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Key Points:
- Streamflow trends in countries bordering the northeast Atlantic show a north-south latitudinal gradient, with strong decreasing trends in southern regions
- Climate trends largely explain the evolution of annual streamflow in northwestern Europe
- Climate trends cannot fully explain the large reductions in annual streamflow in southwest Europe, with land use changes and water demand from irrigation playing an important additional role

Supporting Information:
- Supporting Information S1

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Climate, Irrigation, and Land Cover Change Explain Streamflow Trends in Countries Bordering the Northeast Atlantic

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Abstract Attribution of trends in streamflow is complex, but essential, in identifying optimal management options for water resources. Disagreement remains on the relative role of climate change and human factors, including water abstractions and land cover change, in driving change in annual streamflow. We construct a very dense network of gauging stations ($n = 1{,}874$) from Ireland, the United Kingdom, France, Spain, and Portugal for the period of 1961–2012 to detect and then attribute changes in annual streamflow. Using regression-based techniques, we show that climate (precipitation and atmospheric evaporative demand) explains many of the observed trends in northwest Europe, while for southwest Europe human disturbances better explain both temporal and spatial trends. For the latter, large increases in irrigated areas, agricultural intensification, and natural revegetation of marginal lands are inferred to be the dominant drivers of decreases in streamflow.

Plain Language Summary Reduced water resources availability is one of the most serious impacts of climate change since reductions in streamflow may cause noticeable ecological and socioeconomic impacts. However, attribution of streamflow trends to climate change is complex given the influence of other drivers of catchment change, including human and vegetation water uses, agriculture, and land use change. We show that for northwestern Europe most observed trends in annual streamflow are associated with climate change. However, in southwestern Europe there is a clear mismatch between observed trends in river flows and climate, with increasing vegetation and/or irrigated agriculture better explaining observed changes. Our results highlight the importance of human management in explaining large-scale hydrological trends and the need to carefully evaluate both climate and land use changes to disentangle drivers of streamflow trends.

1. Introduction

Countries bordering the northeast Atlantic Ocean (Spain, Portugal, France, the United Kingdom, and Ireland) are highly sensitive to changes in climate (natural and human forced) and hydrology, with the region having a high population density and intense water use (Thober et al., 2018). In southwestern Europe, water scarcity is frequent as a consequence of climatic drought events (González-Hidalgo et al., 2018), with consequences aggravated by the general reduction in streamflow recorded over recent decades (Coch & Mediero, 2016; García-Ruiz et al., 2011; Lorenzo-Lacruz et al., 2012; Yeste et al., 2018). These decreasing trends are likely to have caused more severe hydrological droughts (Vicente-Serrano, Lopez-Moreno, et al., 2014). In northwestern Europe, wetter conditions and increasing trends in streamflow have been pronounced in the last decades (Dixon et al., 2006; Hannaford, 2015; Hannaford et al., 2013; Harrigan et al., 2018). Nonetheless, hydrologic droughts have also been frequent historically (Murphy et al., 2017) and more recently in the United Kingdom (Folland et al., 2015).

Disentangling how both climate change and human impacts, via water management and land cover change, are affecting river flows is an important scientific challenge with practical implications. Some studies suggest that human influence is the dominant driver of recent trends through dam construction, urban water demands, and irrigation (He et al., 2017; Wada et al., 2013). Some even estimate that the frequency of low flows has increased 20–35% globally as a consequence of urban and agricultural water consumption (Wada et al., 2013). There are several regional examples of large river flow reductions attributed to increased irrigation withdrawals and increased natural vegetation that have enhanced rainfall interception and leaf transpiration (Filoso et al., 2017; Vicente-Serrano et al., 2017). For example, in China it is suggested that a large proportion of observed reductions in streamflow can be attributed to land use and land cover changes (Li et al., 2007; Liu et al., 2013; Zhang et al., 2009). These effects are also observed in southwestern Australia (Liu et al., 2019), in tropical catchments in Puerto Rico (Beck et al., 2013), and in highly modified basins of Brazil (Chagas & Chaffe, 2018).

Other studies emphasize climate variability and change as the main driver of streamflow trends (Fenta et al., 2017; Glas et al., 2019; Xie et al., 2015). For example, in the United States, most research stresses that climate is the main driver of recent streamflow trends (Brauer et al., 2015; Cruise et al., 2010; Ficklin et al., 2018; Frans et al., 2013), with the exception of small catchments characterized by large changes in the urban area (Cuo et al., 2009). In a recent study covering more than 3,000 gauging stations over the continental United States, Ficklin et al. (2018) indicated that natural and modified hydrological basins showed similar streamflow trends between 1981 and 2015, arguing that climate trends were the main driver of observed changes.

It is expected that a reduction in precipitation causes a decrease in surface water resources. Additionally, enhanced atmospheric evaporative demand (AED) may also reduce streamflow by promoting enhanced water fluxes to the atmosphere, predominantly via plant transpiration, but also via direct evaporation from soils (when soil moisture is available), streams, reservoirs, and lakes (Jasechko et al., 2013). Enhanced AED has been suggested as the main cause of streamflow reductions in near-natural catchments of southern Europe (Martínez-Fernández et al., 2013).

Understanding the relative role of climate and human impacts on recent streamflow trends is a necessary foundation for water resource adaptation and management strategies. Numerous studies have analyzed streamflow variability and trends within our study domain; however, these have been based on a limited number of gauging stations from near-natural catchments (e.g., Stahl et al., 2010, 2012). Limiting analysis to only near-natural catchments has hampered rigorous evaluation of the relative role of climate variability, water management, and land cover changes in explaining observed streamflow trends.

We analyze long-term trends in annual streamflow records from a very dense network of gauges from the region of Europe bordering the northeast Atlantic. This region offers the opportunity to identify different mechanisms driving recent streamflow trends given its diverse climatic and environmental characteristics. The region is also marked by different intensities of river regulation, water management, and water uses (García-Ruiz et al., 2011; Hannaford, 2015), while divergent climate trends have been identified in northern and southern parts of the domain in recent decades (Stagge et al., 2017). In Spain, there is high water demand from irrigated agriculture given strong summer dryness (Pinilla, 2006). There has also been a large increase in natural revegetation in the mountain regions (García-Ruiz et al., 2015) that has been associated with reduced water yield in headwater catchments (Beguería et al., 2003; López-Moreno et al., 2011). On the contrary, to the north of the region (Ireland and the United Kingdom) urban supply is the main water demand and river regulation is not as intense (Garner et al., 2017).

Having identified trends in annual streamflow across the region, we use regression-based techniques to assess the drivers of detected trends. Thus, we employ a network of 1874 gauging stations (see section 2) to identify spatially coherent streamflow trends over the period 1961–2012 and attempt to attribute the role that climate, land use change, and water management have had on the evolution of change in streamflow records across the region.

2. Data and Methods

2.1. Streamflow Data Set

We compiled a database of available monthly streamflow data from hydrometric and water management agencies in Ireland, the United Kingdom, France, Spain, and Portugal (see supporting information). The complete original database comprised 4,664 gauging stations over the region (Figures S1 and S2). Only series with at least 75% of data available for the years 1961–2012 were retained. Within this data set the majority of gaps were found at the beginning of the study period, predominantly for stations from France and the United Kingdom (Figure S3). For this reason, we applied a reconstruction and data gap filling processes using all available streamflow information (see supporting information). The final data set corresponded to a total of 1,874 stations for the period 1961–2012 (895 in France, 474 in the United Kingdom, 472 in Spain, 16 in Portugal, and 17 in Ireland).

2.2. Climate, Environmental, and Terrain Data

A metadata entry was created for each hydrological station, providing a range of catchment characteristics. The drainage area of each gauging station was obtained using a digital elevation model (EU Copernicus data and information program, https://www.eea.europa.eu/data-and-maps/data/copernicus-land-monitoring-service-eu-dem) at a spatial resolution of 25 m and ArcHydro tools in ArcGIS 10.2©. We also obtained characteristics of the drainage basins, including the mean elevation, total forest coverage, and the surface area of irrigated crops. Land cover information was obtained from EU-CORINE Land Cover (https://land.copernicus.eu/pan-european/corine-land-cover). In addition, we obtained normalized difference vegetation index (NDVI) data at the spatial resolution of 0.01° from the Global Inventory Modelling and Mapping Studies (GIMMS3g) data set (Pinzon & Tucker, 2014), for the period 1981 to 2012. The GIMMS3g were summarized annually, and the mean NDVI for each year was quantified for the 1,874 drainage basins. Climatic information was also obtained for each drainage basin. Monthly precipitation, together with maximum and minimum temperature were obtained from the 0.25° ECA&D gridded data set (Haylock et al., 2008) from 1961 to 2012. The other variables necessary to calculate the radiative and aerodynamic terms of the AED (solar radiation, wind speed, and relative humidity) were obtained from the European Centre for Medium-Range Weather Forecasts Re-Analysis (ERA)-Interim data set for 1979 to 2012 (Dee et al., 2011), from the ERA-20C Reanalysis for 1961–1978 (Poli et al., 2016; for relative humidity and wind speed) and from the ERA-20CM Reanalysis (Hersbach et al., 2015; for solar radiation). ERA reanalysis products have shown good performance in identifying recent temporal variability and trends in relative humidity (Vicente-Serrano et al., 2018), solar radiation, and wind speed (Szczypta et al., 2011) for the region of interest. Monthly series of AED were obtained using the FAO56-Penman Monteith equation (Allen et al., 1998). Finally, mean annual series of total precipitation and AED were calculated for each of the 1,874 drainage basins. The AED series were not affected by possible temporal inhomogeneities in the data sets given the use of ERA-Interim, ERA-20C, and ERA-20CM for different periods (results not shown).

2.3. Methods

First, we analyzed the significance and magnitude of trends in annual streamflow, precipitation, and AED. For this purpose we used water years (starting in October). To determine the significance of trends, we used the nonparametric Mann-Kendall statistic that measures the degree to which a trend is monotonically increasing or decreasing (Kendall et al., 1987; Mann, 1945). Nonparametric tests were preferred as they are less affected by the presence of outliers and nonnormality of the series (Lanzante, 1996). Autocorrelation was considered in the trend analysis of the annual series through use of the modified Mann-Kendall trend test, which returns the corrected probability values (p values) after accounting for temporal pseudo-replication (Hamed & Ramachandra Rao, 1998). The statistical significance level was set at 5%. To assess the magnitude of change in the annual series, we used a linear regression analysis between the series of time (independent variable) and the annual streamflow series (dependent variable).

We calculated the magnitude of change of the different variables between 1961 and 2012 based on the raw values (i.e., millimeters for precipitation and AED, and cubic hectometers per basin area as well as total cubic hectometers for the annual streamflow). However, the main analysis is based on percentage changes, thereby removing the influence of the large range of streamflow magnitudes across the rivers analyzed. To calculate the percentage change in streamflow for each basin between 1961 and 2012, we considered the predicted value of the variable (precipitation, AED, and streamflow) for the years 1961 and 2012 using the coefficients obtained from the linear regression analysis described above. Specifically, the predicted values for 1961 (P_{1961}) and 2012 (P_{2012}) were obtained as

$$P_{1961} = \propto + \beta \cdot 1961, \quad (1)$$

$$P_{2012} = \propto + \beta \cdot 2012, \quad (2)$$

where α and β are the y intercept and slope coefficients, respectively. Using the P_{1961} and P_{2012} values, the percentage increase or decrease between 1961 and 2012 ($C_{1961-2012}$) in comparison to the initial value was obtained according to

$$C_{1961-2012} = \frac{100P_{2012}}{P_{1961}} - 100. \quad (3)$$

The spatial relationship in the sign and significance of trends was calculated by means of the coefficient of contingency, which measures the degree of association between categorical variables (Clark & Hosking, 1986). This coefficient varies between −1 and +1 with qualitative interpretation identical to that of Pearson's correlation coefficient.

To determine the influence of the annual climate trends on annual streamflow trends, we used multiple regression in which precipitation and AED were the predictive variables. First, we performed a spatial regression analysis to determine if the spatial distribution of observed changes in the dependent variable (percentage change in annual streamflow) is explained by the percentage change in annual precipitation and AED (independent variables). Second, we developed a temporal stepwise multiple regression analysis for each gauging station to determine how temporal variability and trend in the annual streamflow series (dependent variable) are explained by the evolution of both annual precipitation and AED (independent variables) in each basin. Specifically, stepwise regression is an automatic procedure that prevents model overfitting (Hair et al., 1995). In each step, variables (in this case precipitation and AED) are considered for addition to, or subtraction from, the model based on the Fisher (F) test probability. If the probability is sufficiently small ($p < 0.05$), the variable enters in the model; if not, the method considers that the inclusion of the variable would overfit the model without adding additional explanatory capacity, and the variable is excluded.

We applied independent multiple regression models for each basin of the form:

$$S = a + b \cdot P + c \cdot AED, \quad (4)$$

where S, P, and AED are the annual streamflow, precipitation, and AED (in cubic hectometers), respectively, and a, b, and c are the coefficients of the regression model obtained by means of least squares.

In each basin we obtained a series of regression residuals by differencing observed and predicted annual streamflow, obtained from the regression coefficients (a, b, and c) and the P and AED series (see equation (4)). The series of regression residuals are obtained by

$$R_i = S_i - [a + b \cdot P_i + c \cdot AED_i], \quad (5)$$

where R is the value of the residual series for the year i. S, P, and AED are the values of annual streamflow, precipitation, and AED, respectively, for the year i and a, b, and c are the coefficients of the regression model obtained from equation (4). The temporal series of regression residuals allowed us to assess possible changes in the role of the climate variables on the streamflow variability and trends (Figure S9). Trend in the resulting residual series was also assessed with the modified Mann-Kendall statistic and the slope of the regression line, described above.

Possible nonlinear associations between streamflow and climate were assessed. We focused on precipitation given possible nonlinear relationships with the runoff coefficient (Kachroo & Natale, 1992; Figures S10 and S11). The results showed a predominant linear relationship between precipitation and streamflow in the region and support the use of linear regression in each basin.

3. Results and Discussion

3.1. Trends in Annual Streamflow and Climate

Trends in annual streamflow for each of the countries bordering the Northeast Atlantic exhibit a strong spatial gradient, characterized by predominantly increasing trends across much of the British and Irish Isles, with decreasing trends in the Mediterranean basins of Spain and Southern France (Figure 1a), consistent

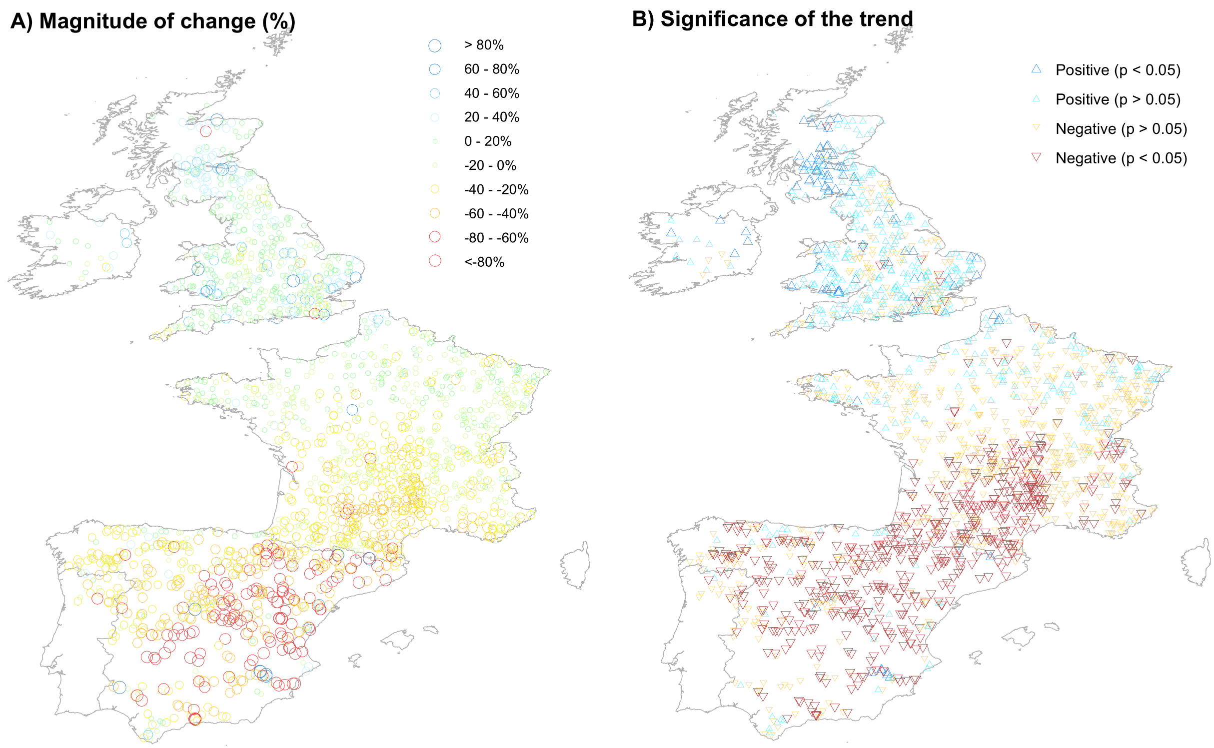

Figure 1. Trends in annual streamflow from 1961 to 2012. (a) Spatial distribution of the magnitude of change in annual streamflow and (b) the corresponding significance of trends (at $p < 0.05$) over the same period. Each circle represents one gauge station.

with previous studies in the Mediterranean region (García-Ruiz et al., 2011; Lorenzo-Lacruz et al., 2012) and in northern Europe (Giuntoli et al., 2013; Harrigan et al., 2018). Over the period 1961–2012 reductions of more than 40% in annual streamflow are evident for many gauging stations in Spain, with some showing reductions of >80%. For most stations across the Iberian Peninsula (IP) and southern France, the reduction in the annual streamflow is statistically significant (Figure 1b). Similarly, the increase in the annual streamflow was statistically significant in the north of the British and Irish Isles. Northern France and central and southern Great Britain are transitional, with few significant trends. These findings have noticeable implications for water availability and management, particularly in regions where runoff production is low (e.g., the south and east of Spain [Figure S12]), and where the magnitude of change in both runoff (mm/m^2) and absolute streamflow production (total annual cubic hectometers) is large (Figure S13).

Trends in annual precipitation totals also show a north-south gradient, characterized by significant increasing trends in the north of the British and Irish Isles, and predominantly significant decreasing trends in northern parts of the IP and southern France (Figure 2). Notably, northern IP and southern France are regions that record high precipitation totals, with a large decline in the annual precipitation (>300 mm) over the 51 years analyzed (see changes in absolute magnitudes in Figure S14). In southern Spain, although precipitation trends tend to be negative, they are not statistically significant. Consistent with previous studies (Robinson et al., 2017; Vicente-Serrano, Azorin-Molina, et al., 2014), trends in AED (see section 2) are predominantly positive and statistically significant, with the exception of some areas of the British and Irish Isles and southern Spain. Over the whole region the magnitude of change in AED is lower than that observed for precipitation and the magnitude of change in absolute values is smaller than that observed for precipitation (Figure S15).

There is strong spatial coherence between changes in precipitation and streamflow but less so between changes in streamflow and AED (Figure 2e). The coefficient of contingency between streamflow and precipitation trends (four spatial categories according to the sign and significance of the trend as shown in Figure 1) is 0.59 ($p < 0.001$), and between streamflow and AED trends, −0.26 ($p = 0.001$). However, the

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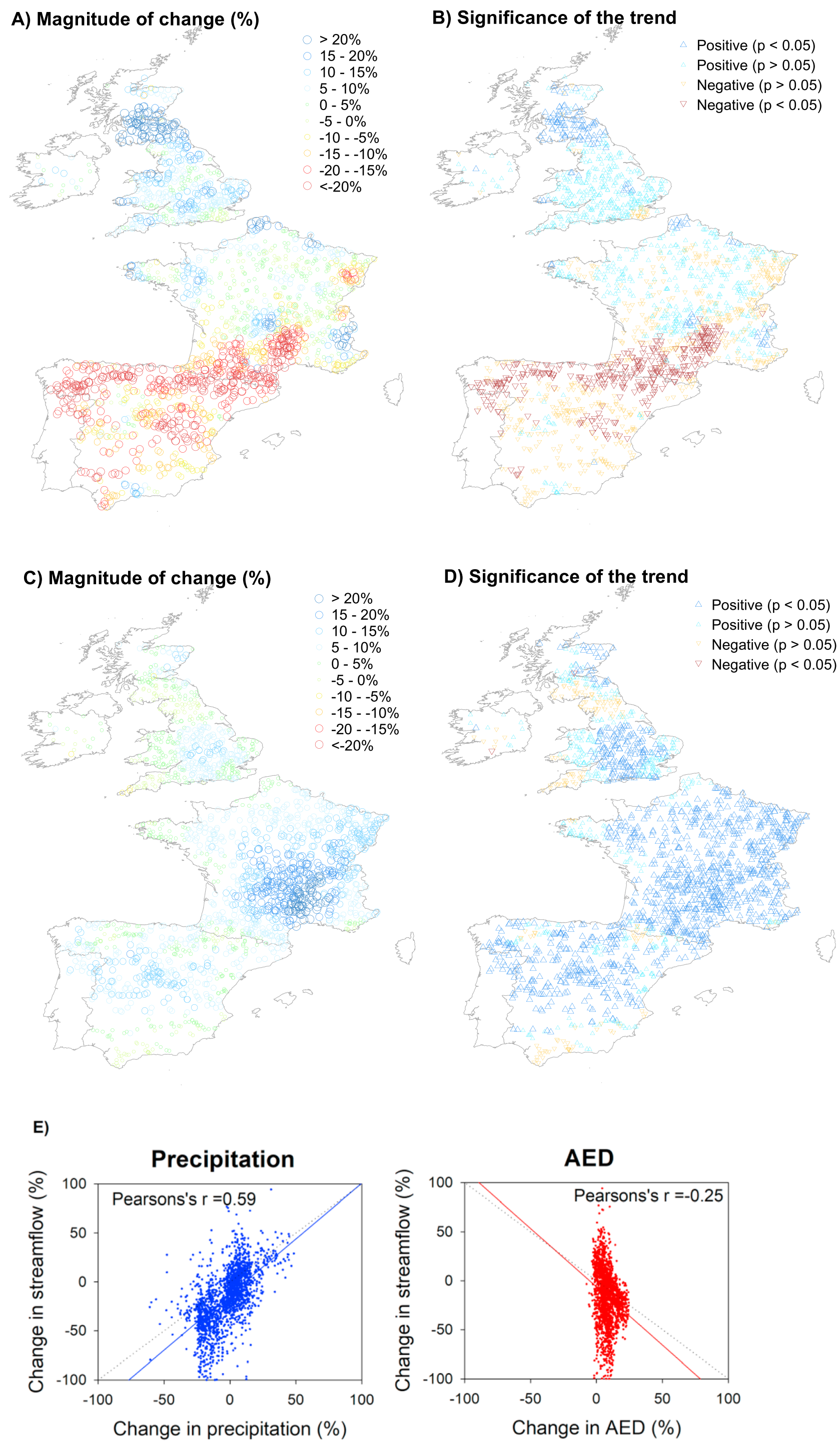

Figure 2. Trends in climate variables and their consistency with the observed trends in streamflow. (a) Spatial distribution of the magnitude of change in annual precipitation (1961–2012) and (b) their statistical significance (at $p < 0.05$). (c) Spatial distribution of the magnitude of change in annual atmospheric evaporative demand (AED; 1961–2012) and (d) their corresponding significance (at $p < 0.05$). Each point represents an individual gauging station at which the annual AED is integrated throughout the entire drainage basin. Note the different scale of the legends in panels (a) and (c). (e) Spatial relationship between the percentage changes in annual streamflow, annual precipitation, and AED. Solid line represents the least square regression line, and dotted line denotes the 1:1 line.

spatial patterns in the magnitude of precipitation trends accounts for 35% of the spatial variability of the streamflow trends. The spatial patterns of AED explain a smaller proportion (6%), which is consistent with recent findings at the global scale that suggest a small response in streamflow to changes in AED, in comparison to precipitation (Yang et al., 2018).

The spatial distribution of changes in annual streamflow shows notable differences relative to the climate variables (Figure S16). In southern France and most of the IP streamflow reductions are greater than expected according to the trend in the climate variables alone. This implies that nonclimatic factors are responsible for this spatial dissociation. Temporal correlation between annual precipitation and streamflow is positive for the majority of basins, although the correlation is stronger in the north than in the south. In the same context, correlations between streamflow and AED are predominantly negative, particularly in southern France, northwest IP, and northern England (Figure S17).

3.2. Where Are Trends Explained by Climate?

Linear regression models using annual streamflow as the dependent and annual precipitation and AED as independent variables were developed for each gauging station (see section 2). These models allow for the prediction of the temporal variability and trends in annual streamflow, as a function of the climate evolution. Importantly, the resulting residuals enable identification of possible temporal changes in the drivers of trends in annual streamflow (Beguería et al., 2003). This procedure implies that a significant decrease in model residuals for a gauging station reveals a decreased in the contribution of the climate variables to streamflow variability and trend (Figure S9).

There are important spatial differences in the trends of regression residuals across the study area (Figures 3a and 3b). Our regression models are better at simulating the temporal variability and trends of annual streamflow for basins in eastern France and the British and Irish Isles than the IP. In the north of our domain the trend of the residual series is predominantly nonsignificant, meaning that observed annual streamflow trends are mostly driven by recent climate trends, as already stressed by previous studies (Hannaford, 2015; Hannaford & Marsh, 2008; Harrigan et al., 2018; Murphy et al., 2013). In the United Kingdom and Ireland, some differences between neighboring stations are evident which may reflect well-known human influences (e.g., reservoirs and abstractions) in individual basins (Tijdeman et al., 2018) but also possible effects of arterial drainage (i.e., artificial widening and deepening of the river channels to improve discharge conveyance), which affects many large basins in Ireland and the United Kingdom (Harrigan et al., 2014). In France, model residuals are dominated by nonsignificant trends, indicating that observed trends in annual streamflow are explained by climate.

For the IP, climate explains a lower percentage of the variance of annual streamflow (Figure S18). This is particularly evident in the basins of southern IP, where the model residuals show a predominant negative trend. These changes were statistically significant for a high percentage of the basins (Table S1). For these basins, streamflow volume has decreased more than expected, given annual precipitation, and AED. In the north and west IP the pattern is opposite, with model residuals exhibiting a predominantly positive trend, indicating that streamflow has increased more than expected from climate alone. This region has been frequently impacted by forest fires in past decades (Martínez-Fernández et al., 2013; Moreno et al., 2014). Herein, it is noteworthy to indicate that water yield after any wildfire depends largely on the scale and the type of vegetation (Wine & Cadol, 2016). Accordingly, streamflow can be increased after fire events when a substantial percentage of the basin is burned (Hallema et al., 2018). In this context, the frequent forest fires and the subsequent reduction in tree coverage may explain the streamflow pattern in this region. However, further work is needed to verify this assertion.

3.3. The Influence of Irrigation and Land Cover Change

To investigate alternative drivers of change, we examined how irrigation and changes in vegetation coverage may have impacted trends in annual streamflow. We find that the area covered by irrigated lands, together with areas of increased satellite vegetation activity (closely related to vegetation coverage and density (Cihlar et al., 1991); see section 2) in recent decades, show strong spatial covariation with observed trends from station based regression residuals (Figure 3). Basins that show significant decreasing trends in residuals are characterized by a large surface cover of irrigated crops and are heavily concentrated in southwest Europe. Irrigation represents around 80% of total water use in southwest Europe (Rojas, 2018), having increased in

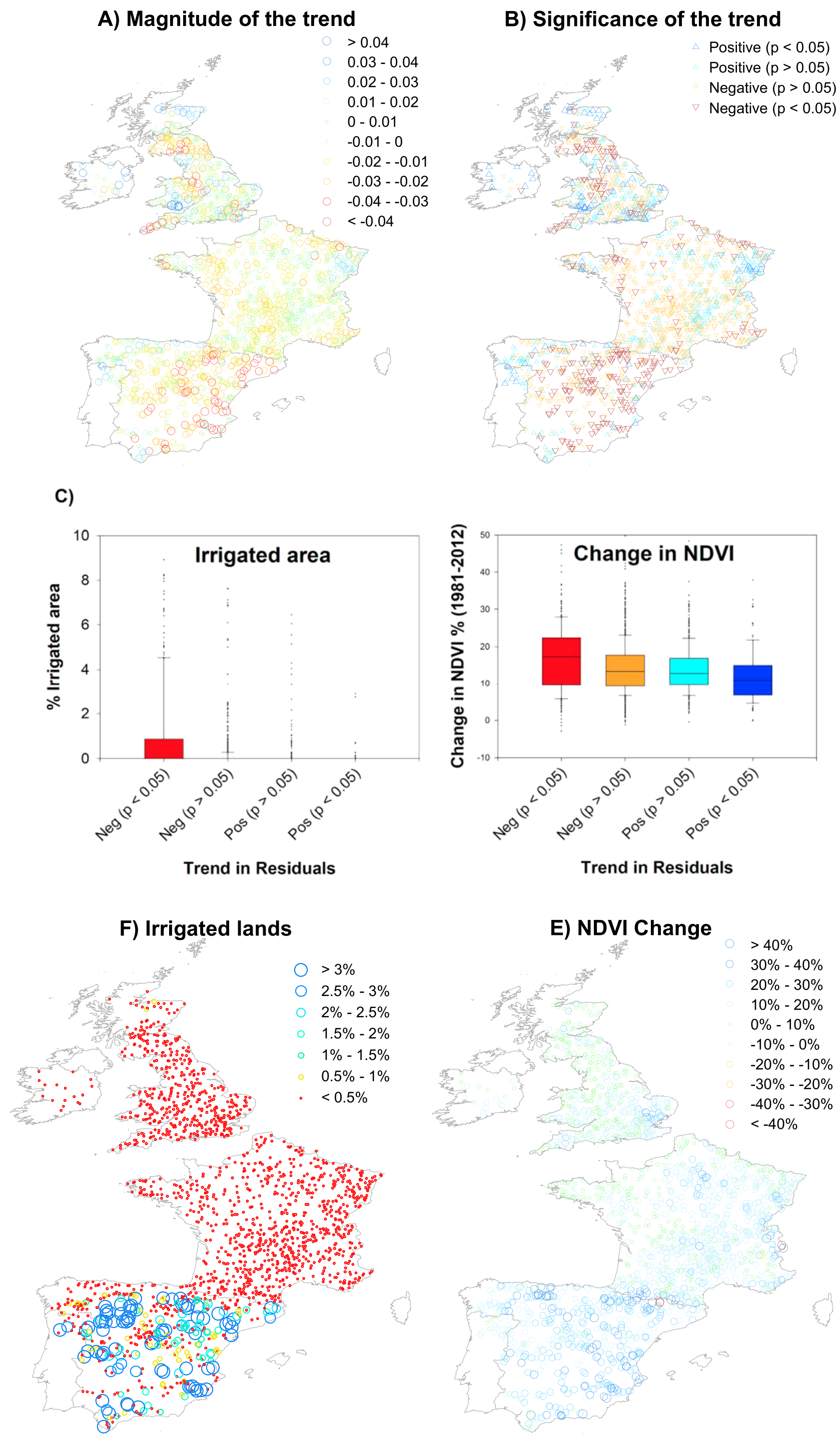

Figure 3. Understanding drivers of change in detected trends. (a) Spatial distribution of the magnitude of the trend of the standardized residuals resulting from the regression models and (b) the corresponding significance of these trends. (c) Boxplots showing the percentage (%) of irrigated lands and the percentage change in the normalized difference vegetation index from 1981 to 2012, as a function of the sign and significance of the trends in the series of residuals. The line in the box represents the median, the upper and lower parts of the box denote the interquartile range, and the whiskers show the 95% and 5% confidence levels. Dots represent the cases that are above or below the 95% and 5% levels. (d) Percentage of surface covered by irrigated lands in each basin and (e) magnitude of change in the annual normalized difference vegetation index (in percentage) from 1981 to 2012.

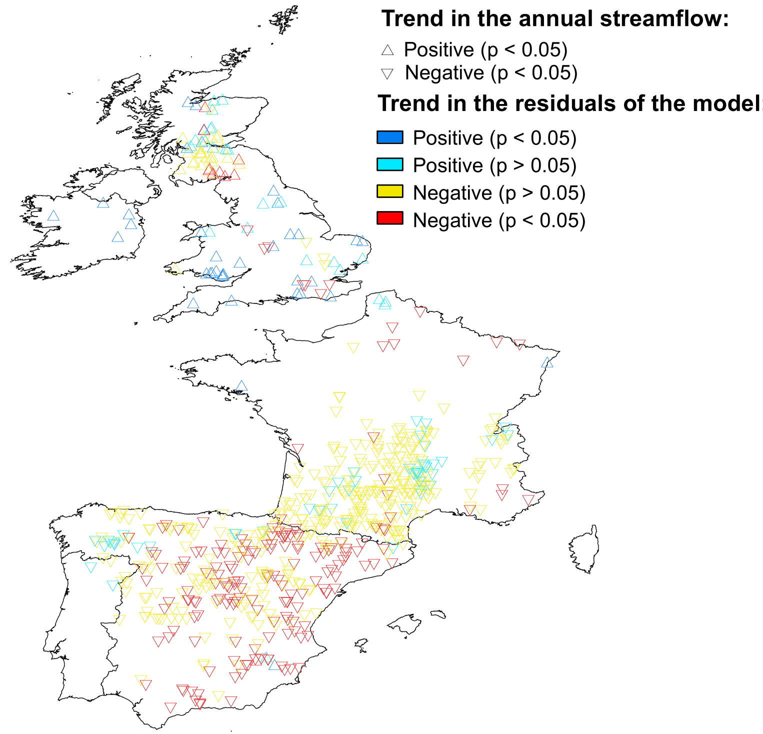

Figure 4. Gauging stations showing significant annual streamflow trends together with the trend in the residuals of the model for each station. The symbols (triangles) represent positive and negative significant trends in the annual streamflow and colors represent the trend in model residuals.

areal extent from approximately 2 million hectares in the 1960s to more than 3.5 million hectares in 2012 (Tamames & Rueda, 2014). The increase in irrigated lands has coincided with an increase in AED in southern Europe (Vicente-Serrano, Azorin-Molina, et al., 2014). This situation may induce an additional decrease in annual streamflow, as AED enhances crop water demand, with subsequent reductions in water returns from irrigation polygons to watercourses (Vicente-Serrano et al., 2017).

Changing vegetation cover also plays an important role in explaining the differential strength of climate in driving annual streamflow trends. The magnitude of change of the NDVI (see section 2) since 1981 varies with the sign and significance of the annual streamflow trends across basins. Those that show significant decreasing trends in model residuals are typically characterized by larger increases in NDVI than basins that show nonsignificant or positive trends. Increased NDVI in recent decades is associated with warmer temperatures, the absence of water limitations for leaf activity and vegetation growth, and a likely role of CO_2 fertilization (Donohue et al., 2013). Additionally, large increases in NDVI for the IP (Figure 3e) have been attributed to abrupt socioeconomic changes in mountain areas, whereby depopulation has led to the abandonment of agriculture and grazing lands (Lasanta-Martínez et al., 2005), with a subsequent and rapid revegetation process by shrubs and forests (Lasanta & Vicente-Serrano, 2007). The headwaters of major rivers, where the largest runoff coefficients are typically found, have been the most affected by afforestation. The general transformation of grasses and crop lands to forests has increased water consumption by vegetation to the detriment of surface runoff production (Robinson et al., 2003).

Figure 4 maps basins with significant annual streamflow trends together with the sign and significance of trends from basin regression residuals. Results reveal a dominance of negative annual streamflow trends, which are not explained by climate, in the southern IP (Figure 4 and Table S2). On the contrary, in southern France, although significant negative trends are also dominant, trends in the regression residuals are predominantly nonsignificant, suggesting that streamflow trends are mostly driven by climate.

In southern France vegetation cover has not increased as much as in Spain since land abandonment and natural revegetation processes have been modest (Mottet et al., 2006), while crop irrigated areas represent a small and stationary percentage of basin land cover (Campardon et al., 2012). In the northern portion of our study domain, patterns in annual streamflow and regression residuals trends are more heterogeneous, due to variations in arterial drainage, groundwater extraction, and interbasin water transfers (Harrigan et al., 2014; Tijdeman et al., 2018). However, the number of basins with trends that cannot be attributed to climate is small.

It could be argued that the physiographic characteristics of the hydrological basins could have a role in influencing the results. In specific, basins in Spain and France, relative to the British and Irish Isles, are characterized by larger drainage areas, with more nested catchments and multiple stations along the main river channels. However, when catchments of comparable size are analyzed together, the results are not affected. Both the magnitude of the streamflow trends (Figure S19) and the trend in the model residuals (Figure S20) show clear differences in observed behavior between catchments located in the north and south of the study area. Independent of basin area, annual streamflow series in Spain are dominated by decreasing trends, in contrast to the predominantly increasing trends in the United Kingdom. At the same time, the trend in the model residuals is predominantly negative in Spain and close to 0 in the U.K. catchments of similar size. It is necessary to note that in Spain, even in small basins with near-natural flow regimes, a general streamflow reduction is recorded. This might be explained by the increased AED, combined with an expansion of the forest cover (Martínez-Fernández et al., 2013). In contrast, a benchmark network characterized by near-natural conditions in the United Kingdom shows general increasing trends (Harrigan et al., 2018).

Finally, other factors may also play an important role in explaining streamflow changes in southwest Europe. For example, groundwater and base flow are strongly controlled by climate variability in the IP (Lorenzo-Lacruz et al., 2017; Neves et al., 2019; Sapriza-Azuri et al., 2015). There are numerous examples that illustrate aquifer overexploitation in regions of the IP to meet irrigated agriculture needs (Díaz-Paniagua & Aragonés, 2015; Dimitriou et al., 2017; Pulido-Velazquez et al., 2015; Rupérez-Moreno et al., 2017). Therefore, it is reasonable to consider that given observed trends in streamflow, groundwater resources may have also declined, producing feedbacks that finally contribute to the strong observed decline of streamflow.

4. Concluding Remarks

By employing a high density network of river flow gauges from countries bordering the northeastern Atlantic, we show that the influence of climate variability and change on annual streamflow can be obscured, or even reversed, due to complex irrigation and land cover changes. The impact of the latter is most pronounced in southern Spain. This suggests that human factors are sometimes more important than climate in understanding changes in annual streamflow trends. Furthermore, while recent studies have concluded that anthropogenic climate change explains declining streamflow trends in the Mediterranean region (e.g., Gudmundsson et al., 2017), we infer that the climate signal is relatively small in comparison to nonclimatic factors in southwest Europe. Increases in irrigated areas, agricultural intensification, and natural revegetation of marginal lands of Mediterranean mountain regions are the main drivers of decreases in streamflow in southwestern Europe.

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