancic et al., 2021; Laaha & Blöschl, 2006b; Waylen & Woo, 1987) and can be influenced by wind speed and humidity (Granata, 2019; Tabari & Talaee, 2014). Cold-season low flows result from long periods of below-freezing temperatures and storage of water in snowpack and ice (Laaha & Blöschl, 2006b; Waylen & Woo, 1987) and/or low precipitation in the cold season. For mixed regimes, warm-season and cold-season droughts should be analyzed separately because of the important hydrologic-process differences (Fleig et al., 2006; Laaha & Blöschl, 2006b).

In some cold areas, low flows can be more sensitive to temperature than to precipitation with warm winters resulting in higher winter low flows, reduced snowpack storage, and lower summer low flows (Cooper et al., 2018; Dierauer et al., 2018). Conversely, warm-season low flows can continue into the cold season (Fleig et al., 2006; Van Loon et al., 2015). Degraded accuracy of estimates of winter flows under ice can make changes in cold-season low flows difficult to resolve (Whitfield & Hendrata, 2006).

A further complication in low-flow characterization is the fact that many rivers globally are temporary or intermittent. Streamflow permanence can range from continuous flow in perennial streams to long periods of zero flow in ephemeral streams. Intermittent streams usually have zero flow during the dry season. However, periods of zero flow result from a variety of processes (Buttle et al., 2012; Costigan et al., 2017) and streams in arid regions can have zero or low flows occurring in different seasons from year to year or spanning multiple seasons (McMahon & Finlayson, 2003).

1.2. Importance of Reference Hydrometric Networks

Given the challenges of low streamflows to society and the environment, and concerns about how climate change will modify streamflow regimes, there has been a large effort to detect and attribute changes over time in low flows. However, land use and water management changes in catchments can cause streamflow trends that obscure climate-related trends or lead to streamflow trends being falsely attributed to climatic changes (Ledford et al., 2020; McGee et al., 2012). Regulation of flows by reservoirs and urbanization can dramatically affect the magnitude of streamflows and affect flow seasonality (Dudley et al., 2020; Hodgkins et al., 2019). Reservoirs have modified streamflow regimes globally (Cooley et al., 2021). River regulation impacts are much more rapid and dramatic than those that might occur from climate change (McMahon & Finlayson, 2003). Other major water management interventions have been shown to particularly modify low streamflows. Examples include abstractions for public water supply, irrigation, or industry (e.g., Tijdeman et al., 2018) and return flows from sewage treatment works and irrigation which can make up a large proportion of summer low flows (e.g., Rameshwaran et al., 2022). Changes in forest management and agricultural land use and practices can also impact low flows (Dudley et al., 2020; Guzha et al., 2018; Moore et al., 2020; Pike & Scherer, 2003).

Hydrometric networks are designed for a wide variety of environmental and water resources issues (Mishra & Coulibaly, 2009). To avoid confounding influences for studies that analyze streamflows related to climatic variables, there has been an increasing call for reference hydrometric networks (RHNs) that contain long high-quality streamflow records from catchments minimally affected by reservoir regulation and land-use change (see Whitfield et al., 2012 for the principles behind RHNs and their global status, and Burn et al., 2012, for examples of studies analyzing RHNs). Such RHNs are of fundamental importance in the study of historical streamflow trends and their potential attribution to climate change (Burn et al., 2012; Harrigan et al., 2018; Leopold, 1962; Murphy et al., 2013; Whitfield et al., 2012; Yeste et al., 2018; Zhang et al., 2014).

While most RHNs have been established at the national scale, there have been several efforts to bring RHNs together in international trend assessments, to provide consistent analysis of trends in hydrological extremes at continental (e.g., Stahl et al., 2010, who collated RHN and RHN-like networks across Europe) and intercontinental scales (Hodgkins et al., 2017, who brought North American and European scale networks together). Recently, there has been a growing effort to develop an initiative to support the establishment of RHNs on a global scale via the ROBIN network (https://www.ceh.ac.uk/our-science/projects/robin). It is important to draw a distinction, however, between RHNs and a more generalized initiative toward international data sharing of "large sample hydrology" data sets, such as the CAMELS (Catchment Attributes and Meteorology for Large-sample Studies) data sets that have recently been integrated via the CARAVAN Initiative (Kratzert et al., 2023). Large-sample data sets like these are useful for a very wide range of hydrological applications, but typically include catchments with high degrees of anthropogenic disturbance. RHNs, on the other hand, aim specifically to support the identification of climate-driven variability by focusing on near-natural catchments.

1.3. Historical Low-Flow Trends

Decreasing low flows that may accompany climate warming can have negative consequences for aquatic biota (Arismendi et al., 2013). In arid areas, however, decreasing low flows may benefit native species if non-native species are not well adapted to intermittent streams (Leprieur et al., 2006). Understanding low-flow changes is particularly important where water use and demand are increasing (Assefa & Moges, 2018). Because of the importance of low flows, many studies have analyzed historical trends. Trends over time in low flows for minimally altered basins typically use measures of annual low-flow magnitude averaged over multiple days (7, 10, or 30 days).

Differences in low-flow regimes can complicate how low flows evolve through time in response to climatic trends. In regions with warm-season low flows, historical low-flow trends depend on region. Precipitation is a dominant driver of streamflow worldwide while temperature-related evapotranspiration can be a secondary driver (Vicente-Serrano et al., 2022). Regional precipitation trends thus influence differences in regional low-flow trends.

In Europe, trends have been mixed at continental and national scales. Stahl et al. (2010) found that low-flow magnitudes generally decreased in Europe for catchments that typically have warm-season minimum flows. Hannaford and Marsh (2006) and Harrigan et al. (2018) demonstrated a general lack of change in low flows in the United Kingdom while increasing low-flow magnitudes were found in the west of Ireland (Nasr & Bruen, 2017). A consistent decrease in low flows was found in southern France (Giuntoli et al., 2013), the Czech Republic (Fiala et al., 2010), Spain (Coch & Mediero, 2016) and Turkey (Cigizoglu et al., 2005).

In Australia, Zhang et al. (2016) showed that significant trends in low-flow magnitudes in any direction were infrequent for reference basins. Sauquet et al. (2021) found that the frequency of no-flow days increased in several but not all regions of the United States and Australia, while no trend was found in Europe.

In NA, warm-season low-flow trends have been mixed for minimally altered basins, with both increases and decreases in low-flow magnitude. Ehsanzadeh and Adamowski (2007) detected decreasing trends in the Atlantic provinces of Canada and in southern British Columbia, but no trends in the Prairies or eastern Ontario. In the US, trends in annual low-flow magnitudes have shown both increases and decreases, depending on region and period analyzed (Dudley et al., 2020). In the Pacific Northwest, low flow magnitudes have decreased (Kormos et al., 2016; Sawaske & Freyberg, 2014) while increased low flows have been found in parts of the northeastern (Hodgkins et al., 2005) and northcentral United States (Kibria et al., 2016; Kumar et al., 2009).

Cold-season low-flow magnitudes for minimally altered catchments have generally increased or have shown a mix of trends, based on the limited number of studies. Stahl et al. (2010) found that trends were mixed in regions of Europe where low flows occur in winter. Significant increasing trends were found in the European Alpine region (Bard et al., 2015; Laaha et al., 2016) and the Czech Republic (Fiala et al., 2010). In Canada, Ehsanzadeh and Adamowski (2007) detected increased low flows north of 60°N.

Previous work has demonstrated that hydrological change is associated with quasi-periodic oscillations in the climate system (e.g., Hodgkins et al., 2017; Mantua et al., 1997; Maurer et al., 2004; McKerchar & Henderson, 2003; Whitfield et al., 2010). Quasi-periodic oscillations can be observed over decadal time scales (Hannaford et al., 2013; McMahon & Finlayson, 2003; Nalley et al., 2019) and these oscillations have potential for causing apparent long-term trends at the multi-decadal scale. We are therefore interested in relations between extreme low flows and decadal climate patterns relevant to our study areas such as the Pacific Decadal Oscillation (PDO) and the Atlantic Multidecadal Oscillation (AMO). We do not focus on climate patterns that can be important to low flows but have shorter quasi-periodic oscillations, such as the El Niño-Southern Oscillation and the North Atlantic Oscillation.

The PDO affects streamflows in some regions in NA (Hodgkins, 2009; Mantua et al., 1997; Tamaddun et al., 2017). The cool phase of the PDO is associated with higher low flows in the Columbia River catchment in the western United States and Canada (Hamlet & Lettenmaier, 1999) and in southern and interior British Columbia (Wang et al., 2006; Whitfield et al., 2010). On the north coast of British Columbia, however, lower low-flow magnitudes were found during cool PDO phases. Low flows in rivers in Texas (southern United States) are associated with low-precipitation weather patterns that are associated with both PDO and Southern Oscillation Index (Konapala et al., 2018). The PDO represents the effects of a combination of various processes operating at various time scales and only partially represents atmospheric forcing by the North Pacific Ocean (Newman et al., 2016). Few studies focus specifically on relations between annual low streamflows and the AMO. The magnitude of low flows in France had a non-significant relation with the AMO for most catchments (Giuntoli et al., 2013).

1.4. Research Gaps and Scope of Study

Many studies have analyzed trends in annual low-flow metrics. Few studies, however, have focused on trends in low streamflows that have higher return periods than the typical annual low flow. Dethier et al. (2020) analyzed trends from 1950 to 2016 in 2- to 25-year low flows for 541 stations in 15 regions in the United States and Canada, for annual and seasonal low flows based on calendar dates (set 3-month periods). June, July, and August low-flow events (>5-year return period) that coincide with dominant low-flow seasons have increased in frequency in the Pacific Northwest United States and adjoining areas in Canada, the Pacific coast of the United States, and parts of the Rocky Mountains in the western United States. The frequency of low-flow events has decreased in a large part of the eastern United States (parts of the Southeast, Midwest, and Northeast). The present study uses a process-based analysis to identify warm and cold seasons and analyze them separately.

Most studies of low-flow change related to climate variability and change are at the regional or national scale and not at continental or global scales. Many studies report trends in low flows in rivers in which climate is not the only driver; in these studies, low-flow trends can be affected by reservoir storage regulation and water use for urban and agricultural uses. In addition, the diversity of methods and approaches that have been used to compute trends makes comparing results between studies challenging.

This work uses streamflow data from over a thousand stations spanning four continents, and a common methodology, to better understand climate driven historical trends in extreme low streamflow events (5- to 100-year return periods) from different flow regimes. The focus on climate driven streamflow changes is ensured by using streamflow data only from minimally altered catchments. Because extreme low flows occur infrequently at any one station, data are pooled by low-flow regime. Because different processes can affect warm- and cold-season low flows, a novel method is used to analyze low flows separately for different warm- and cold-season regimes. This results in a single time series of extreme low-flow occurrences for each pooled group of stations. We then look for trends over 40- and 70-year periods for each group. We also analyze whether trends can be explained by climate indices that have decadal persistence.

2. Data

2.1. Streamflow Data

Daily streamflow data were gathered from countries in Europe, NA, South America, and Australia. To isolate climatic impacts on streamflow, the study catchments were limited to those with only minor anthropogenic effects on low flows. To this end, following the arguments made in Section 1.2, the analysis was conducted on existing Reference Hydrometric Networks (RHN) in 11 countries where such networks exist. These were supplemented

Table 1
Number of Stations by Continent and Country

Continent/Country		Original	40 years	70 years
Australia	RHN	196	108	0
South America				
Brazil	RHN	24	16	3
Europe				
Austria		45	32	0
Czechia	RHN	18	10	8
Finland		36	25	9
France	RHN	207	158	14
Germany		338	181	50
Ireland	RHN	23	12	0
Norway	RHN	97	65	25
Spain		16	10	7
Sweden	RHN	9	9	7
Switzerland	RHN	31	15	6
United Kingdom	RHN	86	61	4
Subtotal		*906*	*578*	*130*
North America				
Canada	RHN	163	139	29
United States	RHN	462	343	164
Subtotal		*625*	*482*	*193*
Total		1,751	1,184	326

Note. RHN indicates that the country has a formal reference hydrologic network, otherwise the stations used are RHN-like. Original stations are stations that passed initial quality assurance while 40-year (1976–2015) and 70-year (1946–2015) stations passed all study criteria and quality assurance for the respective periods.

by "RHN like" stations that meet RHN criteria (listed e.g. in Whitfield et al., 2012), as defined by local experts, from four additional countries (Table 1). In total, daily streamflow records were obtained from 1,751 stations alongside accompanying metadata.

This study considers records with 40- and 70-year periods (1976–2015 and 1946–2015). The shorter period was chosen as a balance between record length and geographic coverage. Stations were required to have at least 40 years of mostly complete data through 2015; a year was considered mostly complete if it was missing no more than 2% of daily flows (7 days). To be retained for either of these periods, there needed to be at least 6 years of data in each decade so that there would not be a large amount of missing data at any point in the study periods. Catchments were required to have a minimum area of 50 km^2 to avoid issues with small streams, such as some of them being springs that are measured.

Minimally altered status was confirmed for all catchments by members of the research team from each country—catchments with known current or historical disturbance that may affect extreme low-flow trends were not used. This included catchments with more than 10% current urban land (a qualitative judgment in some countries with RHN-like data) and catchments with known substantial land use/land cover change during the periods of record for the study that could substantially affect extreme low-flow trends. Catchments also were removed if they had known current or historical water management that could impact extreme low-flow trends, such as reservoirs/dams, flow diversions (adding or subtracting water), groundwater or surface water abstractions, sewage discharge, return flows, water leakage from water supply pipes, or agricultural activities (such as irrigation, tile drainage additions or changes in the number of farm dams).

The quality of low-flow data was required to be good or fair for low-flow stage and flow measurements for warm-season low flows. Cold-season low-flow data are likely to be low quality where ice is regularly present for extended periods, but it is the best available data. Catchments were removed if streamflow stations had rating curves where quality has changed over time, where the sensitivity of low flows has been impacted by control changes (e.g., with the construction or de-construction of measurement weirs).

Strongly intermittent catchments (36 stations) were removed from the current study, as strongly intermittent catchments could include both seasonal and aseasonal flows (long periods of zero flow punctuated by brief aseasonal precipitation and flows). The strongly intermittent stations were defined as stations with an average of 90 days per year or more with zero-flow.

Other steps helped ensure the minimally altered status of catchments in this study. In addition to the quality control already carried out "at source" by the streamflow data providers, a second tier of screening was applied centrally by the author team. Daily streamflow records were screened for change points and visually anomalous conditions indicating methodology changes or infilled data gaps. These included an initial screening for change points in low-flow attributes and missing data using the R package *FlowScreen* (Dierauer et al., 2017). We didn't find systematic change points that could be indicative of human basin alterations. Additional screening included a visual inspection of daily flow hydrographs for early, middle, and late periods for every potential study catchment. Stations were removed from the study if they showed evidence of streamflow regulation (non-natural hydrographs) or had periods of sustained constant flow that were not associated with natural variability.

After screening, the final data set contained 1,184 and 326 stations for the 1976–2015 and 1946–2015 periods, respectively. The stations are in 15 countries on 4 continents: Australia, SA, Europe, and NA; Europe and NA have the largest number of stations (Table 1). Data are available in Hodgkins et al. (2024).

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2.2. Climate Indices

Two climate indices were used to help differentiate long-term low-flow trends from decadal oscillations: the PDO and the AMO. Monthly PDO and AMO values were downloaded from the National Oceanic and Atmospheric Administration (NOAA) National Centers for Environmental Information (NCEI) (NOAA, 2022a, 2022b). The NCEI PDO index is based on NOAA's extended reconstruction of sea surface temperatures (ERSST Version 5) and is constructed by regressing the extended reconstruction anomalies against the Mantua PDO index (Mantua et al., 1997) for their overlapping period. Monthly AMO values also were unsmoothed values detrended from the Kaplan SST (Kaplan et al., 1998). Values of these indices were averaged for 12 months prior to (and including) the months with highest frequency of annual low flows, for each low-flow regime, with minor changes for consistency between regimes. The months averaged were different for low-flow regimes (Section 3.3) and for continents in the Northern and Southern Hemispheres. For cold Northern Hemisphere Regimes 1C and 2C, and for warm Southern Hemisphere Regimes 3W and 4W, April through March was used. For warm Northern Hemisphere Regimes 2W, 3W, and 4W, October through September was used. While other indices such as El Niño-Southern Oscillation or North Atlantic Oscillation can explain a portion of low-flow interannual variability in some regions (e.g., Bonsal & Shabbar, 2008; Ryu et al., 2010; Steirou et al., 2017), they were not studied in this paper because we wished to focus on decadal oscillations and their potential confounding impact on long-term trend detection.

3. Methods

This section describes our methods for defining: low-flow regimes and seasonal analyses, low-flow variables, low-flow occurrences (for both magnitude and duration) below selected thresholds at each station, grouping of stations, and group tests for trends and variability of low-flow occurrences.

3.1. Defining Low-Flow Regimes and Seasonal Analyses

Each station was assigned to a low-flow regime according to the temporal characteristics of low flows. The regime definition was based on two indices: a bimodality index, quantifying the evidence for two distinct low-flow seasons, and a temperature index, evaluating whether low flows occur during a warm or a cold season. Both the bimodality and the temperature indices used the drought seasonality index proposed by Laaha and Blöschl (2006a). For each calendar month, the total number of days spent below (or equal to) the Q95 threshold was computed $((w_i)_{i=1,\ldots,12})$; Q95 is the flow magnitude which is exceeded by 95% of daily mean flows. The 12 monthly values were standardized by dividing by their sum, so that the standardized values sum to one (Figure 1a, top row).

The bimodality index relies on the following idea: if two distinct low-flow seasons exist, then $(w_i)_{i=1,\ldots,12}$ should have two clear, well-separated peaks. This can be quantified by means of a bimodality index β computed as follows:

$$\beta = \left(\|\mu_2 - \mu_1\| - 1\right) \times \frac{\sigma^2_{total}}{(\sigma_1^2 + \sigma_2^2)} \times (\upsilon_1 \upsilon_2) \tag{1}$$

Where:

- $\|\mu_2 - \mu_1\|$ is the circular distance between the months of the peaks of each season. For instance, if $\mu_2 = 12$ (December) and $\mu_1 = 2$ (February), $\|\mu_2 - \mu_1\|$ is equal to 2 rather than 10. The first term of the product is then equal to 1 and can be interpreted as the number of months separating the peaks. This first term is hence high when the two peaks are far away from each other considering the circular assumption.
- σ^2_{total} is the total (circular) variance of $(w_i)_{i=1,\ldots,12}$, σ_1^2 (respectively, σ_2^2) is the variance computed on months belonging to the first (respectively, second) season only. The circular variance is computed as shown in Equation 2 (adapted from Fisher, 1993). This second term is high when the within-season variances are small in comparison with the total variance.
- υ_1 is the frequency of below-threshold days falling in the first season (i.e., $\upsilon_1 = \sum_{i \text{ in } S1} w_i$) and υ_2 is the frequency falling in the second season. Since $\upsilon_2 = 1 - \upsilon_1$, this third term is maximum when $\upsilon_1 = \upsilon_2 = 0.5$, that is, when both seasons represent a similar fraction of low-flow days.

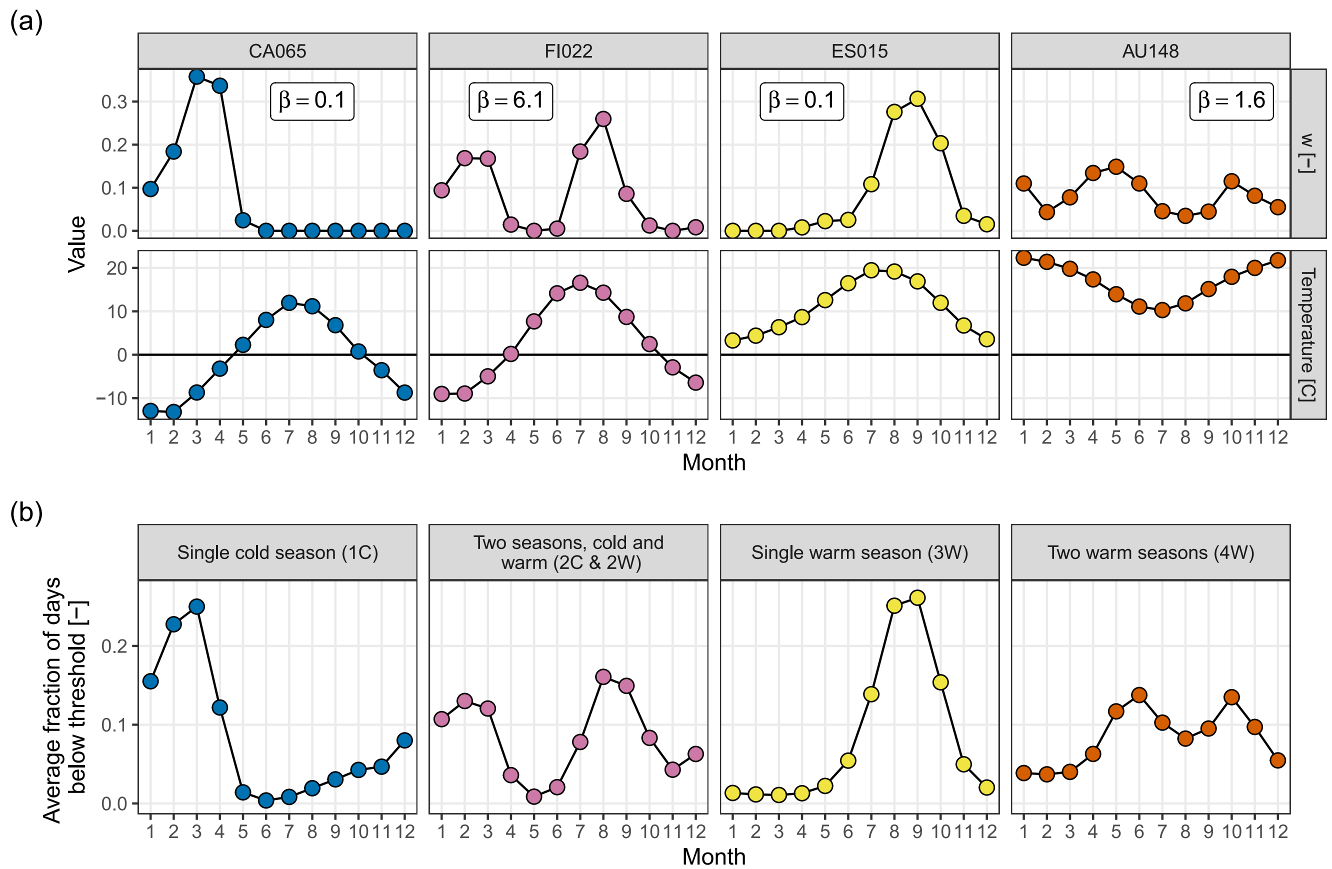

Figure 1. (a) Values of the drought seasonality index $(w_i)_{i=1,\ldots,12}$ and temperatures for four stations characteristic of the different study low-flow regimes (in Canada, Finland, Spain, and Australia, respectively), and (b) drought seasonality index averaged across the stations of each of the four low-flow regimes. Note that stations from the Southern Hemisphere in panel (b) have been shifted by 6 months prior to computing monthly averages.

$$\sigma^2 = 1 - \sqrt{\left(\sum_{i \text{ in season}} w_i \cos\left(\frac{\pi}{12} + i\frac{\pi}{6}\right)\right)^2 + \left(\sum_{i \text{ in season}} w_i \sin\left(\frac{\pi}{12} + i\frac{\pi}{6}\right)\right)^2} \tag{2}$$

In practice, the bimodality index was computed for all possible combinations of two seasons, imposing a criterion that the shortest of the two seasons lasts for at least 2 months. The combination maximizing bimodality was retained as the clearest two-season split.

The temperature index aims at quantifying the temperature of the low-flow season. For a given station and season, this can be computed as the following weighted average:

$$\tilde{t}_S = \sum_{i \text{ in } S} w_i t_i \tag{3}$$

where t_i is the interannual temperature of month in season S. Ideally catchment temperatures should be used, but since this information is not available at all stations, it is replaced with interannual (1960–1990) monthly temperatures computed at the nearest gridpoint of the National Centers for Environmental Prediction-National Center for Atmospheric Research (NCEP-NCAR) reanalysis (Kalnay et al., 1996). The reanalysis produced a global gridded data set that represents the state of the Earth's atmosphere, including air temperature, over multiple decades by use of a numerical weather model and multiple types of atmospheric observations.

Bimodality and temperature indices were finally combined as follows to define four low-flow regimes:

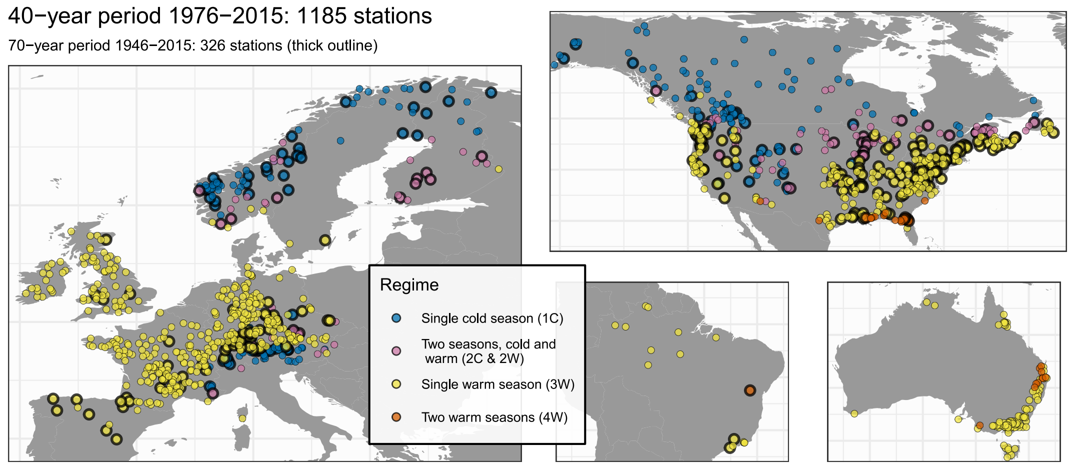

Figure 2. Distribution of the 40-year and 70-year study sites and their low-flow regime across four continents. The background grid has a spacing of 5° latitude and longitude. Thin outlines on the symbols indicate sites with record from 1976 to 2015 while thick outlines indicate ones with record from 1946 to 2015.

A. Single-season regimes for stations where $\beta \le 1$, further decomposed into:
   1. Cold regime for stations where $\tilde{t}_S \le 0$ or ($\tilde{t}_S \le 10$ and $\tilde{t}_S \le median(t_i)$). For a typical example, see station CA065 in Figure 1a;
   2. Warm regime elsewhere (e.g., station ES015 in Figure 1a).

B. Two-season regimes for stations where $\beta > 1$, further decomposed into:
   1. Mixed regime with both cold and warm low flows where $\tilde{t}_{S1} \le 10$ or $\tilde{t}_{S2} \le 10$ (e.g., station FI022 in Figure 1a);
   2. Two warm seasons regime elsewhere (e.g., station AU148 in Figure 1a).

The bimodality and temperature thresholds used in the regime definition were adjusted through a trial-and-error process in order to yield spatial patterns consistent with our empirical hydrologic knowledge. In particular, some stations in high-latitude or mountainous areas (e.g., Alaska, Norway, Alps) tended to be incorrectly classified as "warm" based on the sole use of a 0°C threshold. Correcting this required identifying stations for which low flows occur during a relatively cold period of the year, but not cold enough for the temperature at the nearest NCEP-NCAR gridpoint to drop below zero. This led to the introduction of a 10°C threshold coupled with a comparison with the median temperature.

The four regimes are outlined in Figure 1b (using the monthly proportion of days below Q95) and mapped in Figure 2. For convenience, they were reordered from cold to warm and renamed as follows:

- Regime 1C: a single cold low-flow season (corresponding to case A.1. above);
- Regime 2M: mixed regime with one cold low-flow season and one warm low-flow season (case B.1). As the hydrological processes differ considerably between warm- and cold-season low flows, all analyses were performed on a seasonal basis for stations in this regime. The notation 2C is used to denote the analysis restricted to the cold season, and similarly 2W is used for the analysis restricted to the warm season;
- Regime 3W: a single warm low-flow season (case A.2);
- Regime 4W: two warm seasons (corresponding to case B.2). We did not perform a separate analysis for each season, because the weak seasonality of this regime (see Figure 1b) did not allow a meaningful split into two warm seasons governed by distinct hydrologic processes.

3.2. Low-Flow Variables and Definition of Occurrences at Each Station

Low-flow magnitude and duration variables were computed at each station using the time series of daily discharge. The magnitude is defined as the lowest 7-day discharge for each low-flow year. While this variable is widely used for low-flow analysis, it is not well adapted to intermittent rivers since it might be zero for many years and it was not used for non-perennial catchments. Consequently, low-flow duration was also used (for perennial and non-perennial catchments), defined as the yearly fraction of daily flows below or equal to the period-of-record

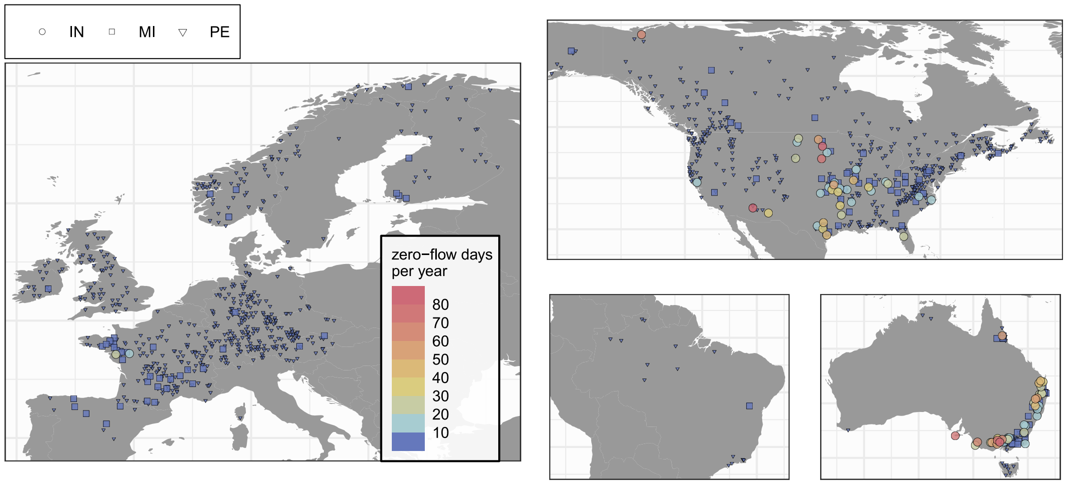

Figure 3. Streamflow intermittence level for study sites. The background grid has a spacing of 5° latitude and longitude. IN, intermittent; MI, mildly intermittent; PE, perennial. Small symbols indicate stations with 0 days with zero flow; the color of larger symbols indicates the frequency of zero flows at that site.

low-flow threshold Q95 (possibly equal to zero for non-perennial rivers). Following Figures 1a and 1b unique low-flow year ranging from May 1st to April 30th was considered a reasonable choice for all stations in regimes 1C, 3W and 4W (November 1st to October 31st for Southern Hemisphere stations). For stations in regimes 2C and 2W, the warm low-flow season was set to the period from May 1st to October 31st (2W), the cold low-flow season from November 1st to April 30th (2C).

These annual series were used to estimate the T-year ($T = 5$, 10, 20, 50, and 100) magnitude q_T and duration d_T at each station (and for each season for stations in regimes 2C and 2W). A specific frequency analysis method was developed to account for the fact that magnitude and duration variables have reachable bounds: magnitudes reach 0 in non-perennial catchments; durations can reach both values 0 and 1 (years with daily flow never/always exceeding the low-flow threshold, respectively). While the treatment of zeros for non-perennial rivers has been studied in the literature (Gustard & Demuth, 2008; Koffler et al., 2016), no standard approach has been recommended to handle the higher bound equal to one for the duration variable. Therefore, a flexible approach based on rectified distributions (Palmer et al., 2017) was developed to treat all magnitude and duration series in the same way.

The concept of rectified distributions is illustrated in Figure 4. In intuitive terms, rectifying a distribution between a and b means resetting all values smaller than a to a and all values larger than b to b. The probabilities of reaching the bounds is then computed from the cumulative distribution function (cdf) of the parent distribution. More formally, let X denote the random variable of interest (magnitude or duration), and let Y denote a continuous random variable, with probability density function (pdf): $f_Y(y)$ and cdf: $F_Y(y)$. X follows the distribution of Y rectified between a and b if:

$$\begin{cases} \Pr(X = a) = F_Y(a) & \text{(prob. of reaching the lower bound)} \\ \Pr(X = b) = 1 - F_Y(b) & \text{(prob. of reaching the upper bound)} \\ \quad \text{for any } a < x < b,\ X \text{ has density } f_Y(x) & \end{cases} \tag{4}$$

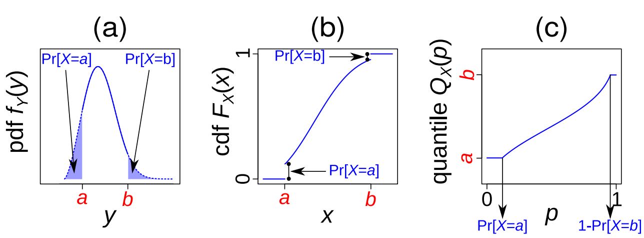

Figure 4. Principle of a rectified distribution between a and b (for magnitude: $\boldsymbol{a} = 0$ and $\boldsymbol{b} = +\infty$, for duration: $\boldsymbol{a} = 0$ and $\boldsymbol{b} = 1$); (a) the continuous probability density function is used between the bounds, while the left and right shaded areas give the probabilities of being equal to the bounds. The rectified distribution has (b) a resulting cumulative distribution function and (c) a quantile function.

Note that a *rectified* distribution should not be confused with a *truncated* distribution. Indeed, the latter only removes the tails of the pdf $f_Y(y)$ (and rescales it to ensure it integrates to unity), but it does not assign a discrete probability mass to the bounds a and b, as the former does. In short, rectified distributions are adapted to random variables having *reachable* bounds, while truncated distributions are for variables with *unreachable* bounds.

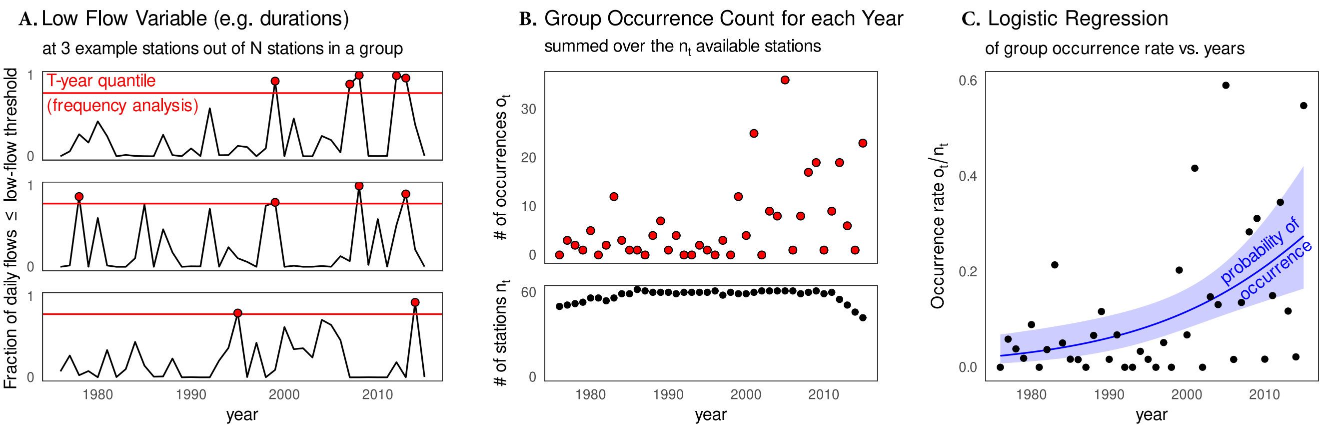

Figure 5. Conceptual methods plots for (a) Occurrence of annual low-flow events that exceed T-year quantiles at example stations (red circles represent an annual exceedance at one station), (b) Annual group occurrence counts for an example group and corresponding total number of stations in that group for each year (red circles represent the number of stations in a group with annual exceedances), and (c) Logistic regression of occurrence rate versus years for an example group. The shaded area in panel C represents confidence intervals around the logistic regression line.

Parameters can be estimated with the maximum likelihood approach. Let $(x_1,\ldots,x_n)$ denote all data, $(z_1,\ldots,z_m)$ the subset of values in the interval $(a;b)$ (i.e., non-a and non-b values), n_a and n_b the number of values equal to a and b. Assuming independence, the likelihood function associated with the *whole* sample $(x_1,\ldots,x_n)$ is the following:

$$L(\boldsymbol{\theta}; x_1,\ldots,x_n) = \left(\prod_{i=1}^{m} f_Y(z_i;\boldsymbol{\theta})\right)(F_Y(a;\boldsymbol{\theta}))^{n_a}(1 - F_Y(b;\boldsymbol{\theta}))^{n_b} \tag{5}$$

Parameter $\boldsymbol{\theta}$ can then be estimated by maximizing this likelihood.

The following choices have been made regarding the distribution to be rectified. For durations, a Gaussian distribution rectified between 0 and 1 was empirically selected as it was found to provide an acceptable fit at most stations (not shown). For magnitudes, extreme value theory suggests using the Generalized Extreme Value distribution for minima (frequently referred to as the Weibull distribution in the low-flow literature, see formula in Appendix A). It was rectified at zero but with no upper bound.

Finally, magnitude and duration series for each catchment were transformed, for each return period T, into annual occurrence series (Figure 5a), defined as follows: occurrence is equal to 1 if magnitude is smaller or equal to T-year magnitude q_T (or duration larger than T-year duration d_T), and is equal to 0 otherwise.

3.3. Grouping Occurrences of Low-Flow Events

The study performs a pooled assessment of low-flow occurrences over time for groups of stations (Figure 5b), based on the four regimes of Figures 1 and 2 and the streamflow intermittence of Figure 3. The mixed Regime 2 is separated into cold and warm seasons which are analyzed separately; for simplicity, these are referred to hereafter as Regimes 2C (cold) and 2W (warm). The group occurrence rate for each year is based on the sum of occurrences of a specific characteristic (magnitude or duration, and return period) for stations pooled by low-flow regime, streamflow intermittence, and/or continent. For each group of stations, there are two time series: the annual sum of occurrences for the stations in a group, and the annual total number of available stations. These time series were then analyzed using binomial logistic regression, separately for each group, to analyze temporal trends and variability in low-flow event occurrence rates (see Section 3.4).

Streamflow intermittence is defined as the mean annual occurrence of daily flows with zero flow computed for the period of record for each station. Perennial stations were defined as stations with no days of zero flow; mildly intermittent (MI) with 1–9 days of zero flow per year; and intermittent stations with 10–89 days of zero flow per year. As indicated before, strongly intermittent stations (90 or more days of zero flow per year) were not included in the study.

3.4. Trend and Variability Tests

Logistic regression with overdispersion correction (Frei, 2013; Frei & Schär, 2001) was used for testing temporal trends in the occurrence rate of low-flow events (Figure 5c). For each return period used in the study (5- through 100-year), the occurrence-rate time series for each group changes, and so does the trend associated with each return period and its significance. Logistic regression with overdispersion correction is described in detail in Hodgkins et al. (2017). Logistic regression is applied with a binomial distribution assumption; however, it often occurs that the sample shows a greater variability than would be expected based on the given statistical model (Hodgkins et al., 2017). This is referred to as overdispersion, which has been studied by statisticians for logistic regression and Generalized linear models (GLMs), and can be quantified by use of an overdispersion coefficient (McCullagh & Nelder, 1989; Mediero et al., 2015).

Logistic regression with an overdispersion correction was found by Hodgkins et al. (2017), through Monte Carlo testing, to be robust to two violations of the binomial distribution assumptions: (a) the trials not being independent due to spatial correlation and (b) the success probability varying from site to site due to estimation errors in frequency analysis. It was not, however, robust to temporal autocorrelation. This could result in rejection rates higher than the nominal level, in other words, significant trends could be due to autocorrelation.

For each group of stations, trends in the annual occurrence rate of low-flow events were analyzed for two periods, 1976–2015 and 1946–2015. Groups were used only if they contained at least 15 stations. This number was chosen as the best balance between minimizing the influence of individual stations on group results and representing areas and low-flow regimes with limited amounts of data. Generalized linear models (GLMs) in R with the quasibinomial family (logistic regression using a binomial family with overdispersion coefficient) were used to look for trends over time in the occurrence rate of low-flow events. The GLM below was used (each group being treated separately), where p_t is the probability of occurrence of the binomial distribution, YEAR_t is the calendar year at time t and (β_0, β_1) are the parameters of the regression that need to be estimated:

$$\mathrm{logit}(p_t) = \beta_0 + \beta_1 \times \mathrm{YEAR}_t \tag{6}$$

In addition, to look at the relation between annual event occurrence rate and climate indices, index values were used as an explanatory variable in the GLMs along with year and an interaction term:

$$\mathrm{logit}(p_t) = \beta_0 + \beta_1 \times \mathrm{YEAR}_t + \beta_2 \times \mathrm{INDEX}_t + \beta_3 \times \mathrm{YEAR}_t \times \mathrm{INDEX}_t \tag{7}$$

This full model was used to judge interactions in the explanatory variables. If the interaction term was not significant, a GLM without interaction was used to assess the main effects.

Trend magnitude is expressed with the odds ratio. An odds ratio of 2 indicates the probability of occurrence is about doubled during the period and a ratio of 0.5 indicates it is about halved. This does not extend to large odds ratios (Chen et al., 2010). The odds ratio cannot be interpreted as an effect measure in the same manner as can be done for linear regression. Odds ratios, or log-odds cannot be compared for similar models across groups, samples, or time points, or across models with different independent variables in a sample (Chen et al., 2010; Mood, 2010).

4. Results

4.1. Trends Over Time in the Occurrence Rate of Extreme Low-Flow Events

4.1.1. 40-Year Period

Most groups comprising stations with defined low-flow regimes in Europe, NA, Australia, and SA had non-significant trends from 1976 to 2015 for selected return periods, with some significant increases and decreases. The group of Regime 1C perennial catchments (Figure 2) consists only of stations in NA and Europe. It had statistically significant ($p < 0.05$) decreases from 1976 to 2015 in the occurrence rate of low streamflow events with 5-year magnitudes and 5- and 10-year durations (Figure 6 for bar plots of results; Figure 7 for scatterplot of 10-year duration regime 1C perennial catchment group and map of stations in that group). The opposite is true for the group of Regime 3W intermittent catchments where the occurrence rate of 5- through 50-year duration events increased significantly (Figure 6; Figure 8 for Regime 3W intermittent group). The group of

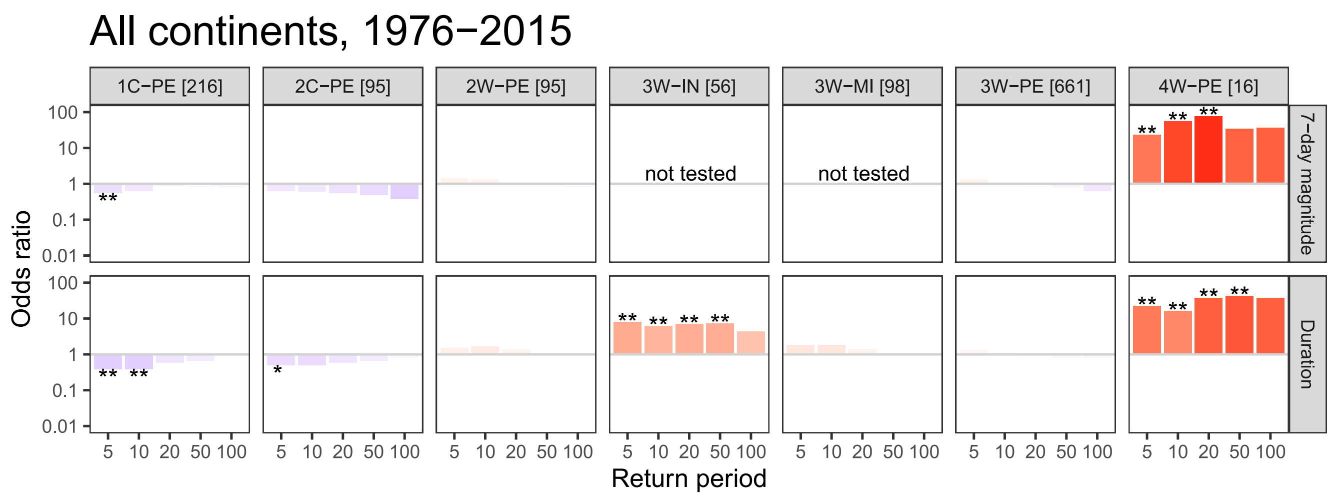

Figure 6. Trends from 1976 to 2015 in the group occurrence rate of extreme low streamflow events (7-day magnitude in top row of plots and duration in bottom row) for groups of stations defined by low-flow regime and streamflow permanence. The number of stations in each group are in brackets. Red bars indicate increases while blue indicates decreases. The significance at $p < 0.05$ is indicated by two asterisks while a single asterisk represents trend significance at $p < 0.1$. Trend magnitude is expressed with the odds ratio. Separate logistic regressions were used for each group for each return period to compute odds ratios and trend significance. See Supporting Information S1 for plots and maps for all combinations of results. Abbreviations: PE, perennial; IN, intermittent; MI, mildly intermittent. The regimes are 1C (one typical cold low-flow season), 2C/2W (two low-flow seasons, one cold and one warm), 3W (one warm low-flow season) and 4W (two warm low-flow seasons). The group occurrence rate is a count of the number of low-flow events for 1 year (magnitude or duration for selected return periods) divided by the total number of stations with data for that year, for a group of stations pooled by low-flow regime, continent, and/or streamflow permanence. While the odds ratio cannot be interpreted in the same fashion as linear regression coefficients, an odds ratio of 2 indicates the probability of occurrence is about doubled during the period and a ratio of 0.5 indicates it is about halved.

Regime 4W perennial catchments consists only of catchments in the southern United States. This group had significant increases in the occurrence rates for 5- to 20-year magnitude and 5- to 50-year duration events. Regime 2C perennial catchments had only one significant decreasing trend ($p < 0.1$), for 5-year duration events. Other groups of streamflow stations had non-significant trends in the occurrence rate of low-flow magnitudes and durations for the 1976 to 2015 period. See Supporting Information S1 for plots and maps for all combinations of temporal-trend results.

When parsed by continent (Figure 9), the results follow the same overall pattern for most regime types. Regime 1C changes for North American perennial catchments are significant ($p < 0.05$) for the same categories as in the overall results while changes for European catchments are not. Regime 3W intermittent catchment increases in occurrence rate are significant for Australia for 5- to 20-year duration events and significant for NA for 5-, 10-, and 50-year duration events. Regime 4W perennial catchments had significant increases in NA for 5- to 20-year magnitudes and 5- to 50-year durations. All significant decreases in these extreme low-flow occurrence rates apply to cold regimes and all significant increases apply to warm regimes, except for decreases in Regime 3W MI European catchments for 50- and 100-year return periods. We note that the 1976 start year for the 40-year period is a known drought year in Europe (e.g., Parry et al., 2012; Zaidman et al., 2002) and discuss the influence of this year on trends in the Discussion section.

4.1.2. 70-Year Period

Most groups comprising stations with defined regimes (Figure 2) have significant decreases in the occurrence rate of extreme low-flow magnitude and duration events from 1946 to 2015 (Figure 10; Figure 11 for group of 50-year magnitude Regime 2C perennial catchments). Regime 3W low-flow magnitude in perennial catchments had non-significant trends.

Given the limited number of catchments with 70 years of data, there also are a limited number of groups where 70-year results can be parsed by continent (Figure 12). Various regimes in both Europe and NA have significant decreases in low-flow magnitude and duration. Perennial European catchments in Regime 1C have significant decreases for the same categories as in the overall results while changes for North American catchments are generally not significant at $p < 0.05$.

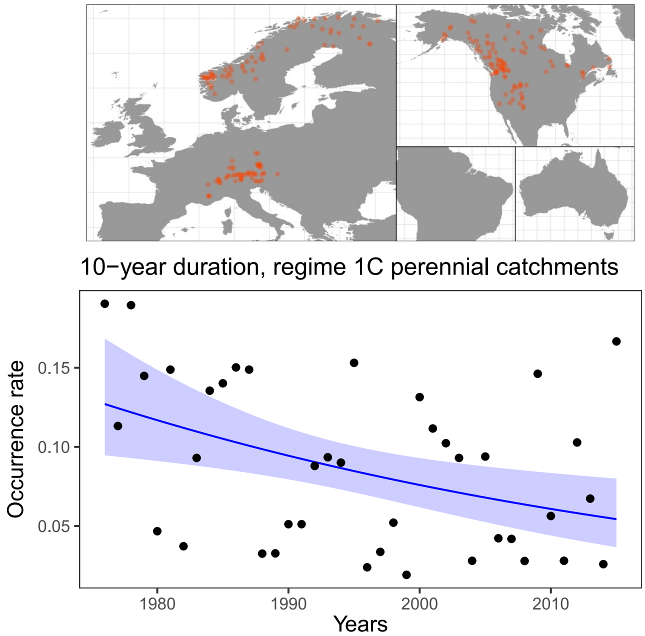

Figure 7. Trend in the group occurrence rate of low-flow events of 10-year duration from 1976 to 2015 for Regime 1C perennial catchments. Red symbols on the map represent the stations that were pooled for this group. The occurrence rate is a count of the number of low-flow events for 1 year (magnitude or duration for selected return periods) divided by the total number of stations with data for that year, for a group of stations pooled by low-flow regime, continent, and/or streamflow permanence.

4.1.3. 40-Year Period for 70-Year Stations

The results for 40- and 70-year periods are not directly comparable as the stations in the 70-year data set (326 stations) are a small portion of the 40-year data set (1,184 stations). To allow a more direct comparison, the analyses for the 40-year trends were repeated with a reduced data set containing only those stations that passed

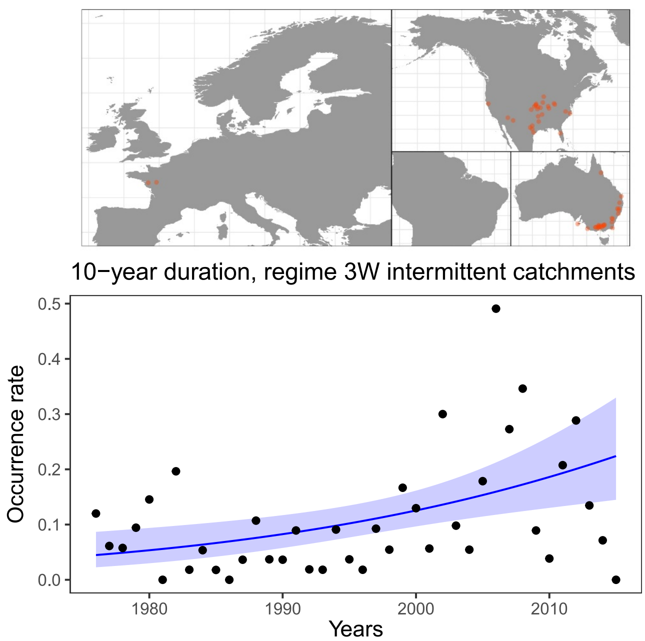

Figure 8. Trend in the group occurrence rate of low-flow events of 10-year duration from 1976 to 2015 for Regime 3W intermittent catchments. See Figure 6 caption for more explanation.

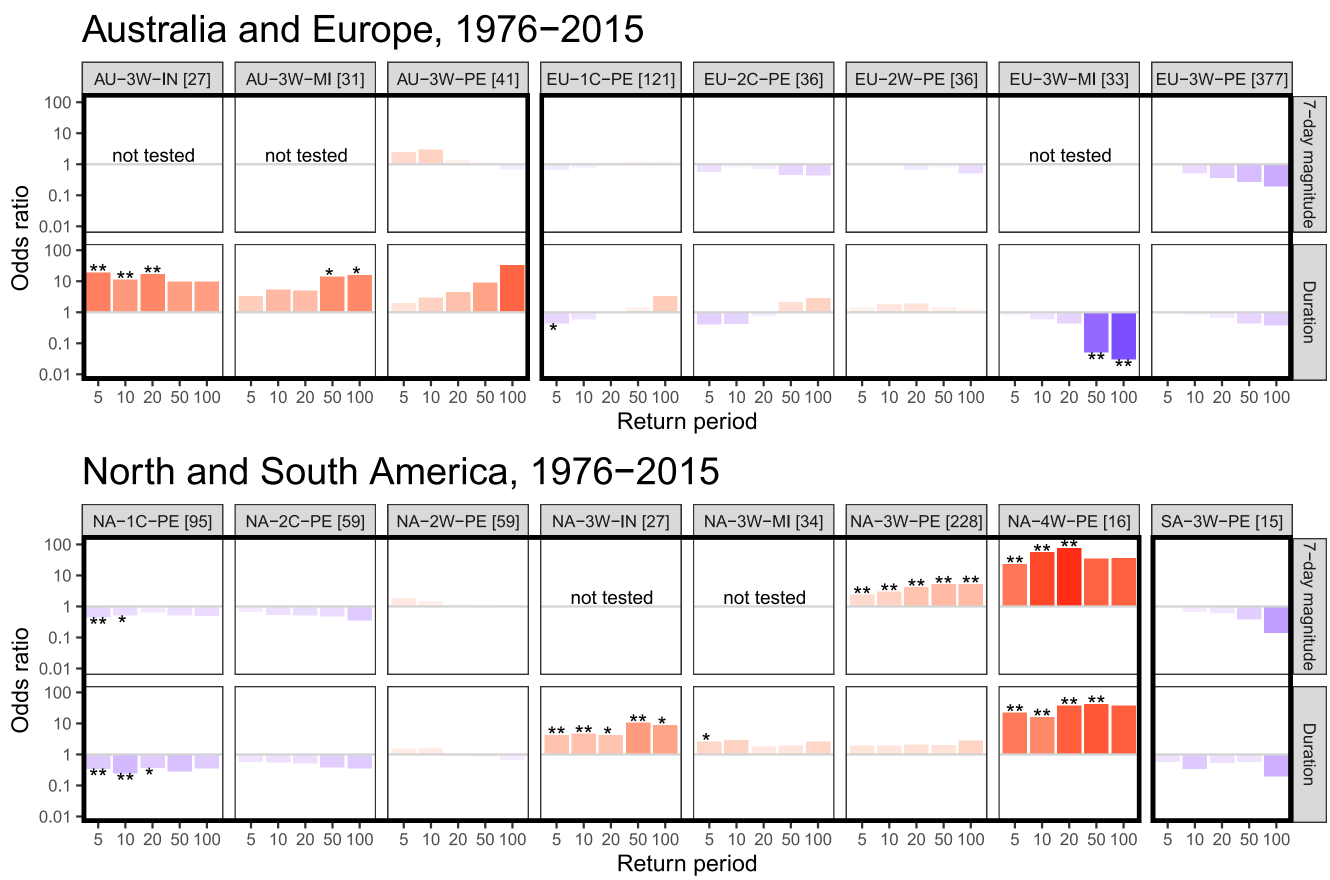

Figure 9. Trends from 1976 to 2015 in the group occurrence rate of extreme low streamflows (grouped by low-flow regime, streamflow permanence, and continent). Red bars with two asterisks indicate significant ($p < 0.05$) group increases while blue indicates decreases. Trend magnitude is expressed with the odds ratio. See Supporting Information S1 for plots and maps for all combinations of results. Continents: AU, Australia; EU, Europe; NA, North America; SA, South America. See Figure 6 caption for additional explanation.

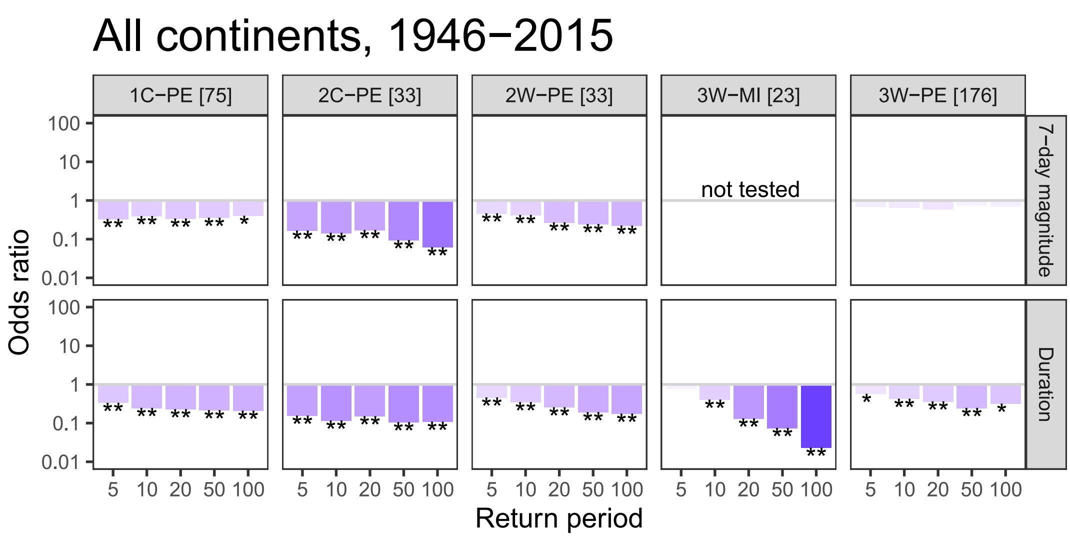

Figure 10. Trends from 1946 to 2015 in the group occurrence rate of extreme low streamflows (grouped by low-flow regime and streamflow permanence). Red bars with two asterisks indicate significant ($p < 0.05$) group increases while blue indicates decreases. Trend magnitude is expressed with the odds ratio. See Supporting Information S1 for plots and maps for all combinations of results. See Figure 6 caption for more explanation.

criteria for 70-year trends. Because of the fewer number of stations in the reduced set, there are fewer regimes that met the minimum criteria of 15 stations.

When continental trends from the reduced 40-year set (Figure 13) are compared to the 70-year trends (Figure 12), the results for the different time periods are noticeably different. Most regimes had significant decreases in extreme low-flow occurrence rate for the 70-year period. For the 40-year period, however, there were few regimes with significant trends and they were mixed between increases and decreases. As an example, Regime 1C perennial basins in Europe had significant ($p < 0.05$) decreases in the occurrence rate of 5- through 50-year 7-day low-flow magnitude events for the 70-year period, while there were insignificant trends for the 40-year period. Similarly, Regime 3W MI basins in NA had significant decreases in the occurrence rate of 10- through 100-year low-flow duration events for the longer period and insignificant trends for the shorter period. An exception was Regime 2C which had significant decreases in NA for some return periods for both the 40- and 70-year periods.

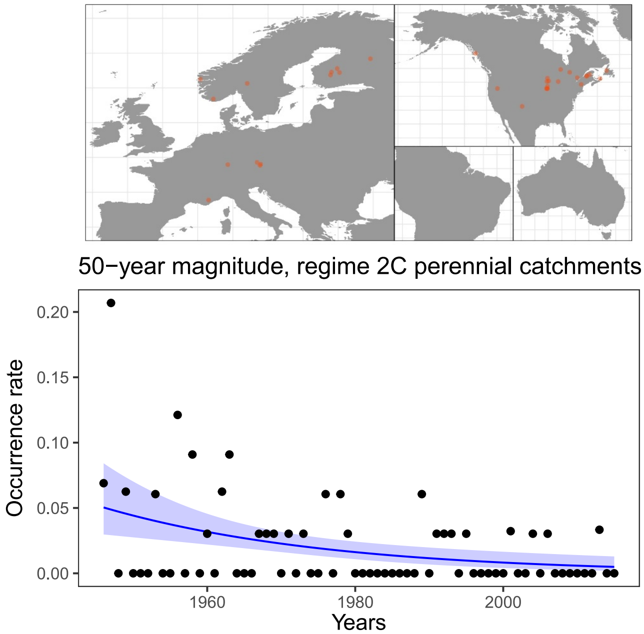

Figure 11. Trend in the group occurrence rate of low-flow events of 50-year magnitude from 1946 to 2015 for Regime 2C perennial catchments. See Figures 6 and 7 caption for more explanation.

4.2. Relations Between the Occurrence Rate of Extreme Low-Flow Events and Indicators of Decadal Climate Persistence—Pacific Decadal Oscillation and Atlantic Multidecadal Oscillation

The PDO has decadal persistence and could potentially explain the significant 40-year extreme low-flow trends in NA and Australia; similarly, the AMO has decadal persistence and could explain significant trends in Europe and NA. The relation between the annual occurrence rates of low-flow magnitude and duration events and these climate indices was explored, for groups of catchments on these continents that had significant trends (Figure 9). Annual average PDO and AMO values and time (years) were used as explanatory variables. Including both a climate index and time in the quasibinomial regressions allows comparison of the relative significance of the index versus time. An interaction term with PDO or AMO and years, for the continents and indices described in this paragraph, was found to be insignificant for groups that had significant 40-year temporal trends. Therefore, logistic regression using only years and PDO or AMO was used to assess the main effects.

For multiple groups of warm regime catchments in NA, the PDO is a more significant explanatory variable than time in years (Table 2). The opposite is true for the cold Regime 1C perennial group in NA; time is a significant

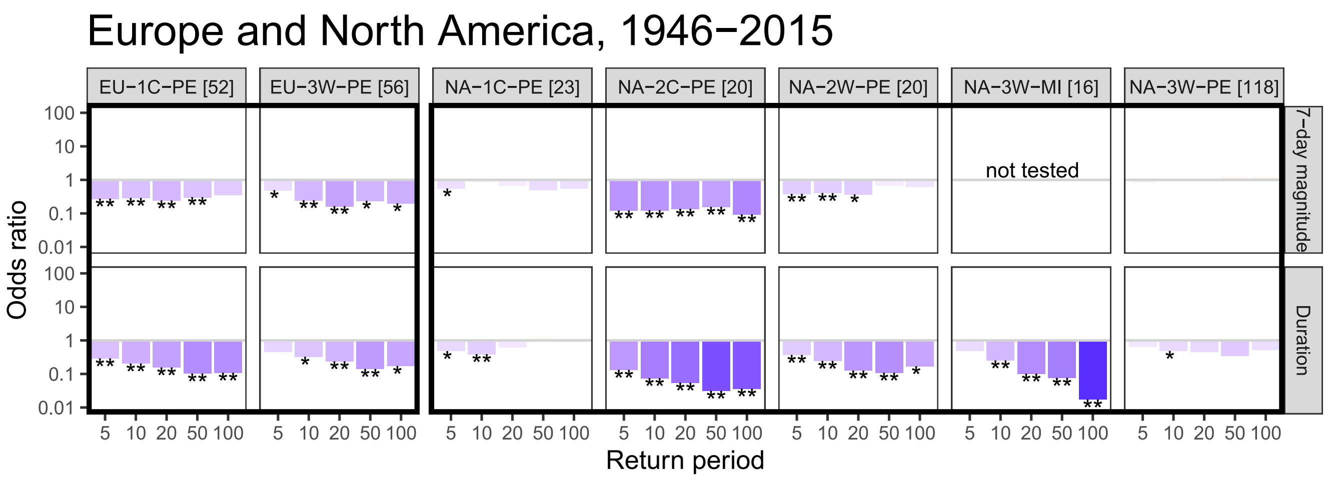

Figure 12. Trends from 1946 to 2015 in the group occurrence rate of extreme low streamflows (grouped by low-flow regime, streamflow permanence, and continent). Red bars with two asterisks indicate significant ($p < 0.05$) group increases while blue indicates decreases. Trend magnitude is expressed with the odds ratio. Continents: EU, Europe; NA, North America. See Figure 6 caption for additional explanation. See Supporting Information S1 for plots and maps for all combinations of results.

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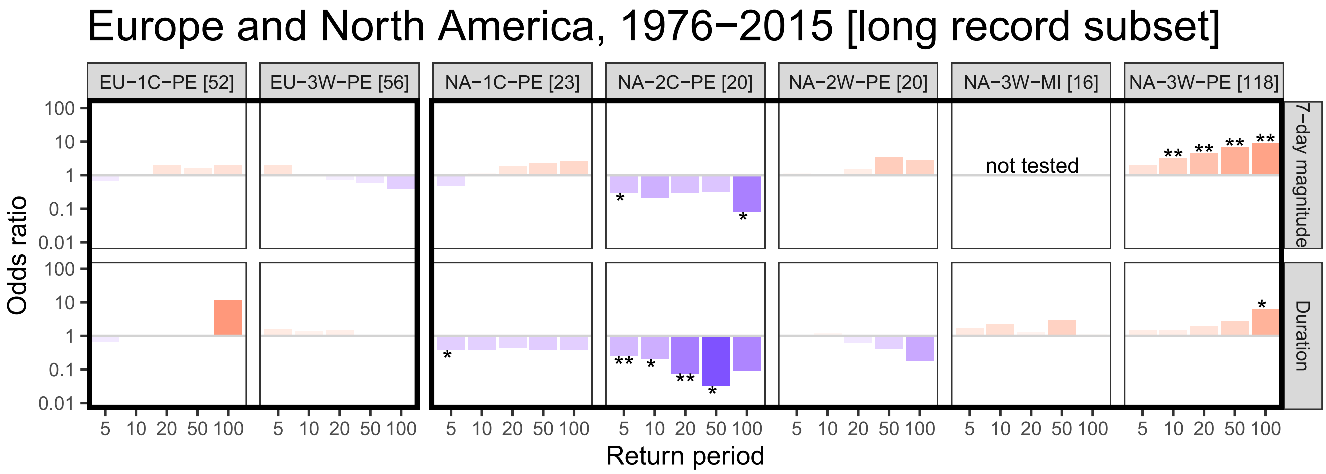

Figure 13. Trends from 1976 to 2015 in the group occurrence rate of extreme low streamflows (grouped by low-flow regime, streamflow permanence, and continent), using a subset of stations with records from 1946 to 2015. Red bars with two asterisks indicate significant ($p < 0.05$) group increases while blue indicates decreases. Trend magnitude is expressed with the odds ratio. Continents: EU, Europe; NA, North America. See Figure 6 caption for additional explanation.

variable ($p < 0.05$) but PDO is not. For intermittent catchments in Australia, time is a more significant variable ($p < 0.1$) than PDO. For Regime 3W intermittent stations in NA (Figure 2), the occurrence rate of low-flow duration events is significantly related ($p < 0.001$) to annual values of PDO but not to time (Table 2). Figure 14 shows the relation between the occurrence rate of 10-year low-flow duration and PDO for this group of stations (time not included in the quasibinomial regression for this figure). The annual occurrence rate of low-flow magnitude is significantly related to PDO for Regime 4W perennial stations, and time is also significant ($p < 0.05$) or nearly so.

There were two return periods in Europe with significant temporal trends in the occurrence rate of low-flow duration events, 50- and 100-year duration events for Regime 3W MI catchments (Figure 9). Both series had significant relations with AMO ($p < 0.05$) but not time when the variables were both in the quasibinomial regressions (Table 3). There were no significant relations between North American low-flow occurrence rates and the AMO for the 40-year period while time (years) was significant for several groups (Table 3).

Relations between low-flow occurrence rates and climate indices were tested for the 70-year period for groups with significant 70-year trends (Figure 12). For Europe, low-flow occurrence rates were tested against AMO and time; there were no groups that had significant relations with AMO. The group of MI catchments in Europe with significant AMO relations for the 40-year period did not have enough catchments for the 70-year period. For NA for the 70-year period, low-flow occurrence rates were tested against PDO and time, again for groups with significant 70-year trends. PDO was less significant than time for all groups. PDO was significant ($p < 0.05$) for only one group (Regime 2C 100-year magnitude events for perennial catchments).

5. Discussion

5.1. Consistency of Low-Flow Trends With Climatic Trends

Decreases in the group occurrence rate of extreme low streamflow events (the proportion of stations in a group that have a low-flow event each year) from 1946 to 2015 in the warm season are consistent with historical precipitation trends in relevant areas of Europe and NA. There were significant decreases in occurrence rates in perennial catchments in Regime 3W in Europe (Figure 12), most of which are in Western Europe (Figure 2). Spinoni et al. (2017) found decreasing drought severity from 1950 to 2014 in the fall in much of Western Europe based on the Standardized Precipitation Index. Summer drought severity for this period decreased in northern France but trends were unclear in the rest of Western Europe.

There were significant decreases in extreme low-flow occurrence rates for North American Regime 2W perennial and 3W MI groups from 1946 to 2015 (Figure 12). Most perennial catchments in Regime 2W are in the northern tier of the United States, the southern tier of Canada, and parts of the interior western United States (Figure 2).

Table 2
Significance (p-Values) of Relations Between the Annual Group Occurrence Rate of Extreme Low Streamflows and the Pacific Decadal Oscillation (Grouped by Low-Flow Regime, Streamflow Permanence, and Continent)

Regime	Permanence	Continent	Return period, in years	Number of stations	PDO, significance	Year, significance
7-day magnitude						
1C	PE	NA	5	95	0.951	***0.048***
3W	PE	NA	5	228	0.129	0.369
3W	PE	NA	10	228	0.146	0.270
3W	PE	NA	20	228	0.157	0.215
3W	PE	NA	50	228	0.090	0.227
3W	PE	NA	100	228	0.080	0.368
4W	PE	NA	5	16	***0.011***	0.060
4W	PE	NA	10	16	***0.017***	0.109
4W	PE	NA	20	16	***0.003***	***0.041***
Duration						
1C	PE	NA	5	95	0.589	***0.009***
1C	PE	NA	10	95	0.674	***0.004***
3W	IN	AU	5	27	0.254	***0.003***
3W	IN	AU	10	27	0.788	0.050
3W	IN	AU	20	27	0.855	0.072
3W	IN	NA	5	27	***0.000***	0.655
3W	IN	NA	10	27	***0.000***	0.958
3W	IN	NA	50	27	***0.000***	0.866
4W	PE	NA	5	16	***0.026***	0.086
4W	PE	NA	10	16	***0.031***	0.207
4W	PE	NA	20	16	***0.028***	0.162
4W	PE	NA	50	16	***0.029***	0.332

Note. These relations are compared to trends over time (for North American and Australian groups with significant trends) by including both PDO and year as explanatory variables. Results are parsed by continent for 1976 to 2015. Bold font and green shading indicate significant relations ($p < 0.05$). Continents: AU, Australia; NA, North America. See Figure 6 caption for additional explanation.

Most MI catchments in Regime 3W are in the central and southeastern United States. Many parts of the northern and central United States have seen increases in summer and fall precipitation in recent decades (Easterling et al., 2017). The southeastern United States and parts of the western United States have generally seen mixed changes in summer and increases in precipitation in the fall. Summer precipitation has generally increased in southern Canada (Vincent et al., 2015).

Winter low flows in cold regions result from storage of water in snow, ice, and frost. Decreases in the group occurrence rate of extreme low streamflow events from 1946 to 2015 in the cold season in parts of Europe and NA are consistent with historical increases in winter temperatures (Deser et al., 2016; Trenberth et al., 2007; Twardosz et al., 2021). Perennial catchments in Regime 1C in Europe had significant decreasing trends in the occurrence rate of extreme low streamflow events (Figure 12); these catchments are mostly in the Nordic countries and the Alps (Figure 2). There is a strong relation between observed low flows and winter air temperature, as seen in Alpine catchments in Europe (Laaha et al., 2016). Fall and winter temperatures increased in most of Europe from 1951 to 2010 (Spinoni et al., 2015). Perennial catchments in Regime 2C in NA also had significant decreases in extreme low-flow occurrence rates (Figure 12) and these catchments are mostly in the northern tier of the United States, the southern tier of Canada, and the western United States (Figure 2). Winter temperature increased across the contiguous United States and southern Canada in recent decades (Vincent et al., 2015; Vose et al., 2017).

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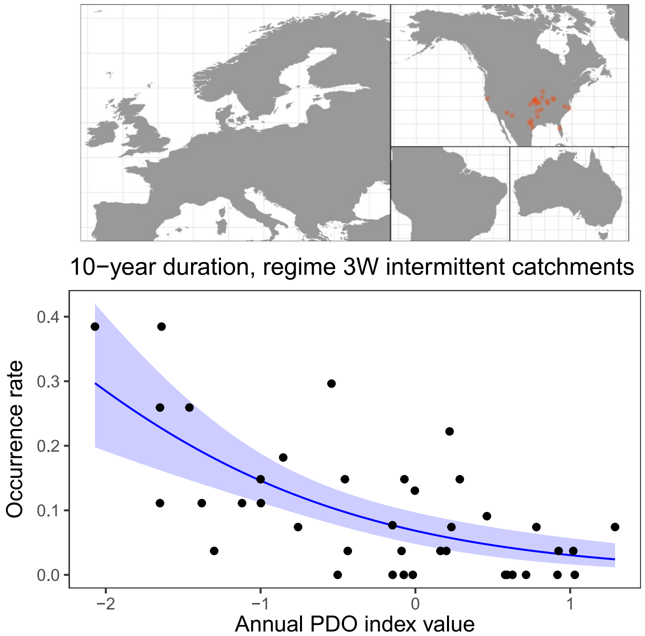

Figure 14. The relation of the annual group occurrence rate of 10-year duration events for Regime 3W North American intermittent catchments to annual 12-month average values of the Pacific Decadal Oscillation (during the period 1976 to 2015). See Figures 6 and 7 caption for more explanation.

There was a significant increase in the occurrence rate of low-flow duration events from 1976 to 2015 at intermittent catchments in Australia for low return-period events (Figure 9). The Australian catchments are located mostly in southeastern Australia (Figure 2). For the period 1970 to 2013, Sauquet et al. (2021) found a high proportion of no-flow conditions at streams in southeastern Australia from the mid-1990s to 2009; this was consistent with years of precipitation deficit known as the "Millennium Drought" in this region (Leblanc et al., 2012; van Dijk et al., 2013).

5.2. Importance of Decadal Climate Persistence

Most of the limited number of significant increases in the group occurrence rate of extreme low streamflow events from 1976 to 2015 (Figure 9), which are largely in NA, are associated with the relation between annual low streamflows and annual values of the PDO. For Regime 3W intermittent stations in NA in particular, which are predominately in the south-central United States (Figures 2 and 3), the occurrence rate of extreme low-flow events is significantly related ($p < 0.001$) to annual values of PDO but not to time in years, when both explanatory variables are included in quasibinomial regressions (Table 2). The PDO was generally in a negative phase from the mid-1940s to the mid-1970s, a positive phase from about the mid-1970s to the late 1990s, and a negative phase from the late 1990s to the mid 2010s (Henley, 2017). There was a significant trend from generally positive to generally negative PDO from 1976 to 2015 (Mann-Kendall test, $p = 0.002$) and no significant change from 1946 to 2015. Thus, most of the limited number of significant increases in occurrence rate from 1976 to 2015 in NA are likely due to decadal climate persistence. McCabe et al. (2004) found that a substantial amount of the historical variability of decadal precipitation drought frequency in the United States was due to the PDO. In warm and cold phases of the PDO, October through March precipitation amount is significantly different in the south-central United States (Louisiana, Arkansas, Oklahoma, Texas, and New Mexico) with the highest significance centered in Oklahoma (Kurtzman & Scanlon, 2007). Based on the CanAM4 model, lower precipitation in the south-central United States during negative PDO periods is associated with the location of high and low pressure centers that result in cold and dry northwesterly winds (Dai, 2013). We found plausible statistical covariability between annual values of the PDO and the occurrence rate of extreme low streamflow events in parts of NA; better understanding of the mechanisms behind this covariability, however, requires climate modeling. McAfee (2014) demonstrated differences in pressure, temperature, and precipitation anomalies in NA between PDO years of the same sign during different observed time periods, suggesting caution in interpretation.

5.3. Importance of Analyzing Different Measures of Low Streamflows

Different measures of extreme low flows do not necessarily change in the same way over time. The trend results for the occurrence rate of events based on low-flow magnitude and duration were generally similar. Cases where the frequency of magnitude and duration events show opposing results were not observed; however, there were cases where trends were significant for one variable but not the other. For example, there were significant increases in the occurrence rate of extreme low-streamflow magnitude events from 1976 to 2015 for Regime 3W perennial stations in NA but not for low-flow duration events. This shows the need to consider different measures of extreme low flows when analyzing historical low streamflows or when modeling projected low flows.

5.4. Importance of Analyzing Different Periods of Record

Trends in the occurrence rate of extreme low-streamflow events from 1976 to 2015 differed from trends from 1946 to 2015. Most low-flow regimes on multiple continents had non-significant trends over the shorter period, with some significant ($p < 0.05$) increases and decreases (Figure 13, using only catchments with adequate record for the longer 70-year period). Most regimes during the longer period, however, had significant decreases in the occurrence rate of low-flow events and some had non-significant trends (Figure 12). Extreme low-flow events became less frequent from 1946 to 2015. This occurred in both cold-season and warm-season low-flow regimes in

Table 3
Significance (p-Values) of Relations Between the Group Annual Occurrence Rate of Extreme Low Streamflows and the Atlantic Multidecadal Oscillation (Grouped by Low-Flow Regime, Streamflow Permanence, and Continent)

Regime	Permanence	Continent	Return period, in years	Number of stations	AMO, significance	Year, significance
7-day magnitude						
1C	PE	NA	5	95	0.840	0.101
3W	PE	NA	5	228	0.174	0.819
3W	PE	NA	10	228	0.283	0.530
3W	PE	NA	20	228	0.648	0.224
3W	PE	NA	50	228	0.917	0.112
3W	PE	NA	100	228	0.998	0.158
4W	PE	NA	5	16	0.608	***0.008***
4W	PE	NA	10	16	0.874	***0.020***
4W	PE	NA	20	16	0.968	***0.018***
Duration						
1C	PE	NA	5	95	0.727	**0.036**
1C	PE	NA	10	95	0.640	**0.015**
3W	IN	NA	5	27	0.381	0.285
3W	IN	NA	10	27	0.189	0.577
3W	IN	NA	50	27	0.283	0.387
3W	MI	EU	50	33	**0.031**	0.857
3W	MI	EU	100	33	**0.019**	0.806
4W	PE	NA	5	16	0.751	**0.045**
4W	PE	NA	10	16	0.621	0.141
4W	PE	NA	20	16	0.806	0.088
4W	PE	NA	50	16	0.989	0.130

Note. These relations are compared to trends over time (for European and North American groups with significant trends) by including both AMO and year as explanatory variables. Results are parsed by continent for 1976 to 2015. Bold font and green shading indicate significant relations ($p < 0.05$). Continents: EU, Europe; NA, North America. See Figure 6 caption for additional explanation.

both Europe and NA (Figure 12). The difference in results between the shorter and longer periods in the current study highlights the complexities of streamflow response to changing climatic conditions.

Decadal periods with low and high occurrence rates of extreme low-streamflow events can lead to trends in one period but not another. For example, for Regime 3W perennial basins in NA from 1946 to 2015, the occurrence rates of 50-year 7-day low-flow magnitude events were generally high in the 1950s and 1960s, low in the 1970s and 1980s, and high in the 1990s and 2000s (Figure 15). This led to significant increases for this pooled group of stations for 10- to 100-year low-flow magnitude events from 1976 to 2015 (Figure 13, for the subset of stations with records from 1946 to 2015) but no significant trends for 1946 to 2015 (Figure 12).

6. Study Limitations

Data available from reference networks, and hydrometric networks in general, are biased toward perennial streams, despite temporary streams being common across the globe (Buttle et al., 2012). In areas where perennial streams exist, they receive the monitoring focus despite the prevalence of temporary streams in many of those landscapes (mountains, semi-arid, and arid lands) (Buttle et al., 2012; Costigan et al., 2017; Leigh et al., 2019). Of the sites used for the 40-year trends in this study, 83.3% were perennial, 10.4% were MI (zero flows <10 days per year) and only 6.3% were intermittent (zero flows ≥10 days per year). Since the minimum number of sites considered acceptable to report for pooled results was 15, groups with stations from the latter two categories often did not have enough stations to report a result; this was particularly true for Regimes 1C, 2C, and 2W. We note

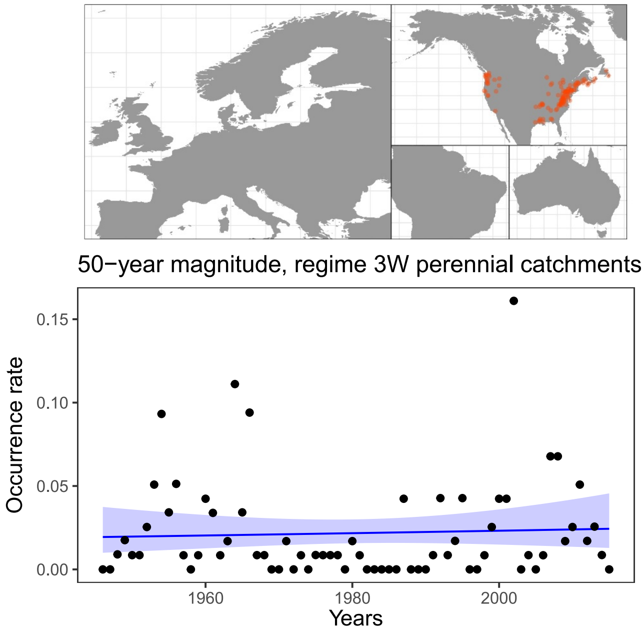

Figure 15. Trend in the group occurrence rate of low-flow events of 50-year magnitude from 1946 to 2015 for Regime 3W perennial catchments. See Figures 6 and 7 caption for more explanation.

also that our statistical tests may have limited power to detect significant trends or relations with climate indices, for groups comprised of a limited number of catchments.

Measuring low flows accurately is difficult and the accuracy is hard to assess. The uncertainty of low-flow measurements differs from other flow magnitudes (Hamilton, 2008). While the problems with measuring low flows are recognized, there are few studies dedicated to rating curves for low flows (Clarke & Brusa, 2001; Garcia et al., 2020; Sörengård & Di Baldassarre, 2017). Low-flow records are generally poor in winter in cold regions during long periods of river ice and this is important if the annual or seasonal low flow occurs under ice; this may make detection of changes in low flows in winter more difficult (Whitfield & Hendrata, 2006). More studies are needed to improve knowledge of the uncertainty and accuracy of low-flow measurements.

Low flows are strongly affected by landscape alterations (Buttle et al., 2012; Costigan et al., 2017; Wang & Cai, 2009; Yu et al., 2018). Even though the stations in the current study were extensively screened to remove cases of human influence on catchment low flows, there could still be some influence of human catchment alterations on trends. It is possible that subtle or undefined catchment land-use or water-use changes had an effect on low flows that was not caused by climatic changes.

Because of the limited amount of extreme low flows in the period of record of any one station, this study pooled stations into groups and analyzed trends in the annual group occurrence rate of events for all stations in each group. However, the pooling presumes that all the stations within the pool have similar trends; when trends of different signs are pooled, the result will be an average of all the stations included in the pool. The results may mask local changes that differ from overall group results (e.g., Laaha & Blöschl, 2006b). Also, links to climate indices can be masked, as both PDO and AMO can have opposing effects on the regional climate in different parts of one continent (e.g., Wang et al., 2006; Whitfield et al., 2010). Follow-up studies at the regional and local level are important to further understand changes in extreme low flows. The pooling used herein could be refined in future work if a suitable pooling variable was available and enough stations remained in the pool.

Temporal trends can be influenced by high influence points near the start and end of periods (e.g., Laaha & Blöschl, 2006b; Weisberg, 2014). Because Europe had its highest occurrence rate of extreme low flows for 1976 to 2015 in 1976 for multiple regimes and return periods, the sensitivity of trends in Europe to this single year of data was tested by removing the 1976 occurrence rate and rerunning the quasibinomial trends. Results did not change for most regimes and return periods, in terms of significant versus non-significant results. Regime 2W perennial stations in Europe went from non-significant changes to significant increases in the occurrence rate of durations with 20- to 100-year return periods. Regime 3W MI stations went from significant decreases to non-significant changes for 50- to 100-year durations.

For low flows, the presence of time series persistence cannot be ignored as it affects the ability to detect trends (Ehsanzadeh & Adamowski, 2010; Khaliq et al., 2009; Kumar et al., 2009). The current study showed that climate persistence affected apparent 40-year trends in the occurrence rate of extreme low-flow events. More work is needed to better quantify and correct trend tests for persistence in quasibinomial regression and to separate the effects of exogenous climate persistence and endogenous catchment storage.

7. Summary and Conclusions

Extreme low flows can be critical to water supply, water quality, and aquatic biota. It is important to understand historical changes and climatic drivers to better anticipate future changes. Low-flow seasonality and climatic drivers differ among nival, mixed, and pluvial regimes and it is important to consider them separately. Cold-season low flows are typically caused by a lack of flow due to extended periods of snow and ice, while warm-season low flows are typically caused by lack of precipitation and potentially by increased evapotranspiration.

Extreme low streamflows are particularly susceptible to influence from many catchment alterations (e.g., reservoir storage and water abstractions). The presence of these non-climatic factors complicates the interpretation of historical changes. Streamflow stations were carefully screened in multiple ways in the current study because of our focus on climate-driven extreme low flows. The stations were from formal national reference networks or stations that met similar criteria from countries without formal networks. Based on additional screening, many stations were found to be not appropriate because of likely human influence or missing data. Care should be taken to set data and station quality criteria and to screen against those criteria when selecting stations, even when drawing stations from published reference networks.

This study seeks to better understand climate driven historical trends in extreme low streamflows from different flow regimes on multiple continents using a common methodology. We analyzed time series of extreme low flows for pooled groups of basins rather than the commonly used annual low flow series for individual basins, because extreme low flows are rare for any given catchment in a given year. Climate driven trends in annual and seasonal extreme low flows for groups were based on data from 1,184 hydrometric stations in 15 countries on 4 continents, using 40 years of record from minimally altered catchments. Similar analyses were completed based on a subset of 326 sites with 70 years of record.

Different low-flow regimes were examined, as defined by a novel method based on the number of monthly days below the Q95 threshold (the flow magnitude which is exceeded by 95% of daily mean flows) at stations and air temperatures. Regimes were defined with (a) one annual low-flow period during the cold season, (b) low-flow periods in both the warm season and cold season, (c) one annual low-flow period during the warm season, and (d) two annual low-flow periods in the warm season. Stations also were grouped by the level of streamflow permanence, from intermittent to perennial, and by continent. Extreme low-flow magnitude and duration were both analyzed. Trends in the group occurrence rate of extreme low-flow events (proportion of stations in a group that have a low-flow event each year with 5-to-100-year return periods) were assessed for each regime using logistic regression with an overdispersion correction. The occurrence rates of extreme low flows for groups with significant trends also were tested for relations with climate indices that have decadal persistence such as the PDO.

Most groups comprising stations in various low-flow regimes in Europe, NA, Australia, and SA had non-significant trends in extreme low-flow occurrence from 1976 to 2015, with some significant increases and decreases. This is consistent with previous research at the continental level which was based on historical annual low flows for near-natural basins in Europe, NA, and Australia (Seneviratne et al., 2021). Most of the significant increases in the occurrence rate of extreme low streamflows from 1976 to 2015 in NA were in the warm season and were more associated with annual values of the PDO than with changes over time. PDO phase is related to precipitation amount in the areas of NA with significant extreme low-flow trends. The group occurrence rates of low-flow magnitude and duration events for the cold-season low-flow regime in NA were found to be decreasing for low return-period events and were more associated with changes over time than with the PDO. These low-flow trends are likely due to generally increasing winter temperatures resulting in more winter streamflow. The significant group increase in the occurrence rate of low-flow duration events at intermittent catchments in Australia (mostly southeastern Australia) for low return-period events was more related to time than to the PDO. This trend is likely due to decreased precipitation in this area.

Trends in the group occurrence rates of extreme low-streamflow magnitude and duration events from 1946 to 2015 differed from trends from 1976 to 2015. Most groups comprising stations from various low-flow regimes with enough data for the longer period had significant decreases in the occurrence rate of extreme low-flow events and some had non-significant trends; this occurred in both cold- and warm-season low-flow regimes in both Europe and NA. These changes are likely associated with documented increased air temperatures in cold-season regimes and increased precipitation in warm-season regimes. The difference in the results between the shorter and longer periods and between low-flow regimes highlights the complexities of streamflow response to changing climatic conditions.

Appendix A: GEV Distribution for Minima

The GEV distribution for minima is used in its parameterization in terms of location μ, scale σ and lower bound α. The pdf, cdf and quantile function are defined for $x \geq \alpha$ as follows:

$$f(x) = \frac{1}{\sigma}\left(1 + \frac{x-\mu}{\mu-\alpha}\right)^{\frac{\mu-\alpha}{\sigma}-1} \exp\left(-\left(1 + \frac{x-\mu}{\mu-\alpha}\right)^{\frac{\mu-\alpha}{\sigma}}\right)$$

$$F(x) = 1 - \exp\left(-\left(1 + \frac{x-\mu}{\mu-\alpha}\right)^{\frac{\mu-\alpha}{\sigma}}\right)$$

$$Q(p) = \alpha + (\mu-\alpha)(-\log(1-p))^{\frac{\sigma}{\mu-\alpha}}$$

Data Availability Statement

Data used for this study are available in Hodgkins et al. (2024). The frequency analysis framework described in Section 3.2 is available as an R package at https://github.com/benRenard/disTRIMbution.

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