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Trends in flow intermittence for European Rivers

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Abstract

Intermittent rivers are prevalent in many countries across Europe, but little is known about the temporal evolution of intermittence and their relationships with climate variability. In this study, a trend analysis is performed on the annual and seasonal number of zero-flow days, the maximum duration of dry spells and the mean date of the zero-flow events, on a database of 452 rivers with varying degrees of intermittence between 1970 and 2010. In addition, the relationships between flow intermittence and climate are investigated using the Standardized Precipitation Evapotranspiration Index (SPEI) and climate indices describing large scale atmospheric circulation. Results indicated a strong spatial variability of the seasonal patterns of intermittence and the annual and seasonal number of zero-flow days, which highlights the controls exerted by local catchment properties. Most of the detected trends indicate an increasing number of zero-flow days which also tend to occur earlier in the year, in particular in Southern Europe. The SPEI is found to be strongly related to the annual and seasonal zero-flow day occurrence in more than half of the stations for different accumulation times between 12 and 24 months. Conversely, there is a weaker dependence of river intermittence with large-scale circulation indices. Overall, these results suggest increased water stress in intermittent rivers that may affect their biota and biochemistry and also reduce available water resources.

Keywords: Europe, Intermittent, Ephemeral, Rivers, Trends, SPEI, seasonality, zero-flows

1. INTRODUCTION

In streams and rivers, flow intermittence is characterized by the cessation of flow, followed or not by complete drying of the channels (Datry et al. 2017). The spatio-temporal patterns of flow intermittence can be extremely variable depending on climatic, geologic or topographic contexts (Costigan et al. 2017). While many studies have been focused on river low-flows characterization and, in particular, the possible long-term trends due to climate change (e.g., Marx et al., 2018), far less work has been dedicated to intermittent rivers and ephemeral streams. Recent studies indicate trends towards less severe climatic droughts over North-Eastern Europe, especially in winter and spring, and the opposite in Southern Europe where more severe droughts, are encountered (Spinoni et al., 2017, Hertig and Tramblay, 2017). Globally, negative trends in streamflow in Europe have been reported by Stahl et al. (2010), in Spain by Gallart and Llorens (2004), Coch and Mediero (2016), in Italy by De Girolamo et al. (2017), Germany by Bormann and Pinter (2017) and in Cyprus by Myronidis et al. (2018).

To our knowledge, no studies have explored the trends in flow intermittence across Europe. Snelder et al. (2013) analyzed French patterns in flow intermittence, using as indicators the mean annual frequency of zero-flow periods and the mean duration of zero-flow periods. Unsurprisingly, the highest values of the two characteristics coincided with the years of severe droughts. Besides climate influences, intermittence characteristics might be strongly influenced by processes operating at small scales, including groundwater-surface water interactions, river transmission losses, frozen surface water, flow reversal, instrument error, natural or human-driven discharge losses (Beaufort et al., 2019, Costigan et al. 2017, Zimmer et al., 2020). Similarly, in different regions of the USA, Eng et al. (2016) classified 265 intermittent streams using as descriptors the number of zero-flow events, the median discharge and the 10th percentile of daily flows, and they showed the strong dependency of these metrics with temporal variations of precipitation and evapotranspiration. More generally, the probability of flow intermittence in rivers worldwide is likely to increase with the projected rise of temperature in future climate scenarios (Döll & Schmied 2012, Osuch et al., 2018, Snelder et al. 2013, Eng et al. 2016).

Previous classifications of European rivers based on their flow regime have usually not integrated flow intermittence or in a relatively small sample of basins (Gallart et al., 2010, Oueslati et al., 2015). This is probably due to the difficulties in conceptually defining the intermittent, ephemeral and perennial aquatic states of streams (Gustard et al., 1992, Oueslati et al., 2015, Delso et al., 2017). For low flows and hydrological droughts, regional classifications at the European scale (e.g. Stahl and Demuth, 1999, Hannaford et al., 2011, Kirkby et al., 2011) or national scale (in Spain, Coch and Mediero, 2016) have been produced using most often the flow exceeded 90% of the time as a threshold for low flows. Only a few classifications of intermittent rivers based on zero-flow indicators have been proposed, in an attempt to relate their spatiotemporal variability with catchment characteristics or climatic variability (Kennard et al., 2010, Snelder et al., 2013, Eng et al., 2016, Perez-Saez et al., 2017, Tzoraki et al., 2016, Dörflinger, 2016, D'Ambrosio et al., 2017, Pournasiri Poshtiri et al., 2019). Identifying homogeneous regions and the drivers of flow intermittence, in terms of seasonality, catchment or climatic properties, could help to estimate intermittence characteristics and trends at the regional level (Pournasiri Poshtiri et al., 2019). Indeed, these intermittent and ephemeral streams are underrepresented in monitoring networks and often ungauged in Europe (Skoulikidis et al., 2017, Costigan et al., 2017).

Besides catchment characteristics, large scale climate variability may also exert an influence on intermittence patterns. Giuntoli et al. (2013) evaluated the relationships between low flows and large-scale climate variability in France, using climate indices such as the North Atlantic Oscillation (NAO), the Atlantic Multi-decadal Oscillation (AMO) and a weather typing approach. Their results indicated an increase of drought severity in Southern France, and the usefulness of lagged climate indices as predictors of summer low flows. Indeed, approaches based on weather typing or composite analysis with climatic data could help to evaluate the synoptic ingredients associated with dry periods and their long-term evolution and trends (Stahl and Demuth, 1999, Ionita et al., 2017). For the summer 2015 drought episode that hit large parts of Europe, Ionita et al. (2017) observed that this event was associated with positive anomalies in 500 hPa geopotential height and Mediterranean Sea surface temperatures. Since these climatic drivers are likely to have different influences in different regions of Europe, there is a need to perform such analysis at the regional scale.

The objectives of this study are: (i) to analyze the seasonal characteristics of flow intermittence in Europe, (ii) to test temporal trends in the number of zero-flow days at annual and seasonal scale and (iii) to analyze the possible relationships between the occurrence of zero-flows and climate indices. This study relies on an unprecedented database of intermittent rivers across Europe, which is presented in the next section, the methodology is presented in section three and the results in section four.

2. DATABASE OF INTERMITTENT RIVERS

The database of discharge time series of ephemeral and intermittent streams have been collected in the framework of the SMIRES COST action (Datry et al., 2017) in the different European countries in addition to individual contributions and stations from the GRDC (https://www.bafg.de/GRDC) database including countries outside of Europe such as Morocco, Tunisia and Israel. The selected rivers are characterized by natural or moderately influenced flow regime with catchment area smaller than 2000km² (Figure 1). The absence of dams or reservoirs upstream of the station gauge has been verified from a GIS analysis using the GRanD database (http://globaldamwatch.org/grand/). It must be noted that the metadata originating from different countries should be analyzed with care and can be misleading since the definition of “natural”, and the distinction between “little influenced” and “heavily” influenced rivers may vary strongly between different countries. Also, since this study is focusing on zero-flow days, it is possible that zero values are put in place of missing data; this is the reason why the data had to be checked carefully in the absence of metadata for many rivers. In cases where the catchment area for a station was missing, the catchment has been delineated using the flow accumulation maps from the HydroSheds database (https://www.hydrosheds.org/).

Instead of using zeros, a threshold of 10^{-4} $m^3 \cdot s^{-1}$ (0.1 $L.s^{-1}$) is considered to identify days with river discharge equal to zero, to account for measurements errors of very small discharge values. However other thresholds, such as 5 $L.s^{-1}$ recommended by Gustard et al. (1992) or Delso et al. (2017) have also been tested, yielding similar results. In addition to this threshold, the individual time series have been checked to verify if the smallest reported daily discharge values were below 10 $L.s^{-1}$. If there were no daily discharge values below 10 $L.s^{-1}$ in a series that contained zero-flow days, the zero-flow days of that series were interpreted as wrongly reported missing values and the gage was removed. The analyses performed in the present work are focusing on the annual and seasonal timescales, with the hydrological year starting April 1 through March 31 since this is common practice in low-flow analysis (Lahaa and Blöschl, 2006). We consider an extended summer season, from April to September, and an extended winter season from October to March. The definition of the hydrological years was governed by a preliminary analysis on the seasonality of zero-flow events in Europe (mainly in summer and fall but also in winter). This reduces the chance of observing a zero-flow event spanning across two consecutive hydrological years. The database includes 452 stations with at least two years with five consecutive zero-flow days. This criterion has been chosen to avoid including in the database some missing data in place of actual river intermittence since it is unlikely that river flow will cease only one day in one year. Indeed, if for an annual time series only a single day with zero-flow is recorded, it could be missing data not properly reported in the metadata. For all stations, all years with more than 5% missing data have been removed. Across most stations (452), there is a common period for analysis between 1970 and 2010 when data are available (Figure 1). Two annual and seasonal metrics of duration are considered:(i) the duration of the longest no-flow event (maximum length of zero-flow days) and (ii) the total duration of no-flow days (sum of zero-flow days). The mean date of no-flow days is also considered in the trend analysis..

3. METHODS

3.1 Clustering of stations based on seasonality measures

Directional statistics can be used to define similarity measures from the timing of zero-flow conditions. The first step is to convert dates into the day-in-year, which is the day of a year starting from 1 April, into an angular value (Burn, 1997):

$$\theta_i = (Julian\ Date)_i \left(\frac{2\pi}{365}\right) \qquad (1)$$

where θ_i is the angular value in radians for the zero-flow day *I* In leap years, the denominator was increased by one. The conversion of Julian days into angular values is convenient to avoid artificial breaks between the last day of the year and the first day of the next year. All zero-flow days can then be seen as vectors with unit magnitude and direction given by θ_i. Then, for a sample of n dates, the $\bar{x}$ and $\bar{y}$ coordinates of the mean date can be determined as:

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} cos(\theta_i) \quad (2)$$

$$\bar{y} = \frac{1}{n}\sum_{i=1}^{n} sin(\theta_i) \quad (3)$$

The mean direction (the mean date) $\bar{\theta} \in [0, 2\pi)$ of zero-flow dates for a given station can be then obtained from:

$$\bar{\theta} = arctan^{*}\left(\frac{\bar{y}}{\bar{x}}\right) \quad (4)$$

where $arctan^{*}()$ is the quadrant-specific inverse of the tangent function. The measure of the variability of the n occurrences around the mean date is the mean resultant length:

$$r = \sqrt{\bar{x}^2 + \bar{y}^2} \quad (5)$$

It should be noted that $0 < r \leq 1$ and that r near to 1 implies little variation and high concentration of data, and $\bar{r}$ near to 0 a large variation and wide dispersion around the mean date.

The clustering is based on the matrix including the $\bar{\theta}$ and r metrics calculated for winter and summer for each station. Then a Euclidean distance between stations has been computed and the Ward method (Ward, 1963) has been chosen as the linkage criterion to create clusters. The identification of the optimal number of clusters is achieved with the help of the silhouette plot and visual inspection of the clusters obtained.

3.2 Trend analysis

Trend analysis has been performed using the modified Mann-Kendall (MK) test (Mann, 1945, Hamed and Rao, 1998) on the annual and seasonal metrics of duration and occurrence and the mean date of occurrence $\bar{\theta}$. The MK rank correlation test for two sets of observations $X = x_1, x_2, \ldots, x_n$ and $Y = y_1, y_2, \ldots, y_n$ is formulated as follows, with the S statistic calculated as:

$$S = \sum_{i<j} a_{ij} b_{ij} \tag{6}$$

where

$$a_{ij} = sgn(x_j - x_i) = \begin{cases} 1, if\ x_i < x_y \\ 0, if\ x_i = x_y \\ -1, if\ x_i > x_y \end{cases} \tag{7}$$

and b_{ij} is similarly defined for the observations in Y. Under the null hypothesis that X and Y are independent and randomly ordered, the statistic S tends to normality for large n. In the current work, the modified MK test proposed by Hamed and Rao (1998) is considered, that is robust in the presence of autocorrelation in the time series tested by modifying the variance of the S statistic. The slope of the trends is computed with the Sen slope method.

In addition, to consider the issue of false positives due to repeated statistical tests (Wilks, 2016), the False Discovery Rate (FDR) procedure introduced by Benjamini and Hochberg (1995) has been implemented to identify field-significant test results. With this method, the results are considered field significant (or regionally significant) if at least one local p-value of the test is below the global significance level. Only 254 of the 452 selected stations, those with at least 10 years with more than five consecutive zero-flow days, have been considered for this analysis to avoid testing trends on very small sample size. The 10% significance level (p-value =0.1) was considered for trend detection, in order to avoid discarding weak trends that might be relevant in a changing environment.

3.3 Relationships with climate

To estimate the relationships between dry spells and climatic drivers, namely precipitation and evapotranspiration, the correlation between the annual and seasonal sum of zero-flow days and the maximum length of zero-flow days with the Standardized Precipitation-Evapotranspiration Index (SPEI, Vicente-Serrano et al., 2010) was analyzed with the Spearman correlation coefficient (rho). The SPEI uses the monthly difference between precipitation and potential evapotranspiration; thus it represents a simple climatic water balance, which can be calculated at different time scales similarly to the Standardized Precipitation Index (SPI, McKee et al., 1993). The SPEI with 6, 12, 18 and 24 months aggregation time have been downloaded from the CSIC Global SPEI database (https://spei.csic.es/database.html). The SPEI values from the CSIC database were computed using the monthly sum of precipitation and potential evapotranspiration at 0.5 degrees spatial resolution and a monthly time resolution from the Climatic Research Unit (CRU) of the University of East Anglia. Version 3.23 of the CRU dataset has been used to compute the SPEI. The SPEI computation is based on the FAO-56 Penman-Monteith estimation of potential evapotranspiration. The details of the SPEI computation were presented by Beguería et al. (2014). For each station, the value was extracted from the SPEI grid cell covering the station, since the size of the basins considered is small (<2000km^2) compared to the CRU mesh (approximately 2500km^2) used as a basis for the calculation of the SPEI.

In addition, different climate indices describing large scale atmospheric circulation patterns have been selected: the North Atlantic Oscillation (NAO), the Atlantic Multi-decadal Oscillation (AMO), the Mediterranean Index (MOI), the East Atlantic Western Russia (EAWR), the Pacific Decadal Oscillation (PDO), and the Scandinavian Index (SCAND). The time series for these indices have been retrieved from the Climate Prediction Center database available online at: https://www.cpc.ncep.noaa.gov. The annual, winter and summer mean values were used according to the definition of hydrological year and seasons previously adopted. For NAO, the seasonal three-month DJF, MAM, JJA, and SON values were also included to account for its within-year variability.

4. RESULTS

4.1 Seasonal spatiotemporal patterns

For 186 stations out of 452 (41%), there is more than 10% mean annual zero-flow days (Figure 2). As shown on the map (Figure 2), the annual percentage of years with zero-flow days can vary strongly even for neighbouring stations. This highlights the influence of local characteristics (geology, land cover, water use…) on zero-flow occurrences. The size of the river is an additional likely explanation for spatially nearby differences in intermittence, with small tributaries flowing into a larger river being more prone to drying. However, there is no clear dependency between the frequency of zero-flow and catchment size, showing that other catchment characteristics, that are not analyzed in the present study, may have a stronger influence on the occurrence of zero-flow days. There is a weak latitudinal gradient in the occurrence of zero-flow days, with the higher mean annual number of zero-flow days in the South (rho= -0.36 with latitude, significant at the 5% level), but with a very strong spatial variability even for neighbouring catchments. This implies that most intermittent streams are not necessarily associated with the most arid climate conditions in Southern Europe. It must be also noted that this observation strongly depends on the density of monitoring networks and their representation of intermittent and ephemeral streams.

Clustering has been applied using the variables $\bar{\theta}$, the mean direction of zero-flow and the variability around this date, r, computed for the winter and summer seasons. Three different seasonality patterns can be identified in Figure 3. The largest one, the summer cluster, is composed of 376 stations having a mean date of occurrence for zero-flow days between May and November (Figure 4). The location of the stations composing this cluster are scattered all across Europe, in different climatic zones ranging from Continental to Mediterranean climate types (Figure 3). The second-largest cluster, the winter cluster, contains 47 stations with a mean occurrence of no-flow events between January and March (Figure 4). It includes stations with a snowmelt-driven annual regime, such as the Pyrenees or Scandinavia, that experience cessation of flow due to freezing. The fall cluster (29 stations) corresponds to late fall (November to January) occurrence of zero-flow days. The main difference in flow regime for the fall and winter clusters is a more sustained runoff rate during January-March for the fall cluster (Figure 4), indicating that zero-flow days for the winter cluster are mostly due to freezing. As shown in this analysis, for most stations (Clusters 1 and 3), the zero-flow conditions are more frequently observed in summer months or during winter or early spring due to snow and ice cover. Yet, as shown in the map in Figure 3, there are no clear spatial patterns that could be identified from this analysis though the stations belonging to the winter cluster are located predominantly in mountainous or northern areas.

4.2 Trend analysis

The trend detection and subsequent analyses have been performed only for the 254 rivers with at least 10 years with a minimum of 5 consecutive zero-flow days. The first trend analysis has been carried out on annual, winter and summer mean dates of zero-flow occurrence, with the $\bar{\theta}$ metric (eq. 4) computed on an annual or seasonal basis. The results, in terms of significant trends, indicate for most rivers located in southern Europe a trend towards earlier occurrence in zero-flow days, mostly for the annual and summer timescales (Figure 5). For the river in the Baltic region, the trend toward later occurrence in zero-flow days for the summer and annual periods can be observed. Conversely, more contrasted trends patterns are detected for winter, with both positive and negative trends in the mean date for stations. A significant trend towards a later occurrence of zero-flows is visible in southern France and central Spain for the winter period.

The second trend analysis is concerning annual and seasonal sums and maximum lengths of zero-flow days. It must be noted that the annual number of zero-flow days and the annual maximum length of zero-flow periods are correlated, with an average correlation coefficient equal to 0.9 for all stations. For the summer and winter, these correlations are lower and equal to 0.74 and 0.70, respectively.

At the annual scale, 60 stations (24%) have positive trends in the number of zero-flow days and more generally there are more positive trends detected by comparison to negative trends for all indicators (Table 1 and Figure 6). Overall, the trends are very similar between the extreme duration of zero-flow periods and the annual sum (Figure 7): on the 60 stations showing a decrease in annual sum, 45 also have decreasing trends in the maximum duration of dry spells (similar behavior is observed for positive trends). Since on average the trends affect about 30% of stations, these trends (both positive and negative) are field-significant according to the FDR procedure. The trend analysis results indicate that at the annual and seasonal timescales the majority of the detected trends are towards an increase in dryness (in about 10% to 23% of stations as shown in Table 1). At the seasonal timescale, there is a marked trend towards an increase in summer zero-flows, but fewer trends detected for winter. When comparing trends at the annual and seasonal scales, in 60 stations with a significant increase of annual zero-flow days, 46 stations also have a significant increase in summer zero-flow days. Conversely, a lower similarity between annual and winter trends is observed. Thus, it can be concluded that the summer drying is the main driver for the decreasing trends in the number of zero-flow days at the annual scale for these stations. Overall, fewer trends are detected for extreme durations compared to annual or seasonal totals (Table 1), with the notable exception of the winter maximum lengths of zero-flow days that are increasing in the majority of stations. The results of the trend analysis have been compared with catchment sizes but no relationship could be found between the trends in river intermittence and the size of the basins considered.

4.3 Links with SPEI anomalies

In the first step, a trend analysis has been performed on SPEI over the different basins for different aggregation periods 6, 12, 18 and 24 months. The results show a clear pattern with positive trends at stations located north of 45°N and negative trends in the south. These trends have been previously detected by Spinoni et al. (2017). At stations located north of 45N due to lower temperature variability, the SPIE index responds mainly to the variability in precipitation. To check if the SPEI anomalies could be explanatory covariates for the inter-annual variability of zero-flow day occurrences, the SPEI with different aggregation time has been correlated with the number of zero-flow days and the maximum dry spell lengths. Results show a strong association of zero-flow days with SPEI anomalies in particular at the annual and summer timescales, with significant correlations in more than half of the stations (Figure 8), with a lower number of significant correlations during winter. The annual or seasonal sums of zero-flow days are more strongly associated with SPEI anomalies than the maximum length of dry spells. The correlations are negative for all SPEI timescales (Figure 9), indicating that negative SPEI anomalies, i.e. pronounced net precipitation deficits, are linked with a larger number of zero-flow days. For about one-third of stations (36%), there is no significant correlations. These stations are mostly located in Spain, southern France, North Africa, Cyprus, but also Belgium, without a clear spatial pattern. Therefore, a strong spatial variability of the spatial pattern is once again evident indicating local influences on the relationship between zero-flow days and SPEI. The strength of the correlations is higher for basins with a larger annual average number of zero-flow days for almost all SPEI timescales. This demonstrates that strongly intermittent basins (i.e. basins with a large proportion of zero-flow days) are more influenced by climatic variations to determine the annual number of zero-flow days. This is probably due to the fact that these streams are often close to the wet/dry threshold and consequently immediately impacted by a variation of precipitation availability. There is also statistically a significant but moderate (rho=0.2) correlation between the strength of the correlations with the SPEI12 and basin size. This indicates that the influence of SPEI12 might be stronger for smaller basins since larger basins are more likely to be more influenced by human activities while small basins respond more quickly to precipitation and might have lower local water storage capacity. Yet, this relationship is not significant for the SPEI18 and SPEI24. Smaller basins have a reduced water storage capability in the context of climate variability so this behavior is expected.

4.3 Relations with large-scale atmospheric circulation

As the large-scale climate drivers have a low-frequency time variability, the correlation analysis should consider long time series. This is the reason why only rivers with at least 30 years of data during 1970-2010 have been considered to analyze the relationships with large scale circulation indices. The AMO and NAO indices are the most influential climate indices on zero-flow occurrences. Since very low correlations were found with the other indices, we focus the analysis of the results with AMO and NAO. At the annual scale, the AMO was the index with the highest number of positive correlations, 21% for the longest annual no-flow event and 23% for the annual sum. Results for both metrics in seasons are presented in Table 2. The summer and the winter AMO are the drivers with the strongest links to the summer and winter metrics. A cluster of rivers positively associated with the winter AMO is well recognizable in northern Europe (Norway, Finland) for both winter metrics (Figure 10). Northern regions including the UK and south Sweden exhibit a negative link between winter AMO and the winter sum of zero-flow days. A similar pattern is observed for the summer with annual AMO. Additionally, the southern Mediterranean part of Europe might be positively influenced by the summer AMO.

The conclusion can be drawn that the AMO is a potential driver of the intermittence in about 20% of stations and its influence can be stretched to the following season. The associations with the NAO are less frequent. However, the apparent cluster of rivers with a negative link to the winter NAO can be observed in the Scandinavian Peninsula for both winter metrics (Figure 10). The rivers positively linked to JJA NAO are scattered over Europe. It is worth emphasizing that this large-scale climate effect can be hidden by more local climate conditions. The relationship between climate drivers and hydrological characteristics in Europe has been previously documented by many researchers (e.g., Valty et al. 2015, Wrzesiński & Paluszkiewicz 2011). Results of the present analysis are to a large extent consistent with results obtained by Hurrell and Folland (2002), Linderholm et al. (2009), Giuntoli et al. (2013) indicating that the NAO and AMO could influence hydrological droughts.

5. DISCUSSION AND CONCLUSIONS

This study provides the first European-scale assessment of the trends in river intermittence over the last decades. The most striking results are (i) the strong spatial variability of the detected trends, and (ii) the seasonality and relationships with climate drivers. Overall, there is considerable spatial variability of flow intermittence. Snelder et al. (2013) previously observed over France that the high spatial heterogeneity in small-scale processes associated with intermittence partly explains the low spatial synchronization of zero-flows. Significant trends are detected in about 30% of stations, with most of detected trends towards an increasing number of zero-flow days, tending to occur earlier in the season, in particular around the Mediterranean basin. For most basins, there is a strong association of zero-flow days with SPEI negative anomalies, but neighbouring basins may exhibit different relationships showing again the strong spatial variability. This indicates that the SPEI could be a valid predictor for zero-flow occurrence, and the decreasing trend in this indicator observed over southern Europe may explain the trends in flow intermittence obtained in this study. Recent studies have shown that these downward trends in SPEI are mostly explained by an increase in the atmospheric evaporative demand rather than a decline in precipitation (Vicente-Serrano et al., 2020, Peña-Angulo et al., 2020). In a climate change context with increasing temperatures, it is likely that this trend will continue in the future, with a possible increase in river intermittence for these regions.

The strong spatial variability observed on trends in intermittence characteristics implies that regional predictions or generalizations for flow intermittence patterns should be interpreted with caution. Any mapping or extrapolation from such regional results may be prone to considerable errors if not considering basin characteristics that are likely to play a strong role in determining flow intermittence properties. In this study, the individual catchment characteristics (i.e. topography, geology, land use, soil types) have not been analyzed, which would require a major work at such a continental-wide scale. Catchment characteristics may be helpful to distinguish the different patterns in flow intermittence since, as shown in this study, the geographical location or basin sizes do not exert a strong control on river intermittence. In particular, it would be particularly interesting to distinguish basins with strong surface-groundwater interactions that could explain some of the patterns described in the present study. However, as noted by Snelder et al. (2013), flow intermittence is also controlled by processes operating at scales smaller than catchments, thus capturing these processes would require a much more detailed investigation than classical regional approaches to take into account the local physiographic characteristics (Tramblay et al., 2010).

A major uncertainty of the present work and, to a greater extent, applicable to all ecohydrological research on intermittent rivers is the definition of the zero-flow days and the lack of regional representativeness of the monitoring networks. With regard to the first aspect, there is a wide variety of measurements procedures in different European countries, leading to different accuracy of the measured discharge values, in particular the minimal values. For example, in the UK or in France the data is provided in $m^3.s^{-1}$ with an accuracy of three decimals, but for many other countries, the minimum reported discharge is sometimes much greater than 1 $L.s^{-1}$ due to different measuring methods. In addition, many rating curves at open channel stations have uncertainty at low flows caused by instability of the riverbed. In the present work, we considered a strict criterion to identify zero-flow days, but a more adequate selection could be made possible if good quality metadata information were available for most rivers, which is not currently the case for several countries. With regard to the second aspect of regional representativeness, several studies have highlighted the lack of measurements for intermittent rivers (Skoulikidis et al., 2017, Costigan et al., 2017). The number of monitored head water streams which are likely to be intermittent is indeed much smaller than the number of perennial and large streams in national and international databases, although their contribution to the water resources is probably high. This questions the rationale behind national measurement strategies for intermittent streams, in particular, the most ephemeral ones, since they may be overlooked in water resources management in comparison to perennial streams. Depending on the national monitoring strategies of the river network, it is possible that the selection of intermittent rivers to be monitored may be biased towards a specific type of rivers within a given geographic location of geological properties.

Another important aspect to take into consideration is the regulation status of the monitored rivers, which may evolve over time and not be available in the stations' metadata. In the present work, the selected basins are those described as natural or weakly altered based on their metadata information. Yet, how to quantitatively define "weakly altered" between different national networks and monitoring protocols? This definition may differ from one country to another without a common objective criterion to define the percentage of natural discharge being diverted or used for water supply. Besides river alterations, often assumed to be an expert judgement, the quantitative evaluation of the water uptake would require extensive work to monitor and collect water consumption data over time. Even for a river considered to be unaltered, diffuse groundwater pumping may occur and therefore have impacts on the groundwater-surface interactions, which could in turn strongly impact intermittence occurrence. Two examples of the influence of river status as described in the metadata on the trend results may be found in the UK. The Coal Burn River is classified as broadly natural but is an experimental catchment set up to assess the impact of afforestation and the trend analysis indicates an increase in zero-flow days, showing that the influence of land-use change might indeed be significant on this aspect of the flow regime. The limestone Slea River that conversely experienced a decrease in zero-flow days was also classified as natural, but further scrutiny revealed a discharge augmentation scheme installed in 1995. Taking into account all these local specificities in addition to the available metadata would require tremendous effort and the information may not always be as readily available. The main findings of the present study are an incentive to implement process-based studies on the intermittence characteristics for different climatic and physiographic environments taking into account watersheds characteristics.

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Data Availability Statement

The different indices computed in the present work are made available to the community for research applications upon request to the first author.

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TABLES

Table 1: Summary of the detected trends in the annual and seasonal number of zero-flow days and the maximum length of dry spells

Variable	Positive trends	Negative trends	No trends
Annual sum	23,62%	10,24%	66,14%
Annual maximum	20,08%	8,66%	71,26%
Winter sum	10,63%	8,66%	80,71%
Winter maximum	23,23%	9,45%	67,32%
Summer sum	23,62%	6,69%	69,69%
Summer maximum	18,11%	9,45%	72,44%

Table 2: Summary of catchments with significant correlations ($\alpha = 0.05$) between seasonal metrics of intermittence and large-scale climate drivers. The subscripts s, w, DJF, JJA, $w1$ refer to the summer (Apr-Sep), winter (Sep-Mar), Dec-Feb, Jun-Aug, and winter from the preceding year, respectively.

a)	Positive correlations		Negative correlations
Variable	AMO_s	AMO_w	NAO_{DJF}
Winter max	18%	16%	11%
Winter sum	21%	19%	11%

b)	Positive correlations		
Variable	NAO_{JJA}	AMO_s	AMO_{w1}
Summer max	11%	21%	18%
Summer sum	9%	22%	21%

FIGURES CAPTIONS

Figure 1: Number of stations having less than 5% missing data each year (left) and catchment sizes (right)

Figure 2: Mean annual percentage of zero-flow days for hydrological years

Figure 3: Cluster analysis on zero-flow seasonality. Colors represent seasonality of zero-flow events classified in three clusters (winter, summer, fall clusters).

Figure 4: Flow regime (left) and mean occurrence of zero-flow days (right) for the three clusters identified in figure 3.

Figure 5: Significant increasing (later date) or decreasing (earlier date) trends in the mean date of zero-flow day occurrence, at the 10% significance level.

Figure 6: Increasing (red triangle up) or decreasing (blue triangle down) trends, at the 10% significance level, for the annual or seasonal mean number of zero flow days (left), the annual or seasonal maximum length of dry spells (right). On average for all indicators and seasons, 28% of stations have significant trends.

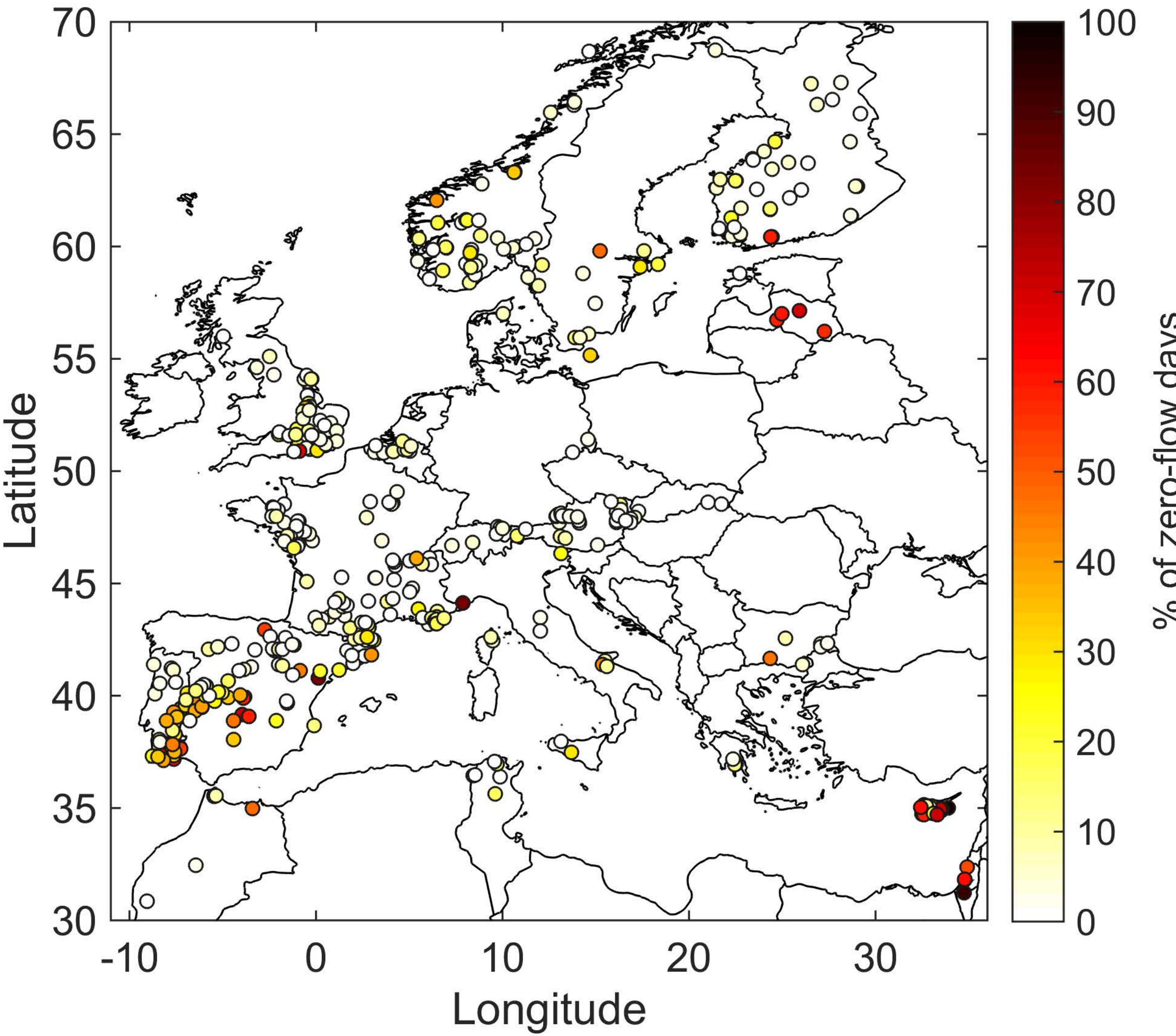
Figure 7: Scatter plot of the relationship between the Sen slope of trends in the annual number of zero-flow days and the annual maximum duration of zero-flow periods.

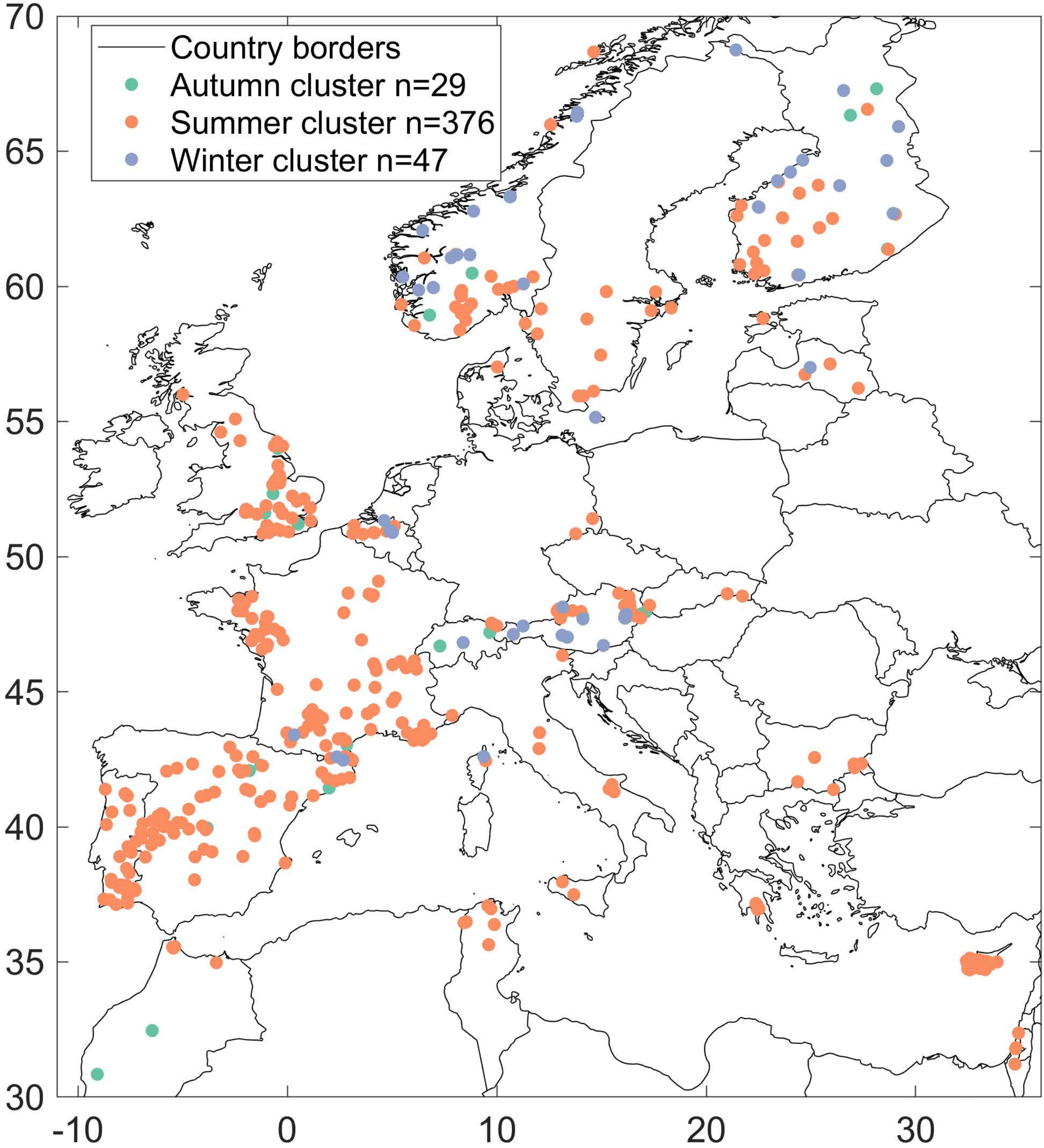
Figure 8: Significant correlations at the 5% level between annual, summer and winter sum of zero flow days, and the maximum length of dry periods with SPEI6, SPEI12, SPEI18 and SPEI24.

Figure 9: Map of the significant correlations between the annual sum of zero flow days (top) and the annual maximum length of zero flow days (bottom) with the SPEI18. The black crosses indicate stations where the correlation is not significant at the 10% level. Correlations are negative because the smaller the SPEI (water deficit), the larger the number of zero-flow days.

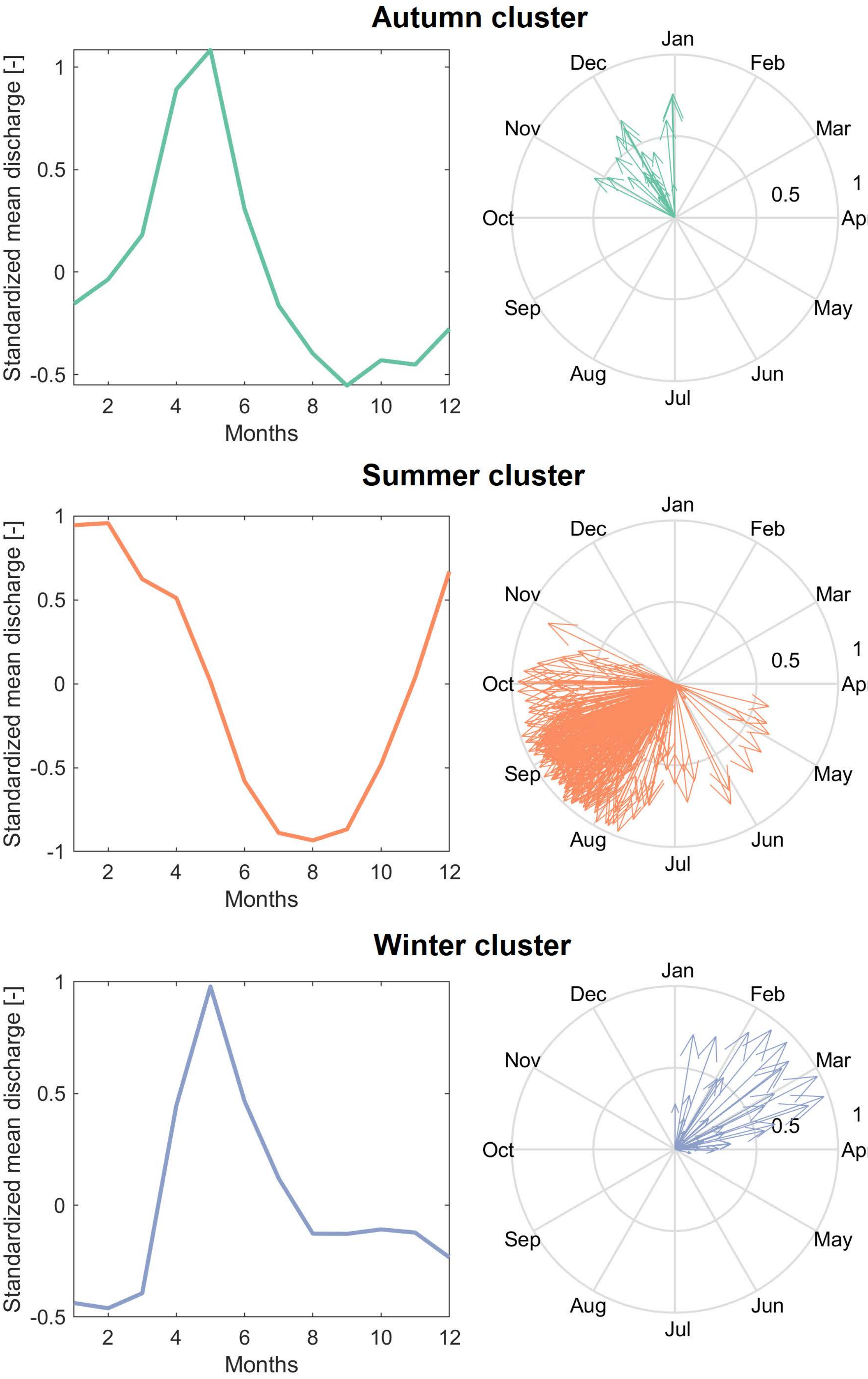
Figure 10: Significant correlations between summer zero-flow days and AMO (left) and between winter zero-flow days and NAO (right).

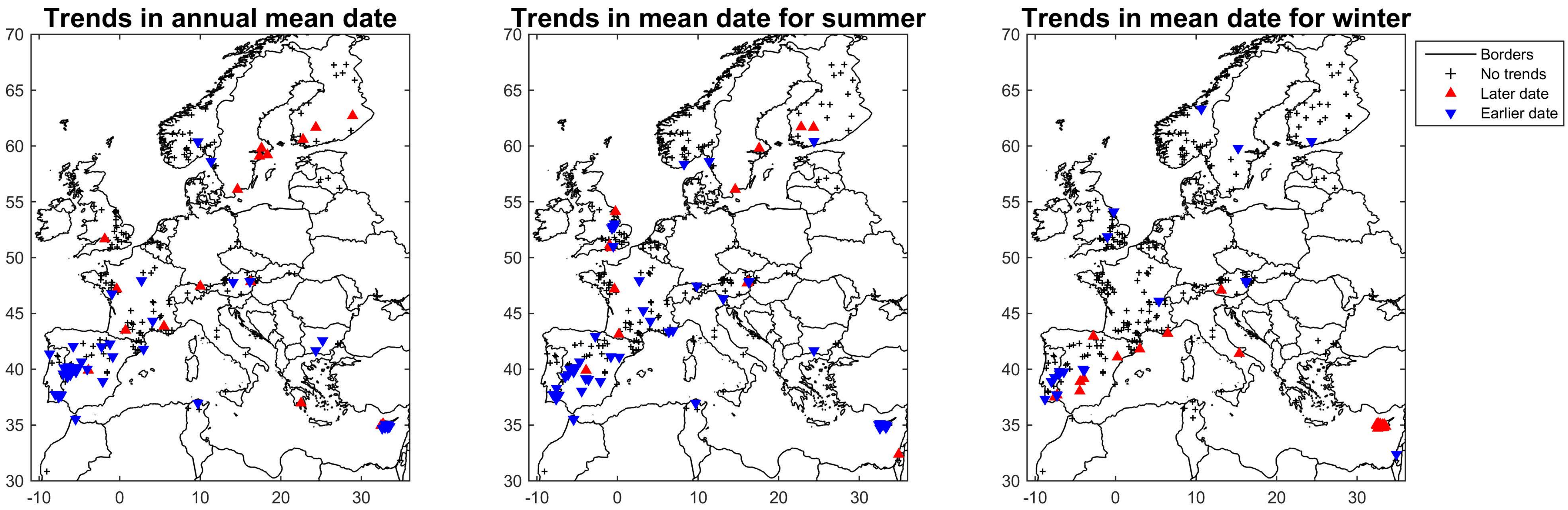

Proportion of stations
Years
1970
1975
1980
1985
1990
1995
2000
2005
0.4
0.5
0.6
0.7
0.8
0.9
1
Number of stations
Catchment size [km²]
0-10
10-50
50-200
200-500
500-1000
1000-2000
0
50
100
150

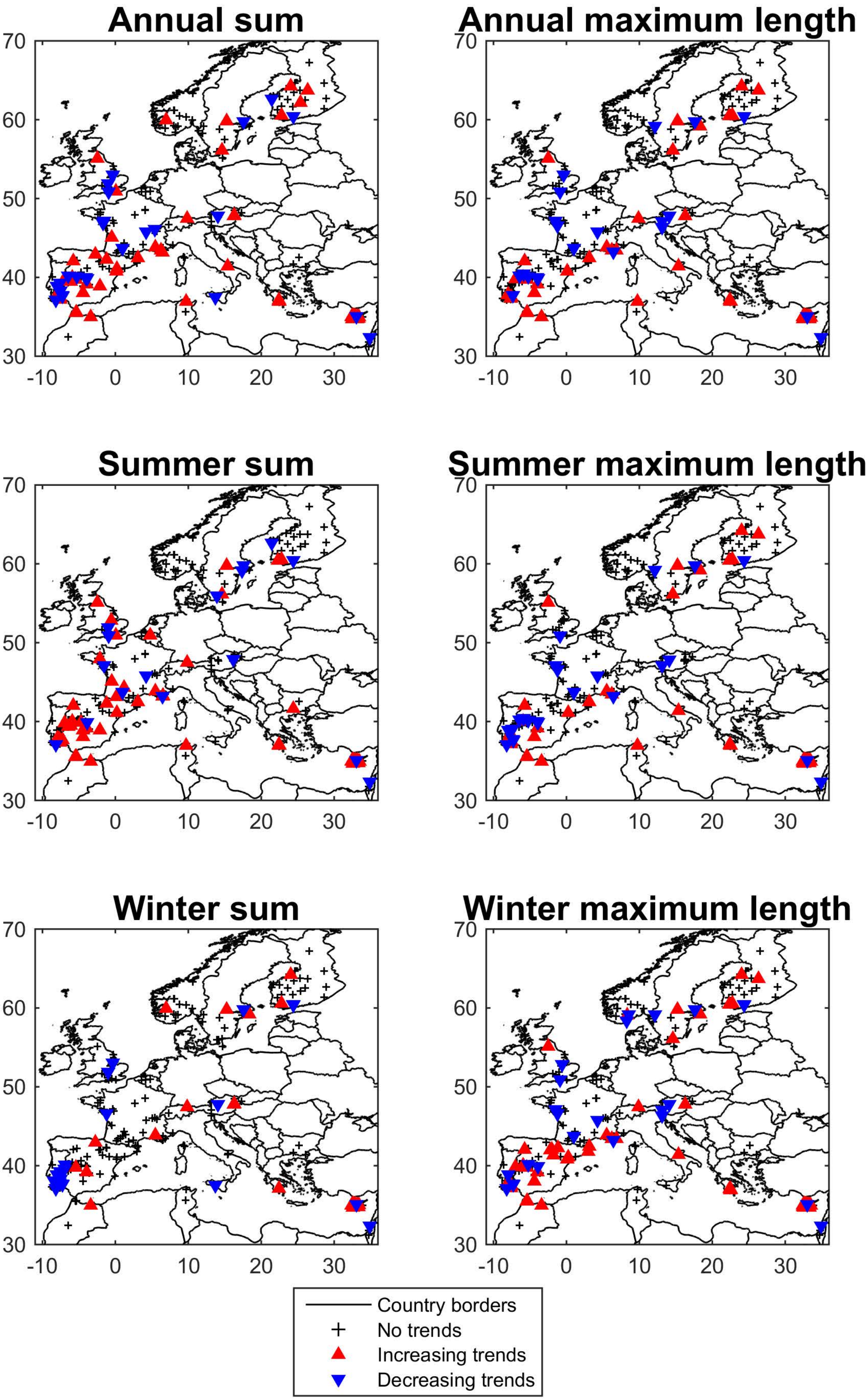

70
65
60
55
50
45
40
35
30
Latitude
-10
0
10
20
30
Longitude
100
90
80
70
60
50
40
30
20
10
0
% of zero-flow days

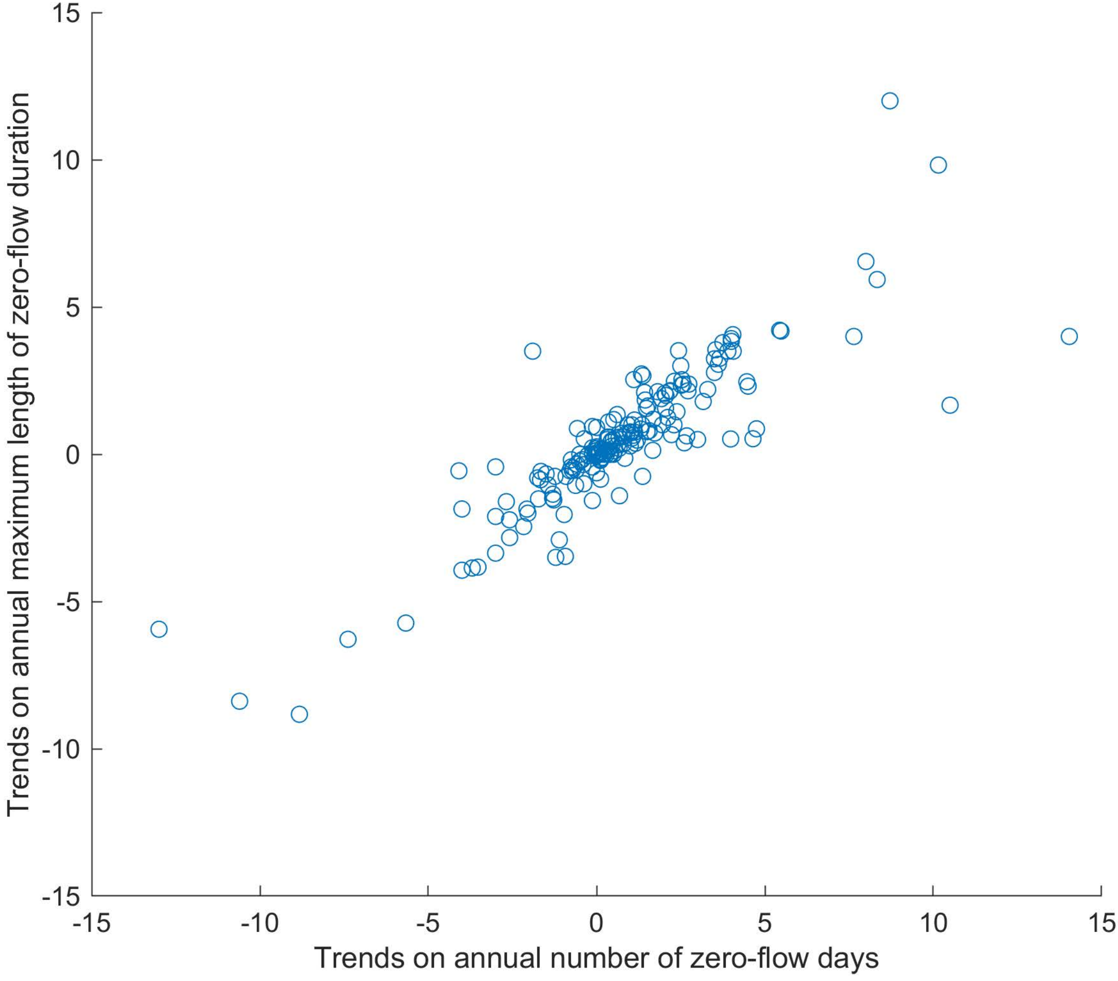


Country borders
Autumn cluster n=29
Summer cluster n=376
Winter cluster n=47
70
65
60
55
50
45
40
35
30
-10
0
10
20
30

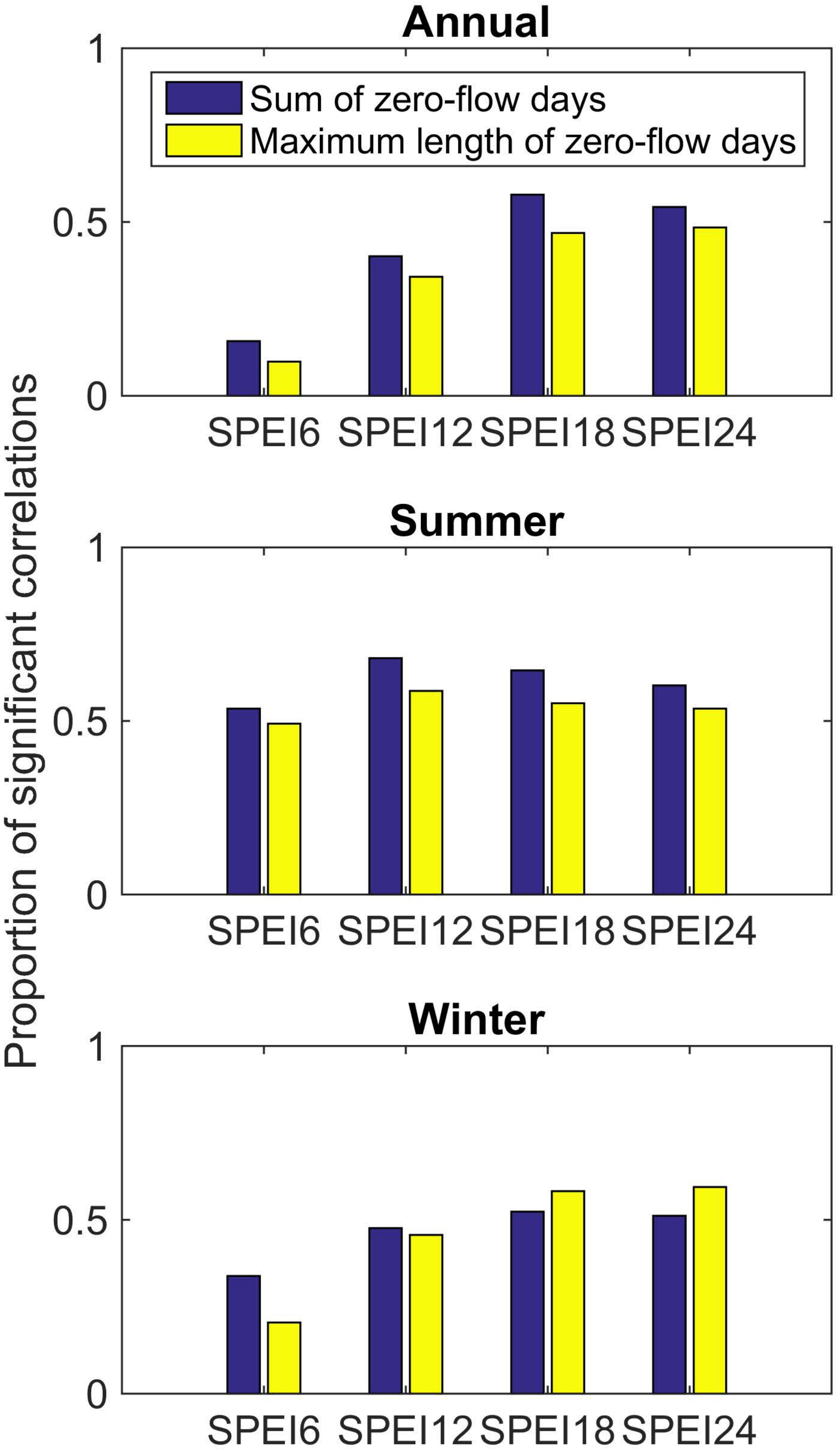

Autumn cluster
Summer cluster
Winter cluster
Standardized mean discharge [-]
Months
1
0.5
0
-0.5
-1
2
4
6
8
10
12
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec


Trends in annual mean date
Trends in mean date for summer
Trends in mean date for winter
70
65
60
55
50
45
40
35
30
-10
0
10
20
30
Borders
No trends
Later date
Earlier date


Annual sum
Annual maximum length
Summer sum
Summer maximum length
Winter sum
Winter maximum length
70
60
50
40
30
-10
0
10
20
30
Country borders
No trends
Increasing trends
Decreasing trends

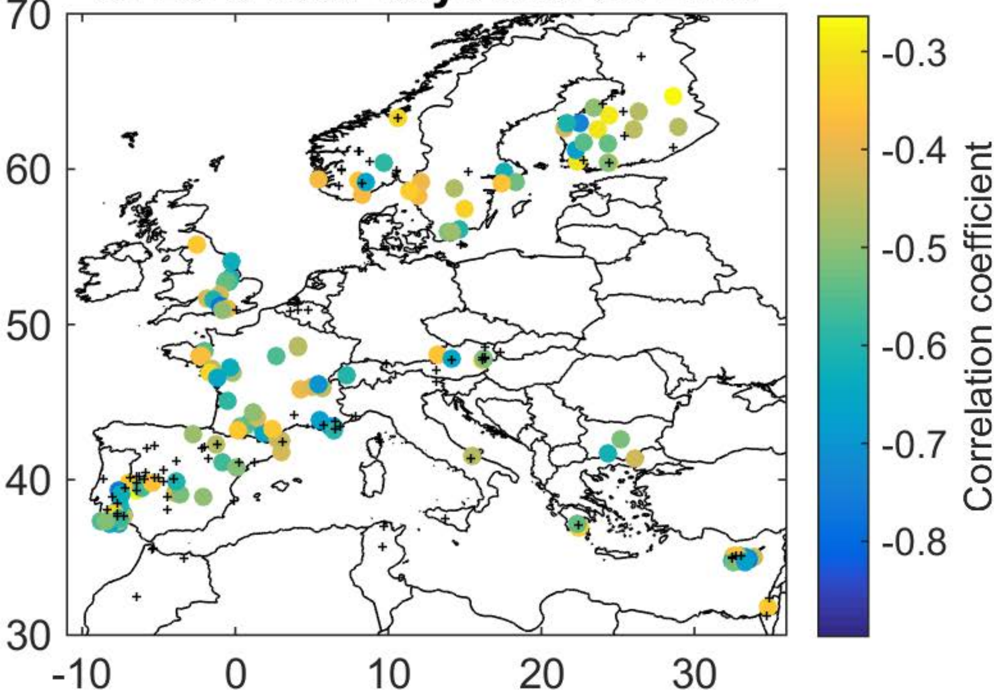


Trends on annual maximum length of zero-flow duration
Trends on annual number of zero-flow days
15
10
5
0
-5
-10
-15
-15
-10
-5
0
5
10
15

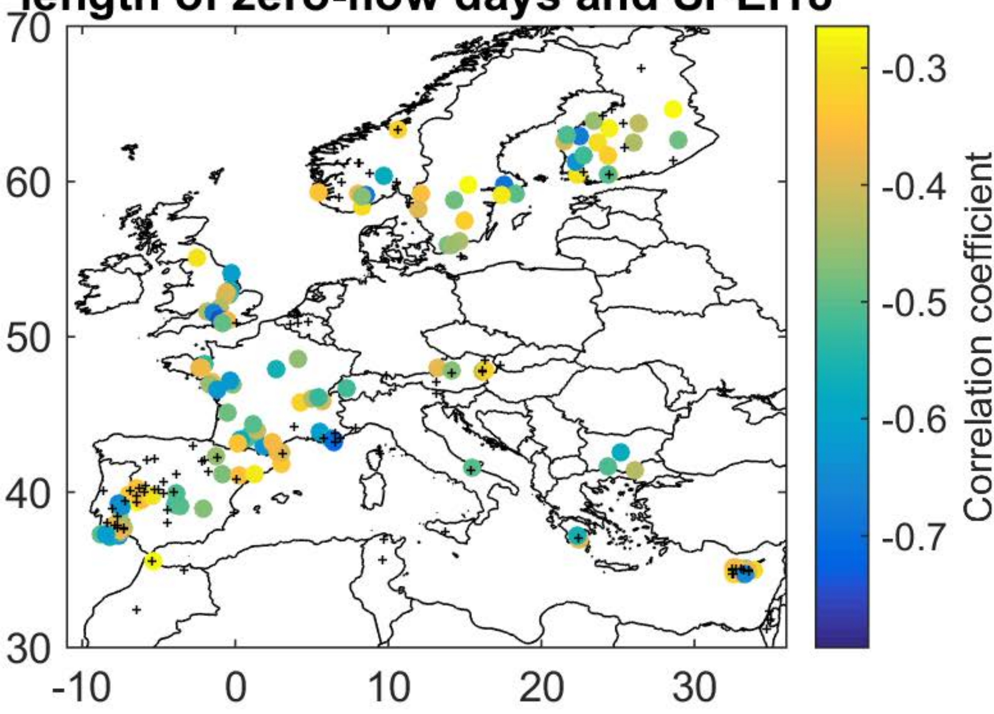


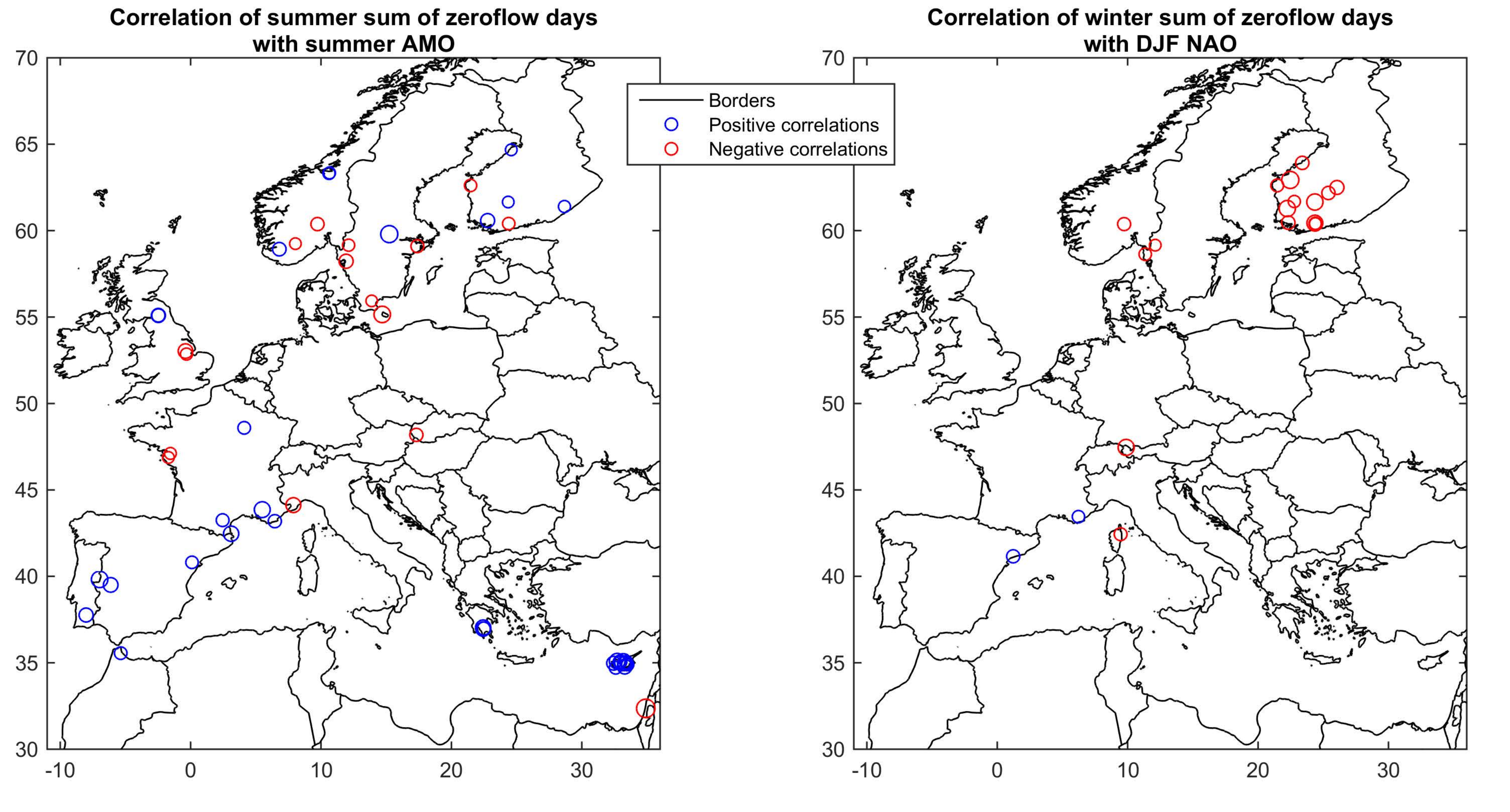
Annual
Summer
Winter
Sum of zero-flow days
Maximum length of zero-flow days
Proportion of significant correlations
1
0.5
0
SPEI6
SPEI12
SPEI18
SPEI24

Correlation between annual sum of zero-flow days and SPEI18



Correlation between annual maximum length of zero-flow days and SPEI18




Correlation of summer sum of zeroflow days
with summer AMO
Correlation of winter sum of zeroflow days
with DJF NAO
Borders
Positive correlations
Negative correlations
70
65
60
55
50
45
40
35
30
-10
0
10
20
30