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4.2. Hydrological drought impacts at the European level

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PART 1. Spatial and temporal variation in hydrological droughts across Europe.

1. Introduction

Drought is one of the most damaging and recurring natural hazards, with devastating socioeconomic, ecological and even political impacts (Von Uexkull et al., 2016, Wilhite and Pulwarty 2017, Ide 2018). Characterizing the severity and risk of drought is not an easy task, given that drought events are rarely confined to a single location; instead, they can affect large areas and extend over months, years, or even decades (Van Loon, 2015). Moreover, drought evolution is influenced by a variety of hydrometeorological variables (e.g. precipitation, evapotranspiration, runoff), which imposes further complexity on drought assessment (Mishra and Singh, 2010, Sheffield et al., 2012). In this context, there are different types of drought: meteorological, hydrological, agricultural, and socioeconomic (Mishra and Singh, 2010, Cayan et al., 2010, Wilhite, 2000). Among them, hydrological droughts are of particular concern for policy makers, due to the reliance of society and ecosystems on water availability in rivers and aquifers (Parry et al., 2005, Van Loon, 2015, Rivera et al., 2021).

Hydrological drought is associated primarily with lack of water in hydrological systems, as evidenced by abnormally low streamflow, or deficits in levels of lakes, reservoirs or groundwater (Tallaksen and van Lanen, 2004). Other sectors may be impacted by these abnormal hydrological conditions, including the quality of aquatic and riparian habitats, water quality, water supply for domestic, agricultural and industrial uses, riverine transport and hydropower production, among others (Parry et al., 2012). Due to recent climate change and variability, as well as unprecedented rates of urbanization, industrialization, and population growth, these negative impacts have accelerated in recent decades (Dai, 2021).

Although drought is driven mainly by lack of rainfall, other factors (e.g. atmospheric evaporative demand, storage in ice and snow, land use change) can also play a role in the occurrence of hydrological drought (Van Loon and Laaha, 2015, Avanzi et al., 2019). Numerous studies indicate that the projected decrease in precipitation across many regions worldwide, particularly in the subtropics, accompanied by a more general increase in atmospheric evaporative demand and thus evapotranspiration, will likely accelerate the severity of hydrological drought in the coming decades on a global scale (Prudhomme et al. 2014, Dai et al. 2021, Diffenbaugh et al., 2015). Furthermore, anthropogenic climate change will intensify the hydrological cycle including its seasonal and year to year variability (Allan et al., 2020) and influence atmospheric/oceanic circulation (Bardossy and Caspary, 1990, Hurrel and Van Loon, 1997), likely inducing significant changes in streamflow regimes and climate extremes like drought (IPCC, 2013, Dai et al. 2021, Spinoni et al. 2014), even in those regions which on average will become wetter in a warming world.

In Europe, there is increasing interest in studies examining long-term changes in hydrological droughts in order to detect any emerging trend that could be linked to climate change processes (Hannaford, 2015). Earlier studies mostly focused on hydrological drought trends on a regional scale (e.g. Wilson et al., 2010, Lorenzo-Lacruz et al., 2012, Myronidis et al., 2018, Harrigan et al 2018, Wu et al., 2018). Unfortunately, the few investigations conducted on hydrological drought trends at a continental scale have employed only a sparse network of gauges (e.g. Fleig et al., 2006, Van Lanen et al., 2013, Hisdal et al. 2001). Exceptionally, Hisdal et al. (2001) characterized hydrological droughts by analysing trends for 612 gauging stations in Europe spanning different periods between 1962 and 1995. They found that it is difficult to conclude that drought conditions have become more severe or frequent in Europe. Later, Stahl et al. (2010) assessed streamflow trends (but not explicitly drought indicators) from 1962 to 2004 using 441 gauging stations across 15 European countries – this dataset is selective by design, to focus on 'near natural' catchments that are free of major human impacts on low flow regimes. In terms of streamflow trends across Europe, Stahl et al. (2010) found two dominant spatial patterns: increasing streamflow (and low flows) in western and northern Europe and the opposite pattern in southern and central Europe. Based on a network of 1874 gauges from Ireland, the United Kingdom, France, Spain, and Portugal, Vicente-Serrano et al. (2019) found that the physical drivers of streamflow trends (specifically on annual average flows) vary considerably between northern and southwestern Europe – increases in the north are strongly climate-driven while in the south irrigation and land cover influences play a role as well as climate.

However, while these studies have provided some large-scale context for potential changes in hydrological drought, the transferability of conclusions is limited by the relative sparseness and geographical biases of the datasets, particularly given the predominance of data from northern and western Europe and relative lack of coverage in the east and south. At the same time, strong spatial variability of hydrological droughts in various parts of Europe has been linked to different local/regional characteristics (Lorenzo-Lacruz et al. 2013; Barker et al. 2016). A quick inspection of these studies therefore highlights the need to analyze long-term changes of hydrological droughts from a wide continental perspective. This assessment is useful for better understanding the general patterns and regional divergences of hydrological drought trends and accordingly a proper characterization of the drivers of these changes at various spatial scales across Europe.

In the present study, we employ a newly developed long term (1962-2017) and dense (N=3,224) network of gauging stations across Europe to investigate whether, in the context of climate change, hydrological droughts show distinct temporal and spatial changes across the continent. Our findings can contribute to more effective planning and management of water resources in Europe and a reliable assessment of the different impacts of drought on society and environment.

2. Data and Methods

2.1. Data

Monthly streamflow data were obtained from national and international hydrometric, scientific and water management agencies across Europe: Agencia Catalana de l´Aigua (Spain), Centro de estudios y experimentación de obras públicas (Spain), Confederación Hidrográfica del Guadalquivir (Spain), Ministerio para la Transición Ecológica (Spain), Environmental Protection Agency (Ireland), Ministère de l'Ecologie, du Développement durable et de l'Energie (France), Sistema Nacional de Informacao de Recurso Hídricos (Portugal), National River Flow Archive (UK), Global Runoff Data Centre (WMO). In addition, data was obtained from the gauging stations published in the study of Vicente-Serrano et al (2019). For the period 1962 to 2017, data from a total of 5,529 stations were available (Figure 1a). Gauging stations are present in catchment with different geographical characteristics, and some are natural, while others are regulated. As gaps were present in many series, reconstruction was undertaken following the methodology described by Vicente-Serrano et al (2019). Specifically, a reference series was created for each target (candidate) station using data from nearby stations located no more than 100 km away, with a common period of at least 7 years, and a Pearson's r correlation greater than 0.7. Series with at least 75% of data available for the years 1962-2017 were retained.

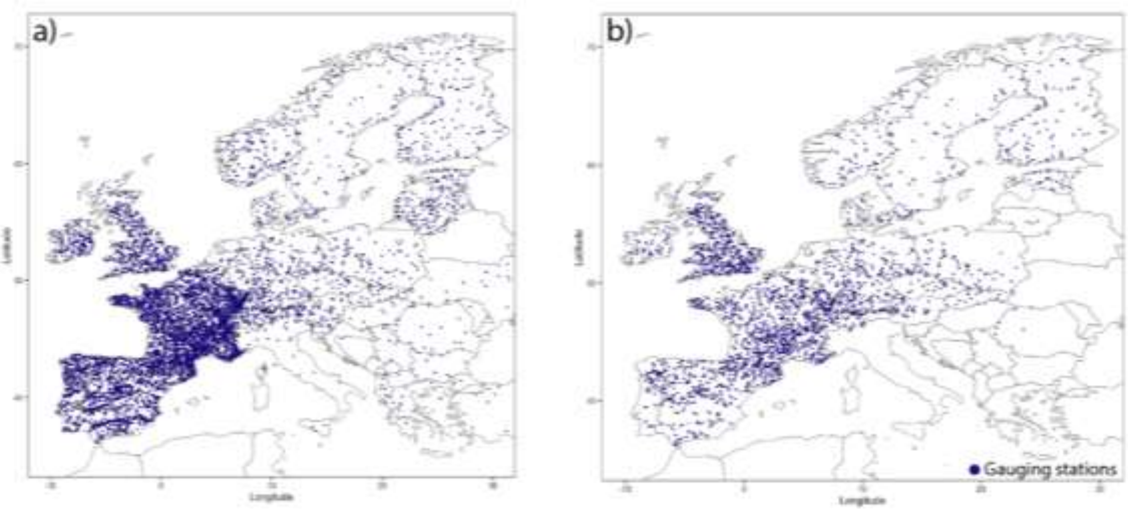

Figure 1. *Spatial distribution of the gauging stations in the study area: a) the full database of stations collected from different sources of information, and b) the selected stations retained for analysis.*

As observed by Vicente-Serrano et al. (2019), the first decade of the study period is associated with the highest proportion of reconstructed data. Accuracy statistics for the reconstruction process were evaluated using the Percentage Bias and Pearson's r derived from the comparison between observed and reference series. In general, the comparison of observed and predicted monthly streamflow datasets yielded positive results, with more than 90% of reconstructions returning a Pearson's r > 0.70). For the years 1962 to 2017, a total of 3,324 stations were included in the final data set, evenly distributed throughout Europe (Figure 1b).

2.2. Methods

2.2.1. Hydrological drought quantification

A hydrological drought is defined as a time period with streamflow below a predetermined threshold that can be related to water deficits (Fleig et al. 2006). The Standardized Streamflow Index (SSI) was used to identify hydrological drought events (Barker et al., 2016). This index compares hydrological drought in different locations irrespective of flow magnitude or river regime characteristics. The monthly streamflow series was transformed into standardized z-scores (Lorenzo-Lacruz, et al., 2013). To obtain a reliable SSI that encompasses large variability in the statistical properties of the monthly data, the series were fitted to the most suitable probability distribution, according to the minimum orthogonal distance between the sample L-moments at site i and the L-moment relationship for a specific distribution, selected from among the general extreme value, the Pearson Type III, the log-logistic, the log-normal, the generalized Pareto and the Weibull distributions. For each streamflow series six SSI series were calculated, corresponding to each of the six probability distribution used, with the selected series showing the most robust adjustment (minimum orthogonal distance in L-moments diagram). After calculating SSI, a threshold of -0.84 was applied to identify the onset of hydrological drought events. This threshold corresponds to the expected event with a return period of 5 years (Lorenzo-Lacruz et al. 2013).

The severity, frequency, and duration of droughts associated with the identified hydrological events were quantified (Van Loon, 2015). Specifically, the frequency is defined as the number of events per year, while the duration of an event refers to the number of months from onset (SSI = -0.84) to termination (SSI = 0). Drought severity was defined as the absolute value of the integral area between the value of the SSI at drought onset and termination in the period comprising the duration of an event (Spinoni et al., 2014, Fleig et al., 2006, Lorenzo-Lacruz et al., 2013).

2.2.2. Spatial regionalization

In order to identify homogeneous regions in terms of the evolution of hydrological droughts, we used a spatial classification approach. We applied a cluster analysis, with the aim of grouping variables with similar properties based on similarities or differences between feature vectors in a data set (Dikbas et al., 2013). In this study, the K-Means clustering method was applied to define homogeneous groups (clusters) of gauging stations according to their monthly SSI. By minimizing the Euclidean distance between each variable and the nearest cluster centre, the K-Means method divides the data set into K clusters (Steinley, 2006). To identify a reasonable number of clusters, we applied a set of performance indicators, including the within-cluster sum of square errors (WSS) metric and post-visualization (El Kenawy et al., 2013, Zhang et al., 2016).

In the cluster analysis of the monthly SSI a significant seasonal variability is present. However, in the hydrological drought trend analysis, we are interested in extracting the general behavior. For this reason, the gauging stations have been grouped into independent clusters of seasonality, and each station has been assigned to the cluster more frequently in most months. Lastly, in each cluster, the gauging station that shows the highest correlation with the rest of the stations was selected as representative to analyze the time series in detail.

2.2.3. Trend analysis

We analyzed the magnitude of change in the monthly SSI, as well as the annual duration, frequency and severity of drought events, over the period 1962-2017 using the Ordinary Least Squares regression method (Moberg et al., 2006). The statistical significance of these changes was tested using the modified Mann-Kendall test (Hamed and Ramachandra Rao, 1998) which allows for consideration of autocorrelation by returning the corrected probability values after accounting for temporal pseudo-replication (Hamed and Ramachandra Rao, 1998, Kiktev et al., 2003, Alexander et al., 2006). To visualize the findings, positive/negative trends were presented in red/blue colours, while the significance of trends, following the Mann–Kendall test, was grouped into three main categories: non- significant, significant at $p < 0.05$, and significant at $p < 0.01$. Finally, we obtained the percentage of gauging stations with positive/negative and significant/non-significant trends for each cluster of the monthly SSI and for changes in the characteristics of drought events.

The false discovery rate (FDR) procedure is applied to the Mann-Kendall test results of the monthly SSI to check if the trends are regionally significant (Tramblay et al., 2019). The detected trends are regionally significant if at least one local null hypothesis is rejected according to the regional significance level (Wilks, 2016). For consistency with the local trend analysis, the global significance level is also set to 5% in the FDR procedure. This study shows the percentage of stations that show a significant trend (p-value<0.05 and p-value adjust<0.05) for in the SSI month.

3. Results

3.1. Features of the Monthly Streamflow of Europe Dataset and map viewer (MSED)

The reconstructed monthly streamflow of 3224 gauging stations for Europe in the 1962-2017 period are included in the MSED map viewer. The MSED map viewer includes the location and the graphic representation of the temporal serie (hm3/month) of 3224 gauging stations. All information available in the MSED map viewer can be downloaded in txt format, freely available on the website http://msed.csic.es/, maintained by the Spanish National Research Council (CSIC). The folder download has geographic information (coordinates, altitude, country and source of data) and information on the reconstructed monthly streamflow (hm3) of each station.

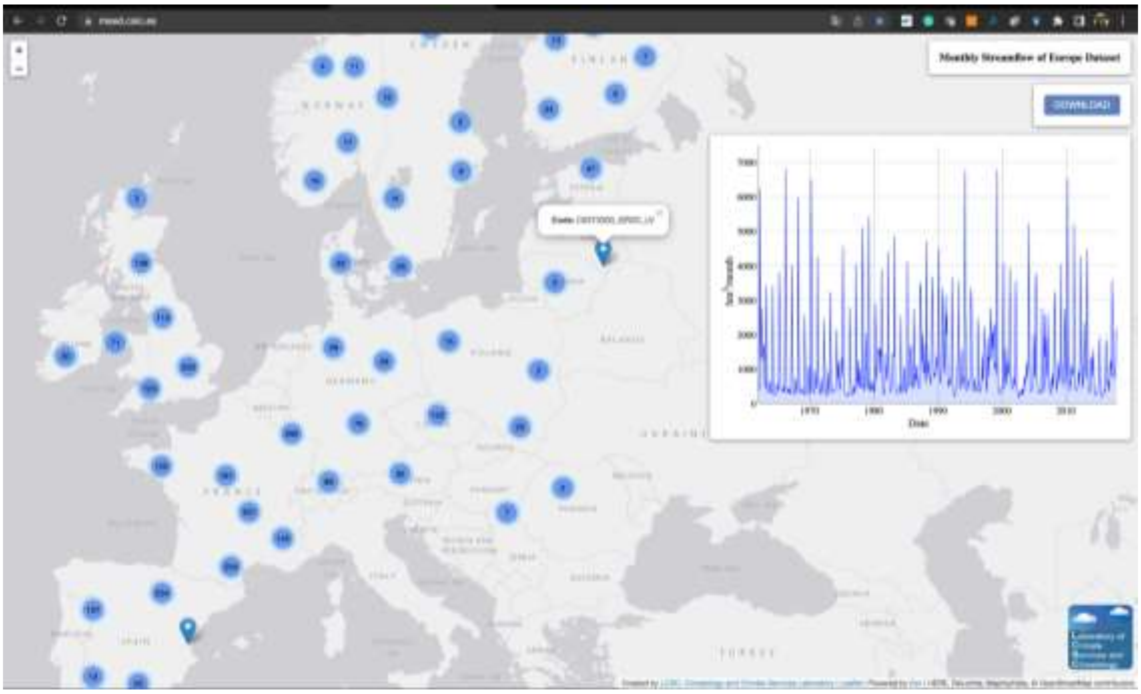

Figure 2. *Monthly Streamflow of Europe Dataset (MSED) map viewer.*

3.2. Spatiotemporal characteristics of monthly streamflow in Europe

Monthly SSI series were clustered into six homogenous regions, with similar temporal evolution from 1962 to 2017 for all months (Figure 2a). The first cluster broadly represents Great Britain across most months, apart from summer months when spatially this cluster is reduced to the north of Britain. The second cluster was assigned mainly to central Europe and is very consistent throughout the year, excluding May. The third cluster is presented in Europe's northernmost region. Norway, Sweden, Finland, Estonia, Latvia, and Lithuania are mostly occupied by this cluster, although Ireland was occasionally included in this cluster in May and from August to November. The fourth cluster is located in the Iberian Peninsula and southeast of France. This cluster is notable for maintaining a high level of spatial consistency over most months. Exceptionally, in April, it only includes the Iberian Peninsula. As compared to other clusters, the fifth and sixth clusters, which are located between the south and central Europe, showed more heterogeneous behaviour throughout the months. Specifically, the fifth cluster mostly represents northern and western France, and it occasionally includes Ireland, part of Great Britain, and southern Germany. On the other hand, the sixth cluster represents the south of France; its spatial extent varies from one month to another.

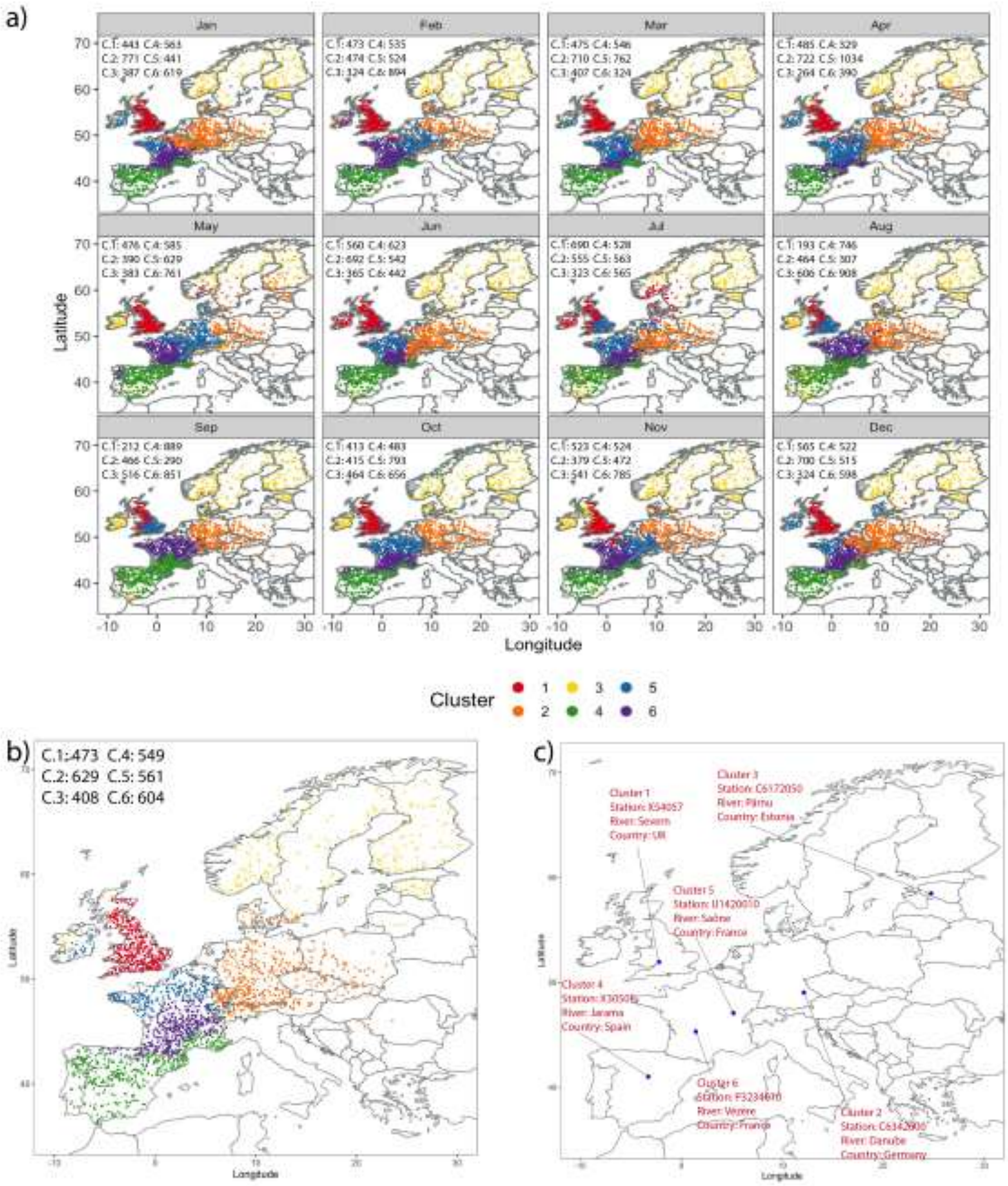

__Figure 3.__ Spatial distribution of a) the six clusters corresponding to monthly SSI (the number of gauges in each cluster is also noted), b) the six generalized clusters summarized from the cluster most frequent in the monthly SSI, and c) the gauging stations selected as representative of the monthly SSI series in each cluster.

From the cluster analysis of the monthly SSI series, six cluster groups are obtained. These cluster groups are relatively spatially homogeneous, although, some seasonal variations are observed. The general spatial patterns of the cluster analysis were obtained by assigning the most frequent monthly cl uster to each gauging station (Figure 2b). Cluster 1 corresponds to Great Britain, cluster 2 spans a wide region in central Europe, cluster 3 occupies northern Europe and the west of Ireland, cluster 4 corresponds to the Iberian Peninsula and southeast France, cluster 5 spans the north and west of France and the east of Ireland, cluster 6 represents central and southern France.

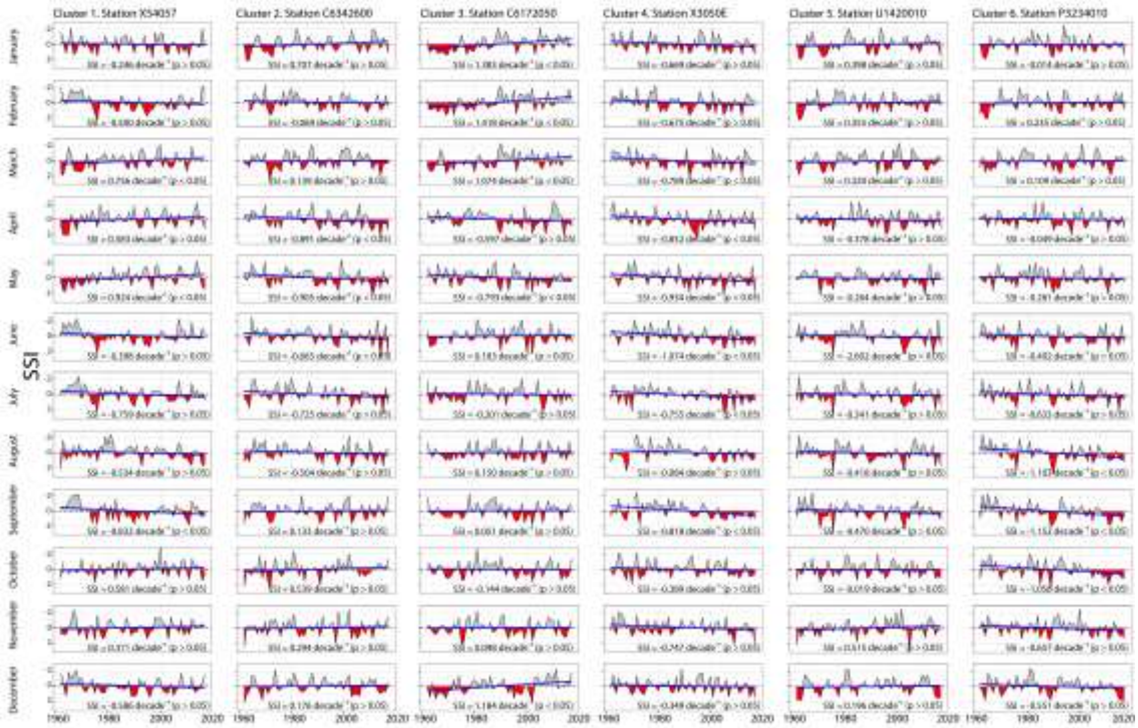

Figure 4. *Temporal evolution of the monthly SSI for each cluster. The magnitude of change, the p-value and positive (grey) / negative (red) SSI values are presented for each panel.*

Subsequently, the gauging station in each cluster that shows the highest correlation with the rest of the stations was selected in order to analyze the time series in detail (Figure 2c). Figure 3 depicts the temporal evolution of monthly SSI for the six representative gauging stations of each clusters. For the first cluster, the X54057 station (Severn River, Great Britain) exhibited a slight negative trend (a decrease in streamflow) from June to February, while a positive trend (an increase in streamflow) was noted during springtime (March, April and May). The second cluster is represented by the C6342600 station, Danube River, Germany. We noted two patterns for this station: a positive trend from September to March, and conversely a negative trend from April to August. For the third cluster, two temporal patterns were observed for the C6172050 station (Pärnu River, Estonia), with a positive trend from December to March, and a negative or lack of trend from April to November. The time series of the X3050E station (Jarama River, Spain), representative of the fourth cluster, revealed a strong negative trend in SSI in all months. The fifth cluster, as represented by the U1420010 station (Saône River, France), exhibited two contrasting trend patterns: a positive trend from November to March, and a negative trend from April to October. Finally, the sixth cluster shows the time series for the P3234010 station (Vèzére River, France), with a dominant negative trend during June to December.

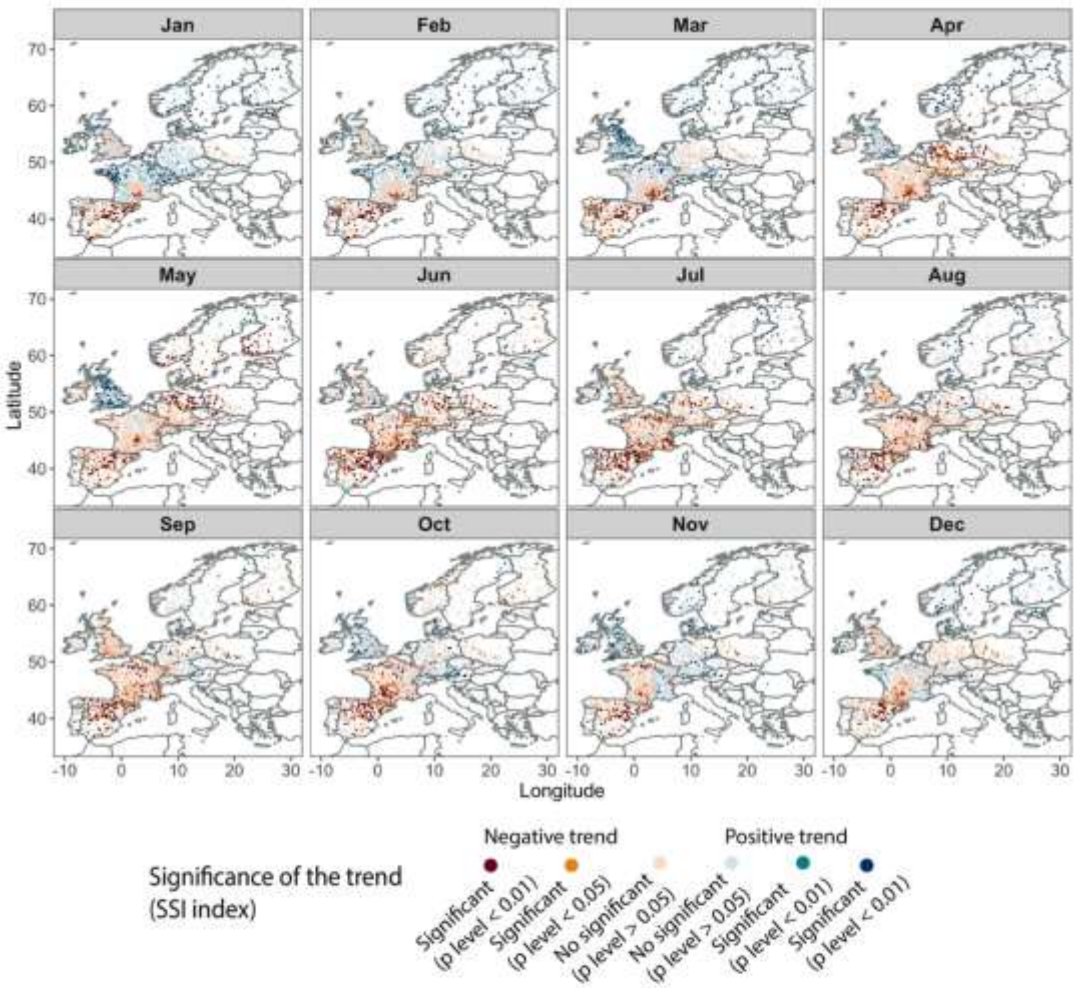

Figure 5. *Spatial distribution of the direction and significance of the trends in monthly SSI over the 1962-2017 period. Each circle represents one gauging station.*

A high percentage of stations show a significant trend (adjusted p-value ($p<0.05$)) for monthly SSI. Figure 5 illustrates the significance of the monthly SSI trend at the station level. For the first cluster, which generally corresponds to Great Britain, SSI showed a positive trend from March to May, as well as in October and November. A negative trend dominated in winter (Dec – Feb) and in summer (June – September) when spatially this cluster is reduced to the north of Britain. More than 80% of the stations belonging to this cluster showed a positive trend during spring months, decreasing to a smaller percentage in October and November. In the remaining months (June – September), except for January and February, the percentage of stations with a negative trend exceeded those with a positive trend.

In the areas that correspond to cluster 2 (central regions of the continent), we identified two patterns of SSI trend: a positive trend from September to March, and a negative trend from April to August. More than 75% of the stations assigned to this cluster exhibited a negative trend from April to August, while a positive trend predominated in the remaining months (except for December). A similar bidirectional pattern was also noted for the third cluster (northern

Europe), with a positive trend from October to April, and a negative trend from May to September. The highest percentage of stations (more than 60%) corresponding to this cluster showed a positive trend from October to April, meanwhile negative trends dominated in the majority of stations in the rest of the year, apart from July and August. In all months, changes in SSI over the Iberian Peninsula and southeast France (cluster 4) were negative, with > 70% of stations reporting a negative trend, and in most cases, half of the gauging stations have a significant trend. Exceptionally, in December, 58% of the stations exhibited a positive trend. Two SSI patterns were noted in the regions corresponding to the fifth cluster (northern and western France and eastern Ireland): a positive trend from November to March (generally above 55% of stations), and a negative trend from April to October (>70% of stations, except for July). Finally, SSI showed a negative trend in the majority of the stations assigned to the sixth cluster in all months (south of France). In a few exceptions, the percentage of stations with positive trends were much higher in January (48%) and February (41% of stations).

3.3. Analysis of the temporal evolution of hydrological drought events characteristics in Europe

From the trend study of the hydrological drought events characteristics, we want to verify if the hydrological events have increased or decreased over time. In addition, the study proves whether these temporal changes follow a spatial pattern, are homogeneous or heterogeeous throughout the study area.

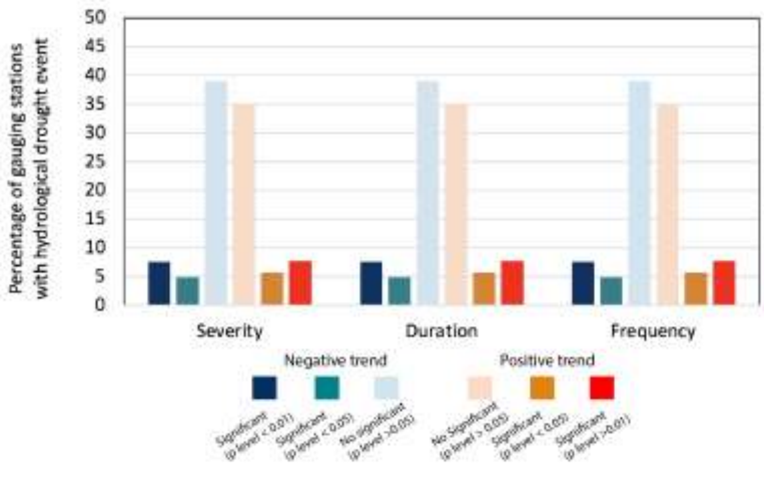

Figure 6. *Percentage of gauging stations with positive/negative and significant/non-significant ($p < 0.01$, $p < 0.05$, $p > 0.05$) trends in hydrological drought event characteristics in the period 1962-2017.*

Figure 6 depicts changes in the duration, frequency, and severity of hydrological droughts. Results reveal that the majority (~75%) of the stations showed a non-significant trend, while only 25% of the stations exhibited a statistically significant trend. Notably, the percentages of stations with positive (increase in the severity of hydrological drought) or negative (decrease in the severity of hydrological drought) trends, either significant or non-significant, were very similar. These results, a priori, suggest that there is no clear trend in hydrological drought at the continental level, indicating the importance of a regional focus.

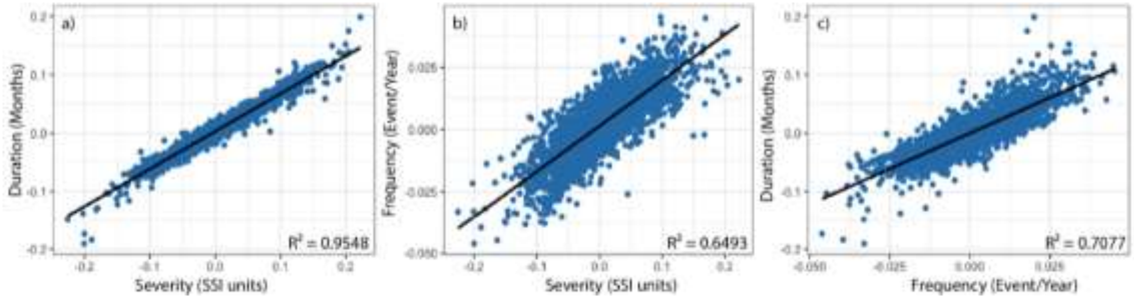

Figure 7. *Relationships between a) the severity and duration of drought events, b) the severity and frequency of drought events, c) the frequency and duration of drought events. The black line indicates the fitted regression line.*

There is a strong spatial relationship between the trend of the different characteristics of hydrological droughts (i.e. duration, frequency and severity) (Figure 7). Figures 8, 9, and 10 illustrate the spatial distribution of the magnitude of change and the statistical significance of the trends in these characteristics. Notably, the spatial distributions of the magnitude of change and trend significance for the three different drought characteristics were very similar. In general, two dominant spatial patterns were observed, with a positive trend (i.e. towards increasing drought) in southern and central Europe and a negative trend (i.e. towards decreasing drought) in Northern Europe.

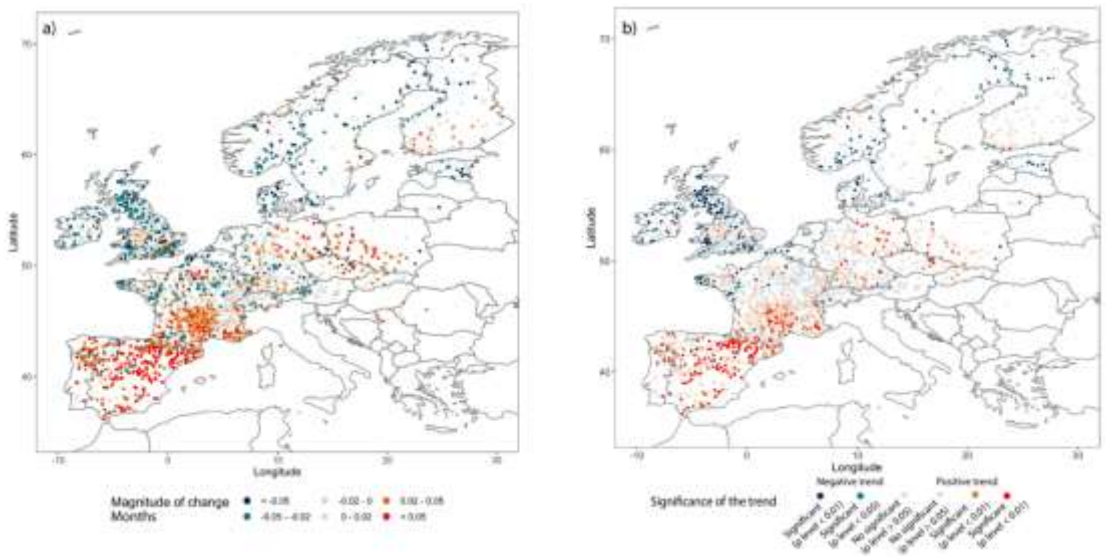

Figure 8. *Trends in the duration of drought events from 1962 to 2017. (a) Spatial distribution of the magnitude of change in SSI and (b) the corresponding significance of trends (at p < 0.05, p < 0.01) over the same period. Each circle represents one gauging station.*

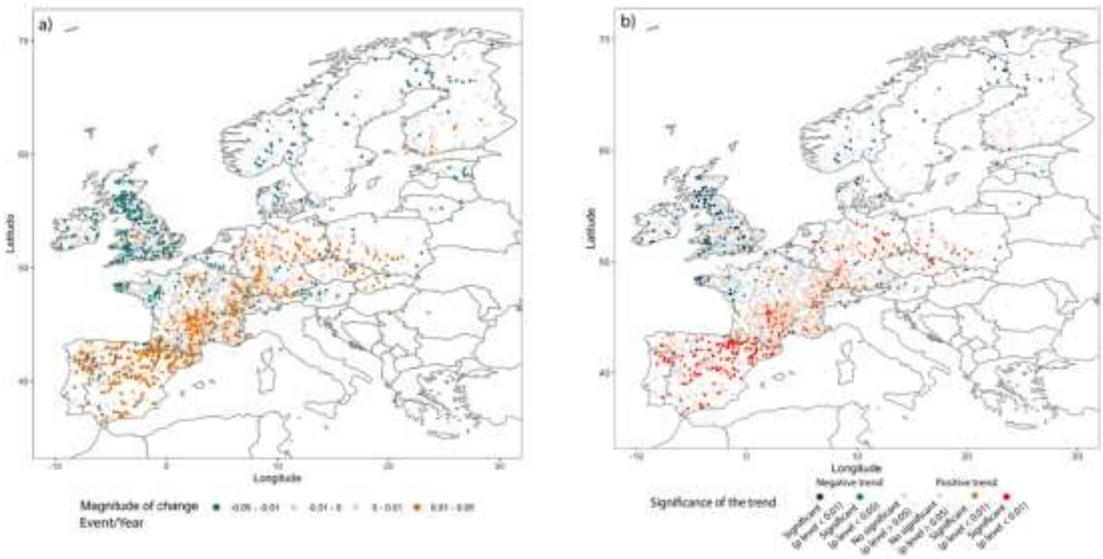

Figure 9. *Trends in the frequency of drought events from 1962 to 2017. (a) Spatial distribution of the magnitude of change in SSI and (b) the corresponding significance of trends (at p < 0.05, p < 0.01) over the same period. Each circle represents one gauging station.*

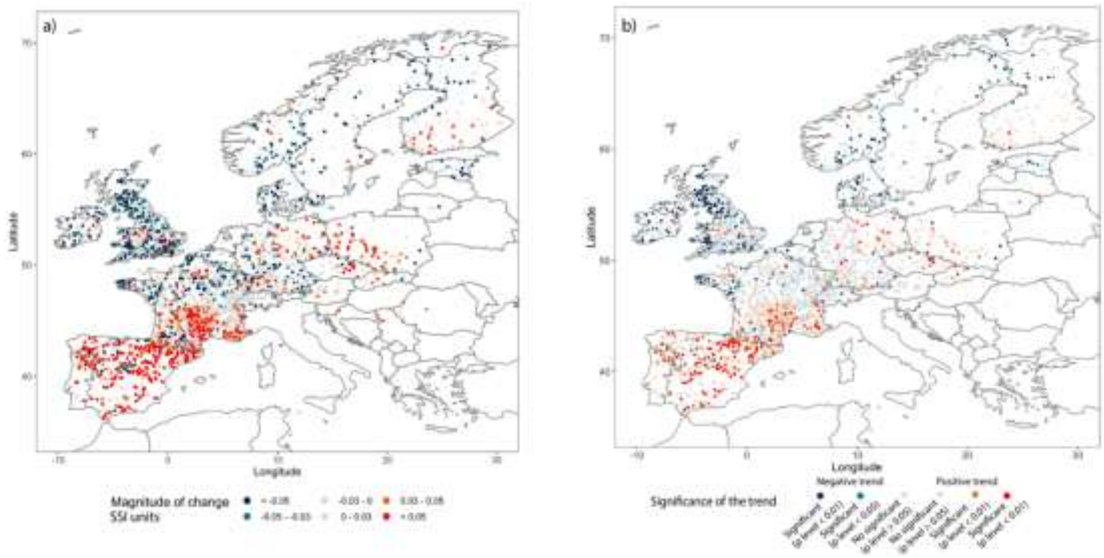

Figure 10. *Trends in the severity of drought events from 1962 to 2017. (a) Spatial distribution of the magnitude of change in SSI and (b) the corresponding significance of trends (at p < 0.05, p < 0.01) over the same period. Each circle represents one gauging station.*

Considerable differences in the frequency, duration, and intensity of drought events were found among the different sub-regions (clusters) (Figure 11). For cluster 1 (typically corresponds to Great Britain), the negative trends of hydrological drought events predominated in most of the stations (> 70%). Cluster 2 spans a wide region in central Europe (e.g. northern France, Belgium, Finland, Germany, Poland, Austria, Czech Republic and Slovakia), making trends less homogenous: non-significant positive (48% severity, 55% duration, and 72% frequency) and negative (52% severity, 45% duration, and 28% frequency) trends predominate. For cluster 3 (northern Europe), the negative trends in hydrological drought events prevailed in the majority of stations (> 70%). For cluster 4 (southern Europe), positive trends predominated in most stations (> 80%), with a large percentage of stations showing a significant positive trend. For cluster 5 (north and west of France), a higher percentage of stations had a negative trend (71% severity, 65% duration, 58 % frequency) rather than a positive trend (28% severity, 36% duration, 43% frequency). Finally, for cluster 6 (south of France), most stations (> 68%) showed a positive trend.

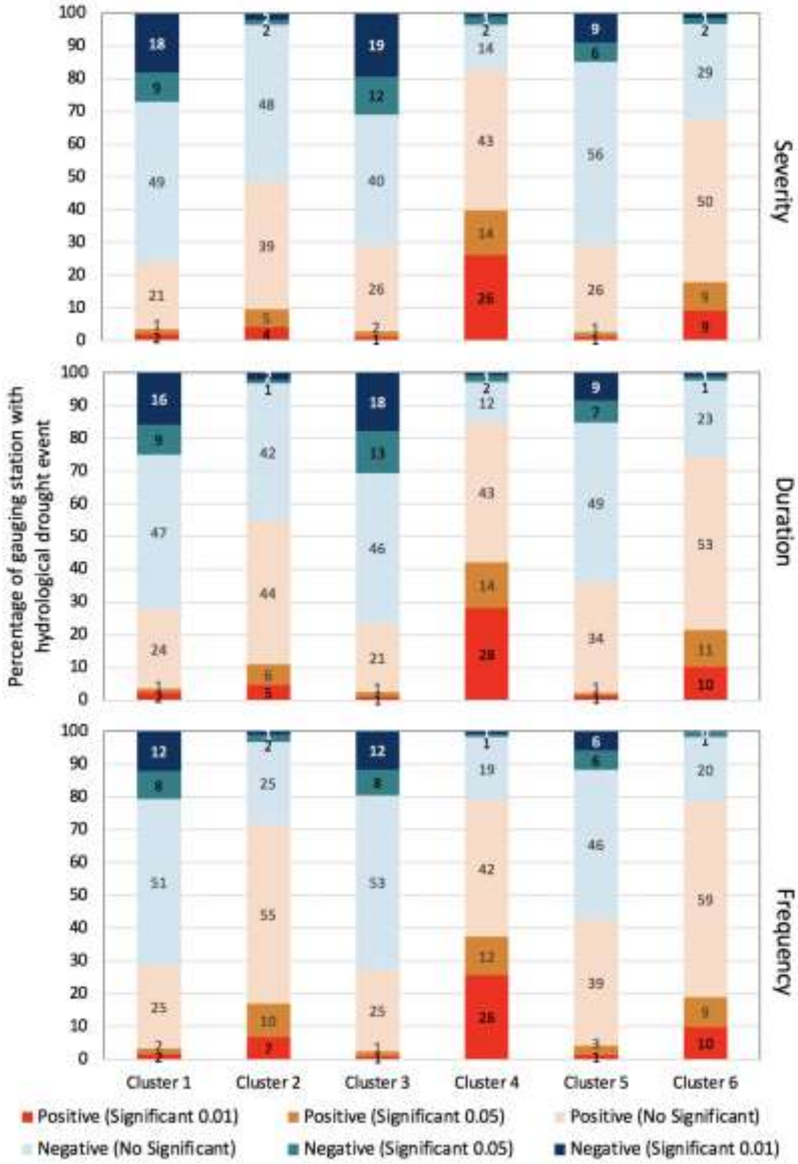

Figure 11. *Percentage of gauging stations with positive/negative and significant/non- significant (at $p < 0.01$, $p < 0.05$, $p > 0.05$) trend in the severity, duration and frequency of hydrological drought events for each cluster.*

4. Discussion

This study analysed spatiotemporal changes in monthly streamflow and hydrological drought over Europe between 1962 and 2017, using a spatially dense dataset with unprecedented geographical coverage compared to past drought studies. Previous studies have employed a much sparser network of gauging stations or focussed on particular regions (e.g. Hisdal et al., 2001, Parry et al., 2012, Van Loon and Laaha, 2015). Most of the previously employed datasets (e.g. Hisdal et al., 2001, Stahl et al., 2010, Hannaford et al., 2011) depended heavily on gauging stations from central Europe, mainly Germany and northern France, and Great Britain, with less representation of regions like southern Spain, Ireland, and large portions of northern and central Europe. As compared to several available streamflow databases (e.g. Hisdal et al., 2001, Stahl et al., 2010, Hannaford et al., 2011, Vicente-Serrano et al., 2019), our newly developed dataset has a greater number of stations, with better representation of the different regions in Europe. This highly dense network over both space (N=3,324) and time (1962-2017) represents a potential asset for the research community in Europe and beyond.

The spatial distribution of the study gauging stations shows spatial inequalities. There are regions of the area of study that have a large number of stations available, which are easily public access, while others present a great lack of information. Among the regions of the first case, the southwest (Portugal, Spain, France), the center-west (Switzerland and Germany), and the UK stand out. The other regions, such as Northern and central-eastern Europe and Ireland, have a homogeneous but not very dense distribution of gauging stations. It is important to highlight the lack of a good network of gauging stations with the aforementioned characteristics in the southeast and east in Europe.

In our study, we identified six homogeneous regions representing the evolution of monthly streamflow in Europe over the past six decades (1962-2017). Previous studies have used this technique to establish a regionalisation of streamflow characteristics in Europe. A representative example is Stahl et al. (2010) who identified 19 European regions based on a cluster analysis of historical streamflow deficiency time-series from the European Water Archive stations. Based on a cluster analysis of 579 gauges covering the period 1961-2005, Hannaford et al. (2011) defined a total of 23 homogeneous regions across Europe, stressing the complex picture of streamflow trends on a continental scale taking into account the differences that occur between the different studies due to the spatial coverage, the density of stations, the study period, the number of regions, and how droughts are defined. In addition, previous studies differ from ours in obtaining a greater number of clusters, so they focus on more complex hydrological processes of a local character. Despite this, we showed similar clustering schemes to those presented in earlier works. For example, our study defined Great Britain (cluster 1) and the Iberian Peninsula and southeast France (cluster 4) as homogeneous regions in terms of streamflow trends, which concurs with the findings of Hannaford et al. (2011) and Stahl et al. (2010).

The differences observed in each cluster between months may be expected in response to the different physical mechanisms controlling the interannual variability of climate and streamflow in the region, such as the North Atlantic Oscillation (NAO), especially during wintertime (Lopez-Moreno et al. 2007, Hannaford et al., 2013, Ionita, 2014). Numerous studies have indicated linked rainfall and streamflow variability with the NAO in northern Europe (e.g. Bouwer et al., 2008, Wrzesinski and Paluszkiewicz, 2010) and southern Europe (e.g. López-Moreno and Vicente-Serrano, 2008, Lorenzo-Lacruz et al., 2011). Our findings suggest that climate variability, particularly the impact of winter conditions during the rest of the year, may play a role in the observed spatial patterns in drought trends (Stagge et al., 2017). These drivers may induce a delay in the response of streamflow to climate variability (Lorenzo-Lacruz et al., 2013, Steirou et al., 2017). However, other local factors may control these differences at a more detailed spatial scale, such as topography (with mountain chains acting as barriers, but also influential through storage in ice and snow at high altitudes) and lithology (notably significant storages in permeable aquifers), which have been highlighted in previous studies over both southern (López-Moreno et al., 2013, Blöschl et al., 2019) and northern Europe (Hannaford et al. 2011, Svensson et al. 2015). Other relevant factors may be related to the consumption of water by vegetation, especially during summer, or anthropogenic activities associated with dam construction and reservoir use that can affect the distribution of the flow throughout the year (Lorenzo-Lacruz et al., 2013, Bastos et al., 2016, Mankin et al., 2019, Guerrieri et al., 2019).

Findings of this study indicate that there are no homogeneous streamflow trends in space nor over months at the continental scale (Blöschl et al., 2019). Spatially, two distinct patterns of streamflow evolution were noted. On one hand, clusters 1 (Great Britain), 3 (northern Europe), and 5 (northern and western France and eastern Ireland) all show a primarily positive trends, indicating an increase in streamflow albeit with seasonal variations (i.e. positive trends in the cold months and a slightly negative trend during warm months). These findings agree with Stahl et al. (2010) who found positive trends in the majority of catchments in western Europe during wintertime, and conversely a negative trend during warm months (April-August). In this study, cluster 2 (central), 4 (Iberian Peninsula and southeast France) and 6 (southern France) showed a negative trend, reflecting a decrease in streamflow in the majority of months. Similar spatial patterns were found at the continental (e.g. Stahl et al., 2010; Gudmundsson et al., 2017) and local scales: Spanish rivers (Ayala-Carcedo, 2001, Lorenzo-Lacruz et al., 2012), Czech rivers (Fiala 2008), Slovakia rivers (Majeráková et al. 1997), the Boyne catchment in east Ireland (Harrigan et al. 2014), among others.

Different studies, mainly on a national scale, have been carried out to understand the causes of the streamflow trends in recent decades (Giuntoli et al., 2013, Murphy et al., 2013), suggesting different drivers as a function of the area of interest. For example, one of the possible drivers of the positive trend in monthly streamflow, especially in winter, is the slight increase in precipitation in northern Europe (Caloiero et al., 2018). In turn, an increase in the atmospheric evaporative demand was also observed (Robinson et al., 2017) in northern Europe, which may explain the decrease in streamflow during summertime. Other studies highlighted the strong influence of anthropogenic activities on the decrease of streamflow in southern Europe, including the increase in irrigated land (Pinilla, 2006), revegetation at the mountain headwaters (Beguería et al. 2003, López-Moreno et al. 2011), and the storage of water from reservoirs (Vicente-Serrano et al., 2017b). In addition to these anthropogenic activities, a strong influence of increased atmospheric evaporative demand and accordingly actual evapotranspiration was evident in southern Europe (Tomas-Burguera et al., 2021).

Most studies carried out on a continental scale have focused on the temporal evolution of streamflow, without delving into the behaviour of hydrological drought events. It is important to note that major patterns in streamflow behaviour do not necessarily reflect in the trends of the severity or frequency of drought events (Hisdal et al., 2001). For this reason, this work evaluated trends in the duration, frequency and severity of drought throughout Europe. Results show a strong spatial gradient that is consistent with the observed evolution of streamflow trends. Interestingly, the northern areas of Europe (e.g. Norway, Sweden, part of Finland and Germany, north and west France, Austria, Great Britain and Ireland) showed a negative trend in the different characteristics of hydrological drought, with a general decrease in the severity of droughts. Conversely, southern and central Europe (e.g. the Iberian Peninsula, south of France, parts of Germany, Poland, and Slovakia) experienced a positive trend in the different characteristics of hydrological drought events, indicating a general increase in the severity of hydrological drought. The transitional region, mainly located in France, exhibited less clear trends. These results are in agreement with previous regional assessments, even those which relied on a lower density of stations (e.g. Dalezios et al., 2000, Hisdal et al., 2001, Fleig et al., 2006, Van Lanen et al., 2013, Van Loon and Laaha, 2015, and Masseroni et al., 2020).

As drought is caused by the accumulation of monthly streamflow deficits, the monthly streamflow has an impact on the frequency and severity of hydrological droughts. The trend in monthly streamflow shows that there is a north-positive and south-negative spatial pattern in winter, but this pattern is less clear in the summer. In the case of hydrological drought trends, a simple spatial pattern, north-negative and south-positive, was observed, which summarizes the impact of various drivers: trend of climatic variables mainly in northern and southern Europe, and also land cover changes and human management practices in southern Europe (Mottet et al., 2006Caloiero et al., 2018, Teuling et al., 2019, Vicente-Serano et al., 2019). An inspection of changes in monthly streamflow reveals that the greatest agreement occurred during winter months (November-March), and on the contrary more divergence was noted during summer months. This finding indicates that hydrological drought trends are highly dependent on streamflow changes during wintertime. There are strong increases in rainfall and streamflow in the northern Europe, and this clearly results in less severe hydrological droughts; despite the slight degreases in some summer months. While recent increases in precipitation in northern Europe (Caloiero et al., 2018) may have led to a decrease in the severity of hydrological droughts in this region, the strong increase of hydrological droughts in southern Europe is much more important than what would be expected according to the climatic variables (Teuling et al., 2019). This pattern can only be explained by the strong influence of vegetation recovery in the headwaters (García-Ruiz and Lana-Renault, 2011), combined with the role of water management practices, particularly the increase in water consumption by irrigated lands (Vicente-Serrano et al., 2017a), which have doubled in surface area since the 1950s (Pinilla, 2006). All these processes may have a substantial effect on streamflow generation (Beguería et al. 2003, López-Moreno et al., 2012).

Also, anthropogenic climate change seems to have a significant impact on the observed intensification of hydrological droughts in Southern Europe (Gudmundsson et al., 2017). This effect is mainly a consequence of increased air temperature, decreased relative humidity, and the general increase in atmospheric evaporative demand (Maček et al., 2018, Tomas-Burguera, 2021). This effect can be seen in the role of the atmospheric evaporative demand in streamflow evolution in highly regulated basins, as compared to headwaters in Southern Europe (Vicente-Serrano et al., 2014). These physical mechanisms could also contribute to the declining trends of streamflow during summertime, as revealed by some regions in northern Europe. An increase of the atmospheric evaporative demand has also been identified in these regions (Robinson et al., 2017).

The present study allow determining the evolution of the hydrological drought in the last decades, which may allow more efficient drought mitigation and management measures (Bokal et al., 2014). National and regional authorities could organize irrigation methods, locations and times based on the results obtained from streamflow trend studies (Rogger et al., 2017). The authorities could promote a best management practices of water in territories affected by a positive trend in the hydrological drought (Brooks, 2013, Forzieri et al., 2014, Samaniego et al., 2019). Drought episodes frequently have a local character, so studies with a large quantity and quality of information from the gauging stations are useful for operational decision-making. In this sense, this study shows for the first time the highest density of spatial information from gauging stations for the study of hydrological drought.

5. Conclusions

Using a newly developed and dense dataset of monthly streamflow gauges across Europe, this study has provided a detailed assessment of change in hydrological drought for the period 1962-2017. Results show that there are large spatial and temporal differences in streamflow across Europe, making any single statement defining changes in drought at the continental scale a challenging task. In general, it is observed that monthly streamflow as characterised by SSI showed a negative trend in southern and central European areas, while a positive trend was experienced in northern Europe. This study revealed distinct patterns at the monthly scale. In southern Europe, a negative streamflow trend was evident in all months. In central and northern Europe, and western France, a clear negative trend was observed during warm months and conversely a positive trend in cold months. Changes in streamflow were generally consistent with the large spatial patterns of hydrological drought changes, with a positive trend observed in southern and central Europe, and a negative trend predominant in northern Europe. These findings suggest that hydrological drought in Europe is not homogeneous in space and therefore is due to different drivers.

6. Reference

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PART 2. Propagation of the climate variability in to the hydrological responses.

1. Motivation

Drought is one of the most complex natural hazards given the challenges of quantification (Lloyd-Hughes, 2014), and the occurrence of different drought types: meteorological, agricultural, ecological and hydrological (Wilhite and Buchanan-Smith, 2005; Wilhite and Pulwarty, 2017). The propagation from meteorological drought to climatic drought is a complex phenomenon because they are dependent not only on the atmosphere, but also on the hydrological processes that feed moisture to the atmosphere and cause storage of water and runoff to streams (Mishra and Singh, 2010).

Meteorological drought is produced mainly by a prolonged precipitation deficiency, which if prolonged over time, generates less input to the hydrological system, and can cause a hydrological drought. En este sentido, una perdida del contenido de la humedad del suelo por groundwater, and evapotranspiration from bare soil and, especially, from plants, debido a cambios en las variables climáticas, como es la radiación, velocidad del viento, etc. The depletion of soil moisture storage causes a decreased recharge to the groundwater system, resulting in declining groundwater levels (Vann Loon, 2013). The low groundwater levels lead to decreased groundwater discharge, which prevents aquifers from further drying, but also causes decreased streamflow (Van Lanen et al., 2004). These processes are summarised with the term 'drought propagation', which denotes the change of the drought signal as it moves through the terrestrial part of the hydrological cycle (Vann Loon, 2013). The term 'drought propagation' is strictly for the translation from anomalous meteorological conditions to hydrological drought, which is differentiated from "spatial propagation", which is referred to as a drought event spreading through the study area.

In general, hydrological droughts develop differently in relatively constant climates as compared to climates with strong seasonality. En el clima contante el factor mas importante es la precipitacion, mientras que el clima estacional los factores varian. En algunos casos la sequía depende de la estación anterior, y de la evapotranspiración en la presente estación. En otros casos, early or late snow or fozen soil melt influences hydrological processes, namely the timing of recharge and discharge to streams (Sheffield et al., 2009; Huntington and Niswonger, 2012). In arid climates, dry periods are irregular and can last long due to erratic precipitation. Streamflow in these climates is highly dependent on groundwater discharge, showing a long recession during periods without rain (Stahl and Hisdal, 2008).

In addition to climatic factors, the spread of drought is determined by the characteristics of the basin. Just as climatic factors trigger droughts, the characteristics of the basin determine the speed of propagation of droughts. In general, storage in a catchment is determined by factors such as the climate (in case of snow and glaciers) and the geology of the catchment (i.e. percentage of hard rock and types of rock), topography (slope, orientation), soil (e.g. soil texture and structure), drainage network, land use, and vegetation. In addition, it must be taken into account that some factors of the characteristics of the catchment, such as land use and vegetation, by changing very quickly throughout the year and over time (Vann Loon, 2013).

According to what was previously commented, it seems important to deepen the knowledge of the droughts propagation, that means, to determine to what extent a meteorological drought can trigger a hydrological drought throughout space and time.

2. Objetives

The general objective of this research is to investigate the spatial and temporal distribution of the propagation of climatic to hydrological variables. More specifically, characterize the hydrometeorological propagation in the study period and area selected.

3. Data and Methods

In this study, the flow data of the gauging stations is necessary, which were obtained from MSED map viewer (Peña-Angulo et al., 2022). Monthly streamflow data were obtained from national and international hydrometric, scientific and water management agencies across Europe. For the period 1962 to 2017, data from a total of 5,529 stations were available. As gaps were present in many series, reconstruction was undertaken following the methodology described by Vicente-Serrano et al (2019). Specifically, a reference series was created for each target (candidate) station using data from nearby stations located no more than 100 km, with a common period of at least 7 years, and a Pearson's r correlation greater than 0.7. The series with at 75% of data available for the years 1962-2017 were retained.

On the other hand, the climatic information was obtained from ERA5 data, which are used to calculate SPI and SPEI. The ERA5 is the latest generation of the reanalysis dataset developed by the European Center for Medium-Range Weather Forecasts (EWMF), which has a spatial cover of 0.25º and a temporal coverage of 1950 to present.

The study obtained correlation statistics for SPEI and SSI index in each gauging stations covering Europe for the whole period (1962–2017). The correlation was realiced between SSI and SPEI in each station by month and window. The magnitude correlation was estimated by the ordinary least squares method; which is widely used in climate studies (Moberg et al., 2006). In the correlation analysis between SSI and SPEI in each station by month and window, it was seleted the temporal scale and the season with the best correlation to know the response time between changes between climatic and hydrological variables. Next, each gauging station was classified taking this information into account, that is, the time window and station with the highest correlation value were indicated for each station. So, the temporal scale was selected with the maximum correlation between SSI (streamflow index) and SPEI-n (1-48 TS, precipitation index) in each month.

4. Results

The study area has climate regimens and catchment properties different therefore, it is necessary to determine the temporal scale (TS) that each basin has to respond hydrologically to climate variability.

To characterize all the study gauging stations in Europe, the SPEI temporal scale and the season with the highest correlation value between SPEI and SSI were selected. From this information, the percentage of stations with the maximum correlation in each of the temporal scale (Figure 1) and each of the months (Figure 2) was obtained.

Figure 1 shows in the warm, from April to September, predominates the long temporal scales. However, in the cold season, from October to March, predominates the long temporal scales. In general, in winter, most of the gauging stations in the study area are characterized by having a rapid hydrological response to climate variations; however, as summer, the number of gauging stations whose hydrological response depends not only of the present climatic variations, but also of what happened in previous months.

Figure 2 shows that the highest correlation values occur in the cold season, and the opposite in the warm season. However, the large spatial differences in the correlation values are observed: in the south, the highest correlation values occur in winter, while in the north it occurs in summer.

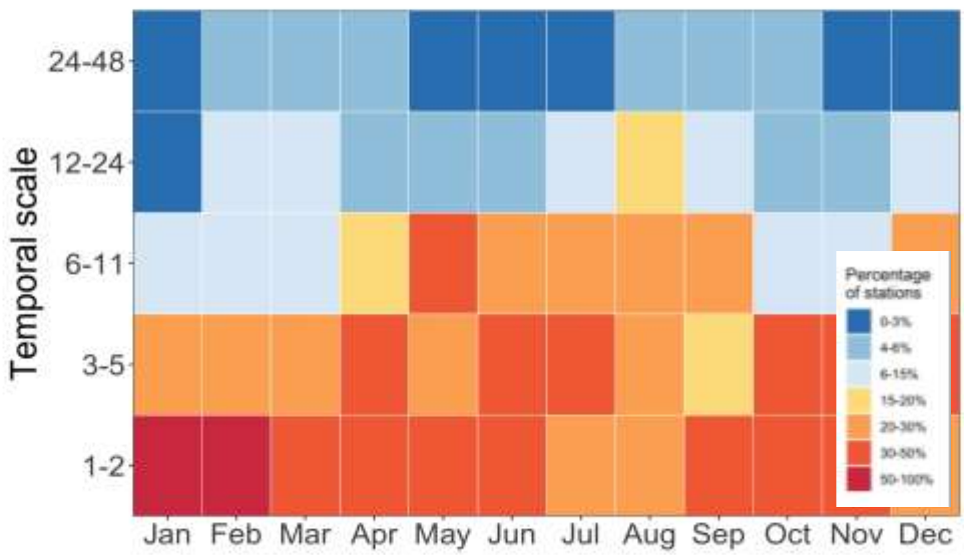

***Figure 1**. Percentage of gaugin station with maximum correlation in each temporal scale.*

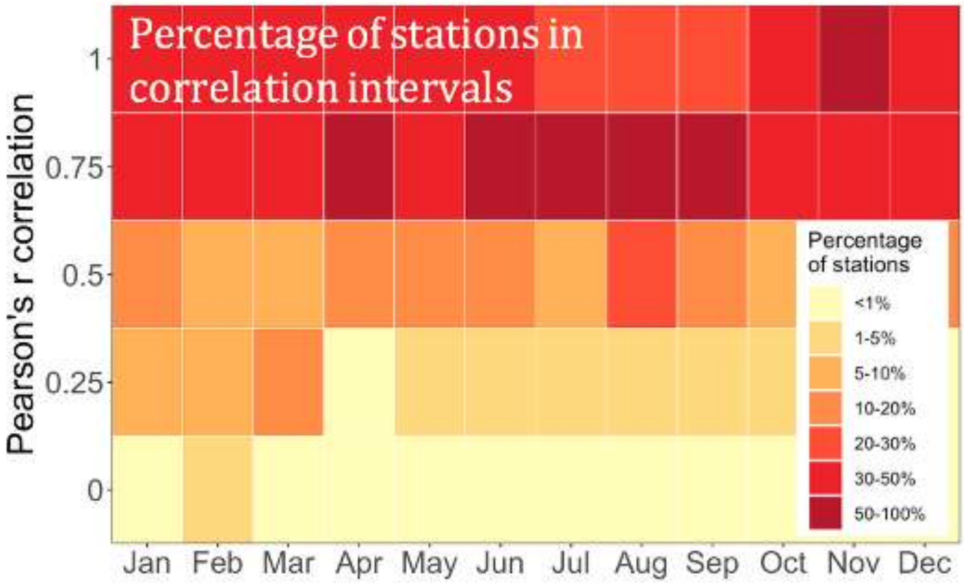

***Figure 2**. Percentage of gauging station in Pearson´s correlation intervals in each month of the maximum correlation.*

Figure 3 shows the short temporal scales predominate in the cold season in most of the territory with the exception of certain areas of the UK, north and interior of the study area. However, the long temporal scales predominate in the warm season, and this predominance has a gradual character, the temporal scale increases as temperatures increase. In the most mountainous region of Europe (Alps, Pyrenees) short temporal scales predominate in cold and warm season.

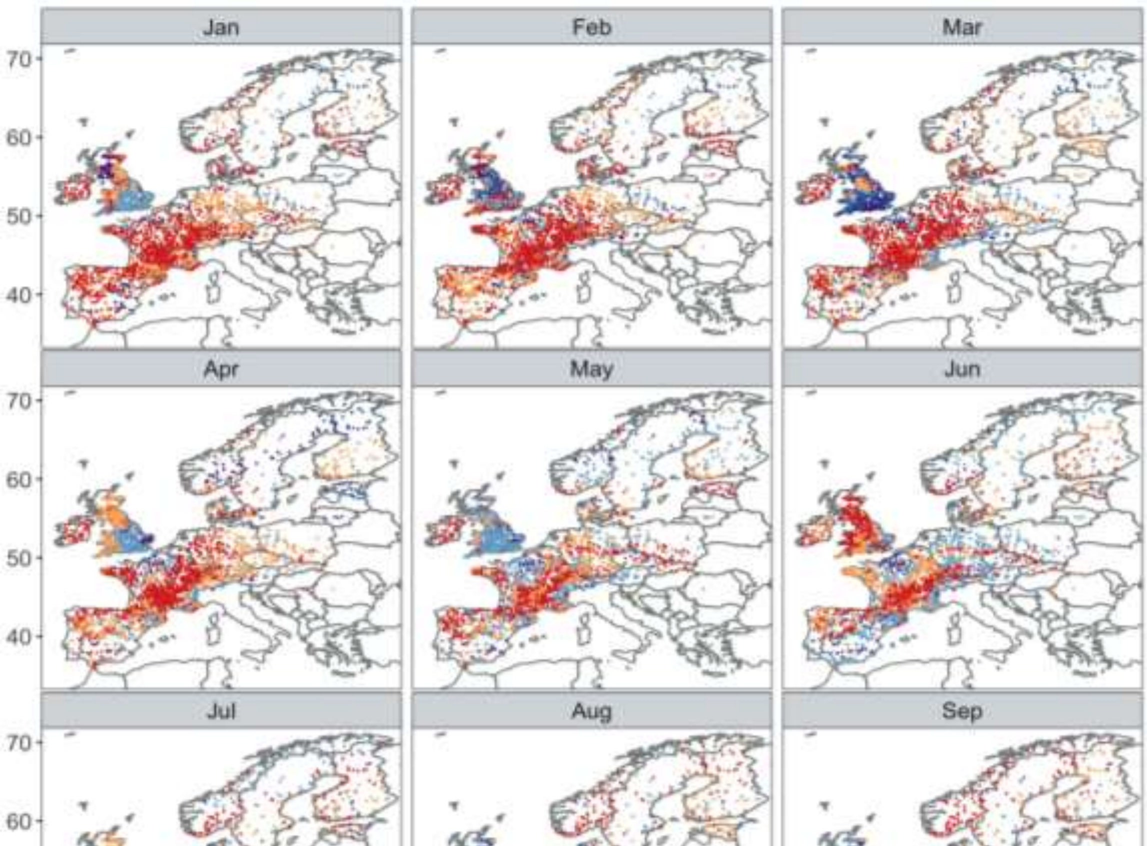

Figure 3. *Temporal scale with maximum correlation between SPEI-n and SSI in each month.*

analysis of the correlation values, geographical patterns have been observed, linked to the presence of mountainous systems, latitude, proximity to the Atlantic Ocean, as well as a series of gauging stations that do not respond to the expected patterns due to their location. It is possible that the gauging stations that do not present a clear geographical pattern, linked to the location, may be due to other factors such as the cathment characteristics or the management of water by human.

Finally, we carry out the classification of the gauging stations taking into account the previous analysis, the season and temporal scale with maximum correlation. Large spatial patterns are observed throughout the seasons and in the temporal scale in the relationship between SSI and SPEI-n (Figure 4).

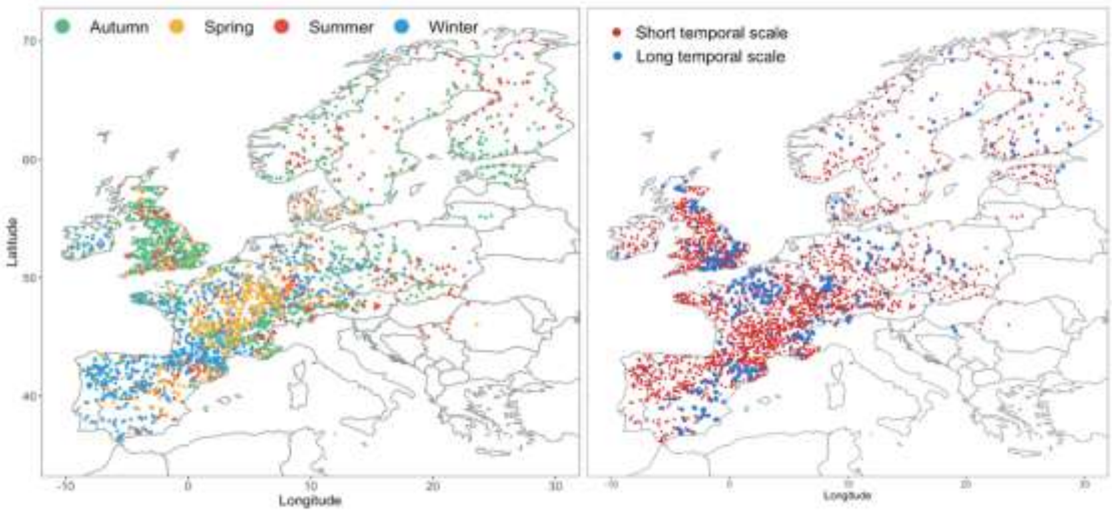

Figure 4. *Spatial distribution of the season (W-S-S-A) and temporal scale (Short < TS6, Long > TS6) with the highest correlation values.*

A classification of the maximum correlation between SSI and SPEI-n by seasons and temporal scale was performed to obtain 6 categories (Figure 5):

- Winter and short temporal scales (28% stations)
- Spring and short temporal scales (20% stations)
- Summer and short temporal scales (10% stations)
- Autumn and short temporal scales (29% stations)
- Spring and long temporal scales (4% stations)
- Summer and long temporal scales (6% stations)

Autumn and Winter with long temporal scale have minimal spatial representation (~1% stations).

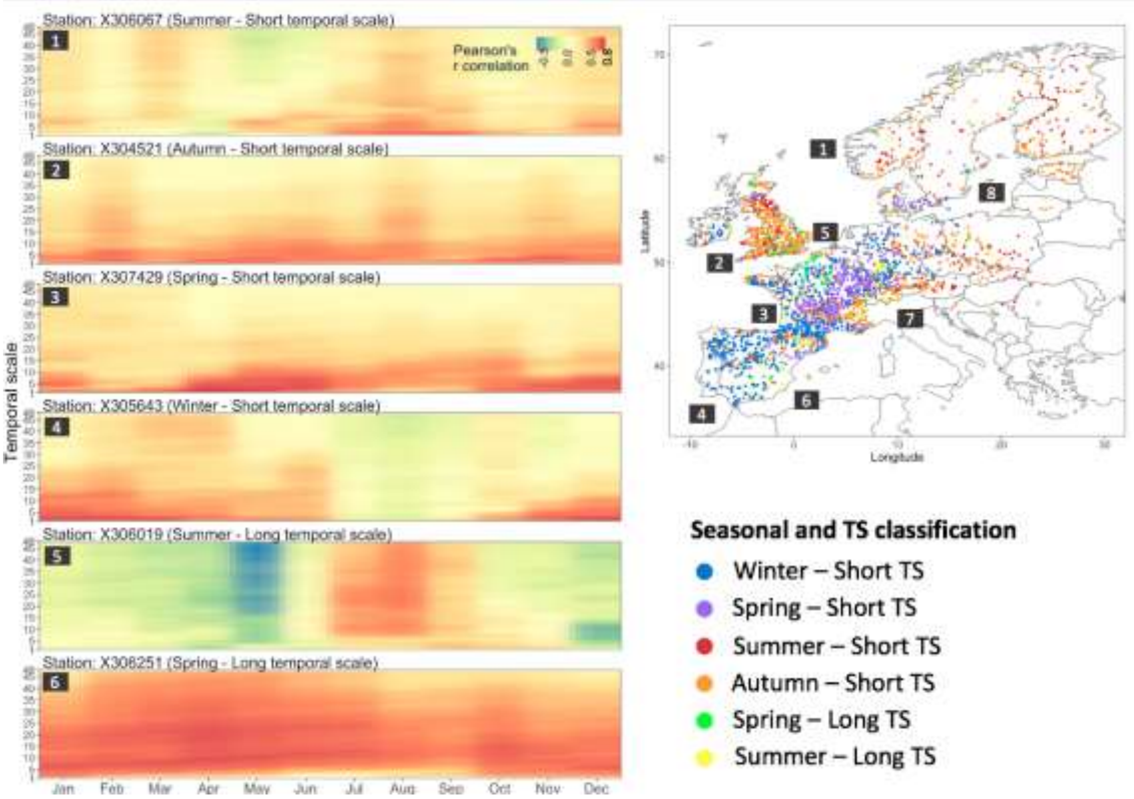

Figure 5. *Examples of spatial distribution of the season (W-S-S-A) and temporal scale (Short < TS6, Long > TS6) with the highest correlation values.*

From the study carried out, we have prove that in the relationship between climate variability and the hydrological response, there are a series of factors that condition this relationship. This raises a second topic for study: what are they and what weight do these other factors have? Regarding the relationship between climatic and hydrological variables, it has been observed, for example, in southern Europe, in Spain and Portugal, that there is a strong relationship between both variables with short time windows in winter. On the contrary, in northern Europe, Finland, and Norway, the greatest relationship between the study variables takes place with short time windows in summer. While the center of Europe, is characterized by having a strong relationship between the variables with short windows in spring. However, there are some exceptions that are worth studying as they can give us information on how other non-natural factors also affect the relationship between climate variability and hydrological response.

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