Distribution, trends and drivers of flash droughts in the United Kingdom.

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Abstract

Flash droughts have been the subject of a great deal of scientific attention in the last decade, but the greatest emphasis has been on relatively dry climates. Here, we characterised the occurrence of this type of rapid-onset drought events in a more humid setting, the United Kingdom (UK), for the period 1969-2021. Our results show that flash droughts have affected both the wetter regions of north-west and the drier regions of south-east in every season over the last five decades. However, the spatiotemporal distribution of flash droughts is highly variable in the UK, with important regional and seasonal contrasts. Transition and North-West~~Central and northern~~ regions were generally the most frequently affected by flash droughts in comparison to ~~southeastern~~ South-East region. Overall, there are non-significant trends in flash drought frequencies in winter, summer, and autumn. Nevertheless, we found a significant ~~and notable~~ increase in the number of flash droughts recorded in spring months. We also analysed the relative contribution of the atmospheric evaporative demand (AED) and precipitation to flash drought development in the UK. Our findings show that~~In the UK,~~ flash drought occurrence responds primarily to precipitation variability in all seasons, and particularly in winter and autumn. In spring and summer, the ~~atmospheric evaporative demand (~~AED~~)~~ is important as a secondary driver for triggering flash droughts, especially in the drier regions of the southeastern the UK. Moreover, the trends observed in AED contribution~~our findings~~ evidence~~d~~ that ~~this~~ its relevance is rising significantly in spring and summer in the S~~s~~outh-E~~e~~ast region, over the study period. The atmospheric and oceanic conditions ~~controlling these anomalies in precipitation and AED that drive~~associated with flash droughts development were also ~~analyzed~~examined. Remarkable anomalies in sea level pressure and 500 hPa geopotential height associated with the presence of high-pressure systems were noted over UK during the development of the most severe flash droughts in all seasons. Likewise, flash drought development typically occurred under negative phase of North Atlantic Oscillation phase in winter and autumn, while in summer and spring positive phase is dominant. We also found positive anomalies in sea surface temperature during the development of flash droughts in spring and summer, while mixed anomalies were reported in winter and autumn. This study presents a detailed characterisation of flash drought phenomenon in the UK, providing useful information for drought assessment and management, and a climatology of flash droughts that can be used as a baseline against which future changes in flash drought occurrence can be assessed.

Keywords: flash drought, precipitation deficit, atmospheric evaporative demand (AED), Standardized Precipitation Evapotranspiration Index (SPEI), ocean-atmospheric conditions, North Atlantic Oscillation (NAO), United Kingdom.

1. Introduction

Drought is one of the most damaging natural hazards worldwide, with major impacts on natural and socioeconomic systems (Mishra and Singh, 2010; Wilhite, 2000; Wilhite and Glantz, 1985). It is also widely regarded as a very complex phenomenon – its development is usually slow, cascading through the diverse sectors affected in periods that range from months to years (Wilhite and Pulwarty, 2017). However, recent studies have demonstrated that some droughts events, commonly termed as "flash droughts", can develop at much shorter timescales (Otkin et al., 2018). Flash droughts are distinguished by an unusually rapid development associated with severe precipitation deficits that are often accompanied by increases in atmospheric evaporative demand (AED) associated, for example, with wave episodes (Pendergrass et al., 2020). Such rapid-onset drought events affects both humid and dry regions, causing important agriculture and environment impacts, particularly alongside elevated temperatures – including rapid decreases in soil moisture that result in agricultural stress and increase the risk of wildfires, and rapid declines in river flow that trigger impacts on aquatic wildlife (e.g. fish kills) and water quality problems like algal blooms, as well as localized challenges in meeting public water supply. In addition, flash droughts pose particular challenge for decision-making and drought management and communication, given their rapid onset (Otkin et al., 2022).

Nowadays, the study of flash droughts ~~has become~~is a topic of great interest to the scientific community and water managers. This interest is becoming even greater in the current context of climate change, where numerous studies suggest an increase in the frequency and severity of this kind of events in different regions around the world (Mishra et al., 2021; Noguera et al., 2022; Wang and Yuan, 2021; Yuan et al., 2018, 2019). Many efforts have been made in recent years to analyse flash drought phenomena using different approaches based on very diverse metrics (e.g. soil moisture, AED, precipitation, climatic water balance, etc.) (Lisonbee et al., 2021). Thus, several studies have assessed this phenomenon in various regions of the world over the last two decades from different perspectives (Walker et al., 2023). Despite progress in the understanding of this phenomenon, there are still many issues that are poorly understood, particularly those related to the drivers and mechanisms involved in triggering flash droughts. This is further complicated by the large seasonal and spatial variations in the characteristics of flash droughts, particularly marked between water-limited (i.e. dry areas ~~characterised by a low~~where evapotranspiration is constrained by water availability) and energy-limited (i.e. humid areas characterised by a high water availability) regions (Mukherjee and Mishra, 2022; Noguera et al., 2021). Furthermore, most of the literature on flash droughts focuses exclusively on a few regions (i.e. primarily United States and China) (Christian et al., 2024). As a result, there are still important gaps in the regional knowledge of flash drought characteristics in many regions of the world.

The greatest attention on flash droughts has been in dry (i.e. water-limited) regions as flash droughts are, intuitively, expected to have less impact in humid regions due to perceived high water availability. However, while they may be seemingly less damaging, flash droughts can also have very severe implications in humid regions (Zhu and Wang, 2021) and their frequency and rate of intensity may also increase under the currently context of global warming (Christian et al., 2023; Yuan et al., 2023). Some global studies suggest potential hotspots in regions characterised by energy-limited regime such as Northern Europe where precipitation is the main driver controlling flash drought occurrence (Mukherjee and Mishra, 2022). Other studies at regional scale also found a high frequency of flash droughts in Europe during the last three decades, which is mainly

Formatted: Indent: First line: 1.25 cm lead by a notable increase of flash drought events associated with rising temperatures (Shah et al., 2022).

~~This~~ Our study focuses on the United Kingdom (UK), a temperate oceanic, mild and mostly humid region characterised by a predominance of energy-limited conditions (Hulme and Barrow, 1997; Mayes and Wheeler, 1997), but with significant variations including some more water-limited areas in the south-east (Kay et al., 2013) – an area with a particularly fine balance between water supply and demand that already experiences significant water stress (Folland et al., 2015). Hence, while the UK is generally regarded as a wet country, it is regularly affected by severe droughts with major agricultural, hydrological, and environmental impacts (Barker et al., 2019; Pribyl, 2020; Spraggs et al., 2015).~~ Many studies have analysed drought phenomena in the UK, including; spatial and temporal characterisation (Burke and Brown, 2010; Rahiz and New, 2012; Tanguy et al., 2021), propagation through the hydrological cycle (Barker et al., 2016; Folland et al., 2015) or drought impact assessment on different environmental and socioeconomic systems (Byers et al., 2020; Dobson et al., 2020; Parsons et al., 2019), among others. However, most of drought studies in UK are focused on long times scales (e.g 12 months), while droughts developing at short-term have had comparatively little attention. In this way, no studies previously analysed specifically the occurrence of flash droughts in UK.~~ Although, ~~M~~most severe droughts affecting the UK are commonly related to long-term precipitation deficits (Marsh et al., 2007; Todd et al., 2013; Barker et al. 2019), dry spells at short-term in combination with anomalous increases in AED can have important agricultural, hydrological, and environmental implications.~~but notable increases in AED at short-term can be essential in explaining the rapid development and aggravation of some extreme droughts. In recent decades, several drought events strongly driven by rises in AED (e.g. associated with heat waves episodes) were reported~~ (Wreford and Neil Adger, 2010). Some studies broadly distinguish between 'multiannual' droughts that primarily affect southeast England (e.g. 2004 – 2006; 2010 – 2012), and within-year 'summer' droughts that can affect all areas (e.g. 1995, 2003) (Barker et al., 2019; Marsh et al., 2007). Many droughts are in fact a combination of these 'types'. It is certainly the case that some of the most testing historical droughts, including the 'benchmark' 1976 drought, have involved heatwave conditions associated with very high AED. Recent examples include the 2018 and 2022 summer drought (Barker et al., 2024; Turner et al., 2021), which caused severe impacts on fluvial and terrestrial ecosystems, water supply or crop yields as a result of a lack in precipitation that was exacerbated by rapid increases in AED.

~~Under climate change, numerous studies suggest a general increase in drought severity (Dai, 2011; Vicente-Serrano et al., 2022) associated with the rise of AED at global scale (Vicente-Serrano et al., 2020; Wang et al., 2012). In this direction, some studies focused on flash drought showed an increase of this kind of events in different regions around the world related to global warming (Mishra et al., 2021; Noguera et al., 2022; Wang and Yuan, 2021; Yuan et al., 2018, 2019). In UK, various studies suggest an increase in drought frequency and severity (Rahiz and New, 2013; Reyniers et al., 2023), as well as the impacts associated with these hydroclimatic events (Gosling, 2014; Richter and Semenov, 2005) as a consequence of climate change. While there is significant uncertainty in future projections of how multiannual droughts will evolve in future (Lane and Kay, 2021), future projections of hotter, drier summers suggest a high likelihood in the increase in more widespread (Tanguy et al., 2023) within-year summer droughts (Parry et al., 2024), and with this, likely increases flash droughts. Before such future changes can be quantified, there is a need to understand an observational baseline of flash drought occurrence and identify any emerging trends.~~

Thus, drought dynamics over the UK are quite complex, affecting the region at different regional and temporal scales (Tanguy et al., 2021). This complexity is a result~~The greatest attention on flash droughts has been in dry (i.e. water-limited) regions as flash droughts are, intuitively, expected to have less impact in humid regions such as UK due to perceived high water availability – noting, as discussed, that in reality parts of the south-east are relatively dry and subject to tangible water stresses. Moreover, while they may be intuitively less prevalent the occurrence of flash droughts can also have very severe implications and their frequency and severity may also increase under global warming. Therefore, it is needed to understand the characteristics of flash drought in these regions, as well as unravel the process and mechanisms controlling its occurrence. The UK climate is complex, with different~~ of the diverse synoptic mechanisms ~~operating at different spatial scales~~controlling climate variability, but also by the strong ocean-atmosphere interactions and the orographic configuration ~~in the region~~ (Mayes and Wheeler, 2013). Among others, the strong influence of large-scale drivers such as North Atlantic Oscillation (NAO) is well ~~known~~recognised for driving precipitation~~controlling climate~~ variability over the UK, especially in northern and western regions and during winter months (Fowler and Kilsby, 2002; Lavers et al., 2010; Murphy and Washington, 2001; West et al., 2019, 2021b). Some studies have also shown that other large-scale circulation patterns such as the East Atlantic Pattern, Scandinavian pattern play a secondary role in modulating precipitation in the UK (Bueh and Nakamura, 2007; Hannaford et al., 2011; Ummenhofer et al., 2017; West et al., 2021a), while there is also an underlying role for slowly-varying modes of ocean-atmosphere variability such as the Atlantic Multidecadal Oscillation and ENSO (Folland et al., 2015; Svensson and Hannaford, 2019). While there is a good general understanding of these mechanisms in driving rainfall variability, their role in droughts is complex, and hence there is a gap in the understanding of the drivers of both multi-annual and short-term flash droughts.

Although numerous studies have analysed drought phenomena in the UK, most of drought studies in the UK are focused on long times scales (e.g 12-months), while droughts developing at short-term have had comparatively little attention. Therefore, it is essential to understand the characteristics of flash drought in these regions and any emerging trends, as well as unravel the process and mechanisms controlling its occurrence. In this study, we present a detailed characterisation of the flash drought phenomenon in the UK, making ~~the first (to the authors' knowledge)~~a comprehensive, national-scale analysis of flash droughts in this region- and one which can serve as a testbed for other relatively wet locations which may expect to see increases in ~~flash drought~~short-term drought severity in future (Parry et al., 2024; Tanguy et al., 2023). To achieve this purpose, we address several objectives: i) to characterise the spatial and temporal occurrence of flash droughts over the UK; ii) to analyse the observed trends in their frequency over the last five decades; iii) to assess the role of the different meteorological factors involved in this type of drought events; and iv) to identify the atmospheric and oceanic conditions under which flash droughts develop.

2. Data and methods

2.1 Meteorological data

We employed gridded precipitation and potential evapotranspiration~~rative~~ (PET) data with high spatial and temporal resolution for the UK in the period 1969-2021. On the one hand, precipitation daily data at 1km^2 was obtained from the Met Office Hadley Centre for Climate Science and Services (Met Office, 2018). All details on the creation and validation of the gridded precipitation data are provided by Hollis et al. (2019). On the other hand, PET daily data at 1km^2 was obtained from Environmental Information Data Centre (EIDC) (Brown et al., 2023). PET data was obtained from maximum and minimum air temperature, relative humidity, sunshine duration, and wind speed by means of Penman-Monteith equation, providing a robust metric of atmospheric evaporative demand (AED). Additional details about the creation, validation, and computation of gridded dataset in (Robinson et al., 2023). Daily information of precipitation and AED was aggregated weekly to calculate the climatic water balance (i.e. difference between precipitation and AED), which was employed to obtain the Standardized Precipitation Evapotranspiration Index (SPEI) (Vicente-Serrano et al., 2010).

2.2 Flash drought identification

We used the SPEI to identify flash droughts as it is sensitive to the variability of precipitation and AED (Tomas-Burguera et al., 2020), thus considering the main meteorological drivers of flash droughts triggering. SPEI is based on the standardisation of the difference between precipitation and AED (i.e. climatic water balance), providing comparable values in time and space (Beguería et al., 2014). In addition, SPEI is a multiscalar index that allows to fit computation time scale to the temporal response of the diverse natural and human systems affected by drought. Thus, many studies have used SPEI to analyse the response of hydrological (Lorenzo-Lacruz et al., 2010; Peña-Gallardo et al., 2019a; Vicente-Serrano and López-Moreno, 2005), agricultural (Peña-Gallardo et al., 2018b, 2019b; Potop et al., 2012) and environmental (Peña-Gallardo et al., 2018a; Vicente-Serrano et al., 2013, 2014; Zhang et al., 2017) systems to drought. Moreover, several studies have also demonstrated the good performance of SPEI for flash drought assessment (Hunt et al., 2014; Noguera et al., 2020, 2021).

In this study, we identified flash drought events over the UK following the definition~~As~~ suggested by Noguera et al. (2020).~~,~~ For this purpose, we ~~employed~~ calculated the SPEI at ~~a short time scale (~~1-month~~)~~ time scale and high temporal resolution (i.e., weekly data frequency~~ (weekly~~). Using a short time scale allows for capturing short-term anomalies characteristic of flash drought, while avoiding considering the meteorological anomalies record at long-term. T~~t~~o identify rapid and anomalous changes in humidity conditions associated with flash droughts onset (Otkin et al., 2018; Svoboda et al., 2002), this method is focuses on the identification of quick declines in SPEI values over short periods that reach a certain severity (moderately dry conditions). Thus, a flash drought is defined as a decline in SPEI 1-month values equal to or ~~less~~ higher than ~~-~~2 z-units over a ~~four~~4-week period ~~(i.e. development phase)~~ that ends in a SPEI value equal to or less than -1.28 z-units (corresponding to a return period of 10 years) (Figure A1). The ~~four~~4-week period established for the identification of the events, which correspond to the development phase, allows ~~the metric~~ to capture rapid variations in humidity conditions~~, but which~~ that persist long enough to expect some impact (Noguera et al., 2020), ~~which is consistent~~agreeing with some of the most widely used definitions for the assessment of flash droughts (Anderson et al., 2013; Chen et al., 2019; Christian et al., 2019; Osman et al., 2020; Mukherjee and Mishra, 2022). Applying this definition, we identified all flash drought events that occurred in the UK over the period 1969-2021 at seasonal scale (winter: DJF, spring: MAM, summer: JJA, autumn: SON), as well as for the growing-season (MAMJJAS). We assigned flash droughts seasonally based on the week in which their onset was identified. ~~Further details of the method employed to identify flash drought events can be found in Noguera et al. (2020).~~

Given the large climatic differences across the UK, we carry out flash drought analysis at regional scale. There is a strong southeast-northwest gradient in precipitation across the UK, with values ranging from >3000mm to <600mm annually (Mayes and Wheeler, 2013). This strong gradient results in important differences between the drought patterns observed in the wetter northwestern and the drier southeastern regions. In order to assess the possible regional differences in flash drought characteristics, we considered three regions: North-West, Transition and South-East (Figure A2~~1~~). The regional division used here is derived from Tanguy et al. (2021), who used a k-mean clustering technique to divide the UK into three regions based on long-term (1862-2015) precipitation patterns. This delineates a wetter (i.e. North-West) and a drier region (i.e. South-East), as well as a transitional region (Transition) between both. Since flash droughts are primarily driven by precipitation variability (Hoffmann et al., 2021; Koster et al., 2019), it is expected to be the most important factor controlling their characteristics and spatiotemporal behaviour in the UK.

2.3 Assessment of the AED contribution

To unravel the contribution of AED to SPEI we calculated the index allowing precipitation to vary according to the observed climate evolution, while the AED remained at its mean value, which was set at the average AED ~~for~~ in each week ~~of the year~~ over the period 1969–2021. This version of the index (hereafter referred to as

SPEI_PRE) that only responds to precipitation variations was compared with the original SPEI series. In order to determine the relative contribution of AED to the development of flash droughts, we considered that the difference between zero and SPEI_PRE was due to precipitation variability, while the difference between SPEI_PRE and SPEI was due to the contribution of AED. The differences were expressed as percentages, and for those weekly data in which SPEI_PRE was equal to or less than SPEI, the AED contribution was considered 0%. This type of approach has been used in numerous studies to calculate the relative contribution of different variables in triggering drought conditions (Cook et al., 2014; Noguera et al., 2022; Scheff and Frierson, 2014; Williams et al., 2015; Zhao and Dai, 2015).

Given that our objective is to analyse the role of the AED as a driver of flash drought development, we examined the contribution of the AED in the weekly data corresponding to the onset of each of the flash drought events identified, as it captures the cumulative anomaly in the climatic balance over the four-week period of the development phase. Furthermore, we specifically analysed the spatial and temporal patterns of the AED contribution to the development of flash droughts for the three regions considered and on a seasonal scale over the period 1969–2021.

2.4 Atmospheric and oceanic data

To analyse the atmospheric mechanism underlying flash drought ocurrence in the UK, we focused on atmospheric conditions recorded during the development phase (i.e. the four-week prior to flash drought onset). In order to show a set of events representative of the atmospheric conditions typically associated with the triggering of flash droughts, we focus on the events with the largest area affected. For this purpose, we selected the top-10 flash droughts identified in each season (winter: DJF, spring: MAM, summer: JJA and autumn: SON) for the period 1969-2021 according to the ~~percentage~~ number of the total grid points that recorded flash drought conditions~~UK area affected~~ in a given week.

We employed daily sea level pressure (SLP) and 500 hPa geopotential height (Z500) data obtained from the National Centers for Environmental Prediction (NCEP)–National Center for Atmospheric Research (NCAR) reanalysis (Kalnay et al., 1996) for the domain study (25ºN-70ºN, 45ºW-45ºE) over the period 1969-2021 at 5º spatial resolution. To illustrate the synoptic situations associated with flash drought, we calculated SLP and Z500 anomalies during the development of the top-10 flash droughts identified in each. The anomalies are relative to the average SLP and Z500 over the period 1969-2021. We also evaluated the possible seasonal relationship between flash drought ocurrence the most important large-scale circulation patterns affecting the UK: North Atlantic Oscillation (NAO). For this purpose, we calculated NAO index (NAOi) following the approach proposed by Jones et al. (1997), which is based on the differences between normalised SLP at the points 36°N, 5°W (Gibraltar, United Kingdom) and 65°N, 20°W (Reykjavik, Iceland). Then, we computed the average anomalies recorded in NAOi during the development of the top-10 flash droughts identified in each season over the period 1969-2021.

To examine the possible connection between the development of flash droughts and oceanic conditions, we analysed sea surface temperature (SST) anomalies during the development phase of the top-10 flash droughts identified in each season (winter: DJF, spring: MAM, summer: JJA and autumn: SON) for the period 1982-2021 according to the percentage of the UK area affected in a given week. We employed daily SST anomalies data obtained from the National Centers for Environmental Prediction (NCEP)–National Center for Atmospheric Research (NCAR) reanalysis for the domain study (25ºN-70ºN, 45ºW-45ºE) over the period 1982-2021 at 0.25º spatial resolution. In this case, we focus on the period 1982-2021, instead of the period 1969-2021, given the temporal availability of the data.

2.5 Trends calculation

We examined the magnitude of change in flash drought frequencies using a linear regression analysis between the time series (independent variable) and the time series of flash droughts (dependent variable). We also employed this approach to calculate the seasonal magnitude of change in Precipitation, AED, and AED contribution to flash drought development. Then, to assess the significance of the trends over the period 1969-2021, we employed the nonparametric Mann-Kendall statistic. Autocorrelation was included in the trend analysis using the modified Mann-Kendall trend test, which returned corrected p-values after accounting for temporal pseudoreplication (Hamed and Ramachandra Rao, 1998; Yue and Wang, 2004).

3. Results

3.1 Spatial distribution and trends

The spatial distribution of flash droughts in the UK shows a large seasonal variability in the UK, as well as important regional differences (Figure 1). In winter, the highest number of flash droughts was recorded in Northern Ireland and central UK, while the south coast and northeastern region reported the lowest number of events. Large areas ~~along~~ across the north-south axis of the UK and Northern Ireland were highly affected by flash droughts in spring, with more than 15 events reported over the study period. By contrast, southeastern and northwestern regions are generally least affected by flash droughts during the spring. A clear gradient in the number of flash droughts was noted in summer, with important variations from the southeast, where a low number of flash droughts are found (5-10 events), to the northwest of the UK, which recorded the highest number of events. In autumn, Northern Ireland and southwestern region were more frequently affected by flash droughts, whereas southeastern and northeastern regions reported the lower occurrence of events.

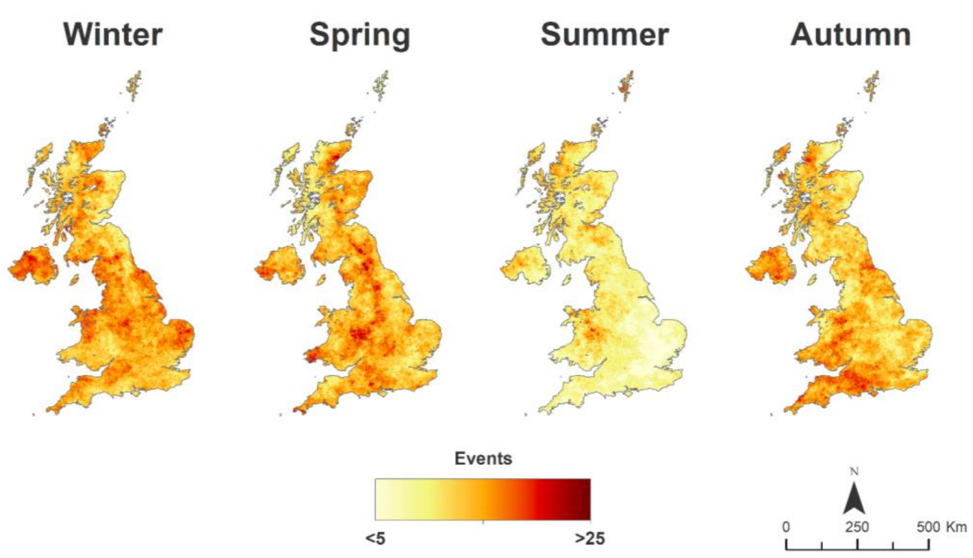

Figure 1. Seasonal spatial distribution of the total number of flash droughts in the United Kingdom for the period 1969-2021.

Focusing on the growing-season, when the impacts associated to flash drought are expected to be greater, it is possible to recognis~~z~~e~~d~~ large areas affected by flash droughts along the north-south axis of the UK (Figure 2). Among others, the west of UK and Northern Ireland were the most affected areas, with more than 35 events recorded. Whereas southeastern UK ~~were~~ was the least frequently affected by flash droughts. The average number of events occurring~~ed~~ for the whole of the UK is around 28 events during the growing-season for the period 1969-2021, although there are some relevant differences between regions. In general, the Transition (TRAN) and North-West (NW) regions were affected more frequently compared to South-East (SE) region. Also, SE region shows the higher variability due to the contrasts observed in the average number of flash droughts reported across the region.

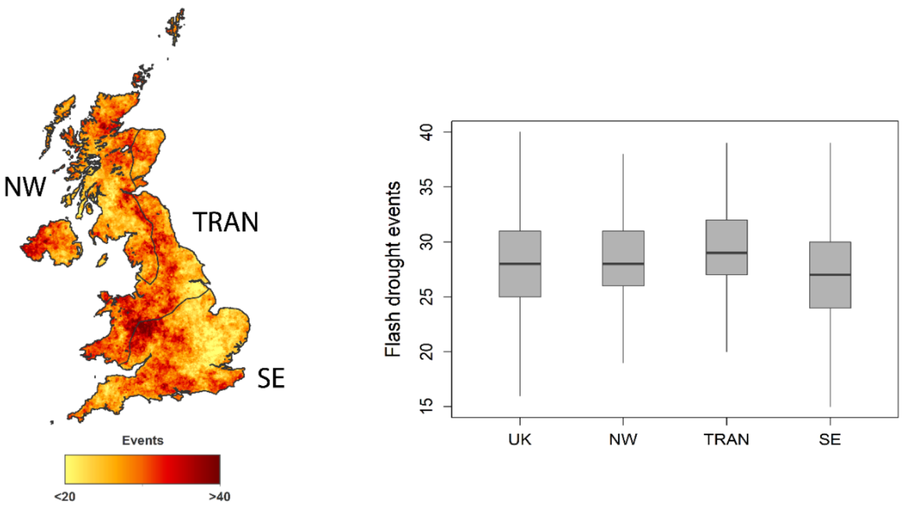

Figure 2. Spatial distribution of the total number of flash droughts during the growing-season (from March to September) in the United Kingdom for the period 1969-2021.

Figure 3 shows the seasonal frequencies of flash droughts (events/pixel) in the UK for each season over the period 1969-2021. The seasonal series show a high interannual variability, highlighting the period around the late 1980s and early 1990s in which the UK was frequently affected by flash droughts. Overall, non-significant trends are observed, with negative and non-significant trends in winter, summer, and autumn. In contrast, there is a positive and significant increase in the number of flash droughts in spring. At the regional scale, seasonal series also reflect a high variability and generally non-significant trends (Figure A3~~2~~). In winter, the Transition (TRAN) and South-East (SE) regions show no relevant changes in the frequency of flash droughts, while a slight and non-significant decrease in the number of events is reported in the North-West (NW) region. On the contrary, positive trends are observed in all regions in spring, although these trends are only significant in NW and TRAN regions. In summer, there are important differences between the NW and TRAN region, with a negative and even significant trend in the case of TRAN region, and positive and non-significant trend in the SE region. The autumn series show negative and non-significant trends in all regions, but especially in SW and TRAN regions as a result of the high occurrence of flash droughts in the early decades of the series.

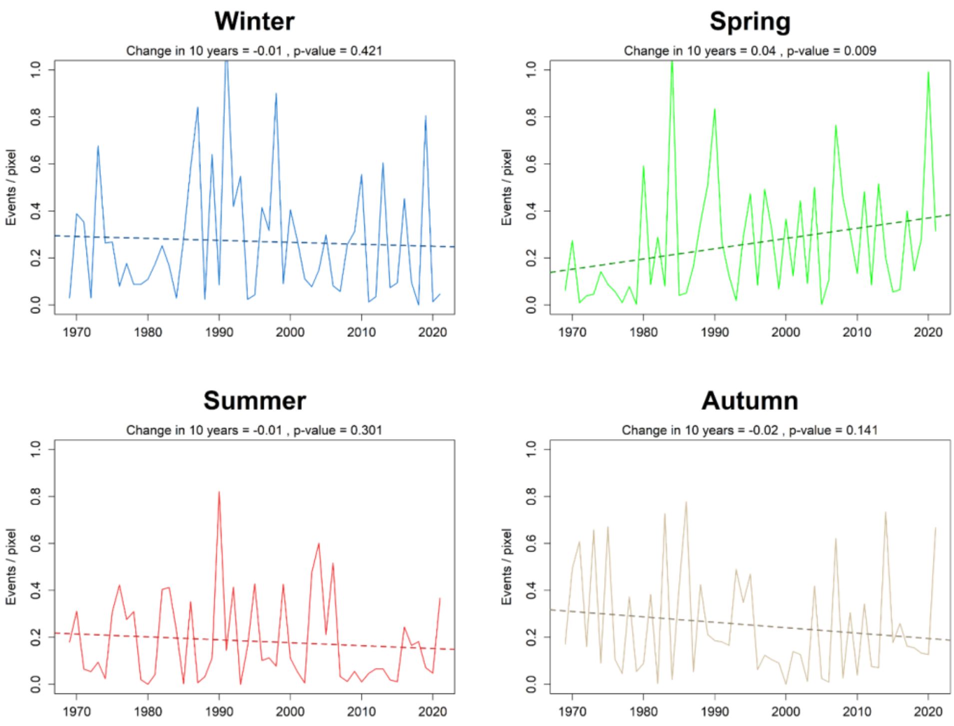

Figure 3. Seasonal evolution of the number of flash droughts (events/pixel) in the United Kingdom for the period 1969-2021.

The spatial distribution of the seasonal trends of flash droughts for the period 1969-2021 is depicted in the Figure 4. In general, there are important spatial and seasonal differences in the trends observed. Non-significant trends over most of the UK are recorded in winter months, and only a few small areas in the north show a significant trend. In spring, there is a clear dominance of positive trends, which are significant in ~~many~~ some areas across the UK. Negative and non-significant trends predominate in summer months, except for the southeastern UK, where positive and generally non-significant trends are noted. In autumn, negative and non-significant trends are also recorded over most of the UK, except for ~~some~~ a few small areas in northern region.

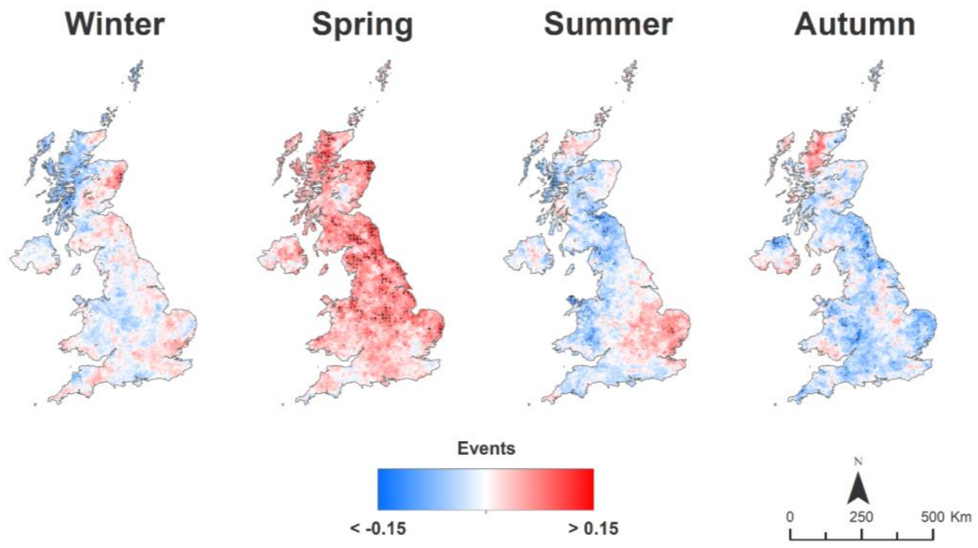

Figure 4. Spatial distribution of the seasonal magnitudes of change per decade in flash drought events in the United Kingdom for the period 1969-2021. Dotted areas represent those areas in which significant trends were reported.

During the growing-season, non-significant trends are noted for the whole of the UK, although there are important spatial differences in the magnitude and sign of the trends (Figure 5). Positive trends were generally reported in eastern and northern regions, observing significant increases in some areas around southeastern and northern UK. By contrast, negative and non-significant trends predominate over the west of the UK. There are also important differences in the frequency of events identified during the growing-season in each region, although non-significant increases are observed. Notable periods of high flash drought occurrence were observed in 1980-1990 over the NW and TRAN regions, and in 2000-2010 over the TRAN and SW regions.~~Highlight period by a high occurrence of flash droughts in 1980-1990 over NW and TRAN, and in 2000-2010 over TRAN and SW regions.~~

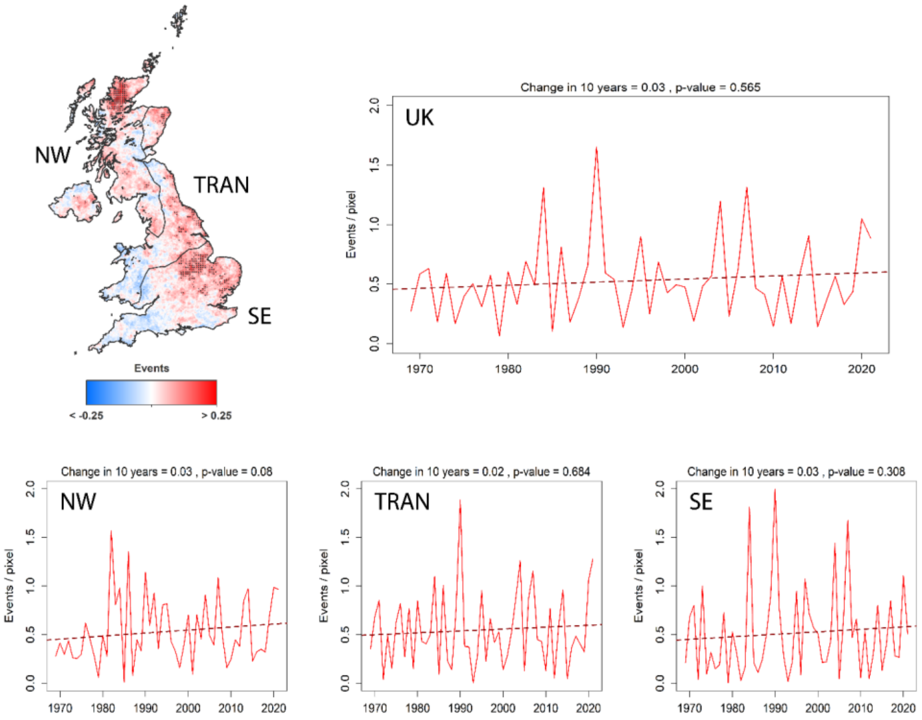

Figure 5. Magnitude of change per decade in the flash drought frequencies (events/pixel) observed during the growing-season (from March to September) over the United Kingdom for the period 1969-2021. Dotted areas represent those areas in which significant trends were reported.

3.2 Flash drought response to precipitation and AED

Figure 6 shows the seasonal spatial distribution of the average contribution of the ~~atmospheric evaporative demand (~~AED~~)~~ to flash drought development in the UK for the period 1969-2021. As expected, the contribution of the AED to flash drought development shows large spatial and seasonal contrasts as a result of the large climatic variability of the UK (Figure A4~~3~~). In general, the average AED contribution exhibits a strong spatial coherence with the average precipitation at seasonal scale (Figure A4~~3~~a). In winter, when the precipitation is very high and AED rarely exceeds 50mm, the average AED contribution is close to zero over most of the UK except for some areas of the east. The maximum values of the AED contribution are found in spring months, with large areas over central, eastern, and especially southeastern UK exceeding 15%. In these areas, the average precipitation reaches its seasonal minimum, while the AED increases notably compared to the winter months. The AED contribution in summer also depicts average values around 15% in a few areas of the south, where the average precipitation is lower and the average AED reaches its maximum values (Figure A4~~3~~b), but in general most of the UK shows a low average AED contribution to flash drought development. In autumn, with the increase in precipitation and the decline in AED, most of the UK shows average AED contribution values close to zero and only some areas of the east record higher average values (5-10%).

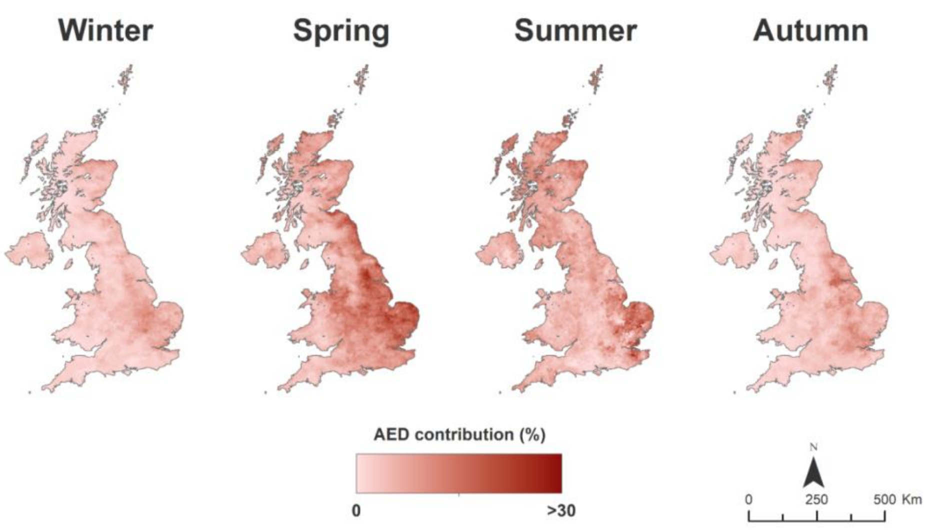

Figure 6. Seasonal spatial distribution of the average contribution of AED to flash drought development in the United Kingdom for the period 1969-2021.

The evolution of the average AED contribution to flash drought development also exhibits important interannual variations in each season over the period 1969-2021 (Figure 7). There is a significant increase in AED contribution in spring, which is particularly notable since the early 1990s. No relevant changes are noted in winter and autumn, while there is a slight and non-significant increase in the AED contribution in summer. In general, the changes reported in the average AED contribution to flash drought shows a consistent relationship with the trends observed in the average rainfall and AED at seasonal scale (Figure A5~~4~~). Thus, spring, the only season with a significant increase in AED, is also the only season that does not show an increase in rainfall, which additionally concurred with a significant increase in AED.

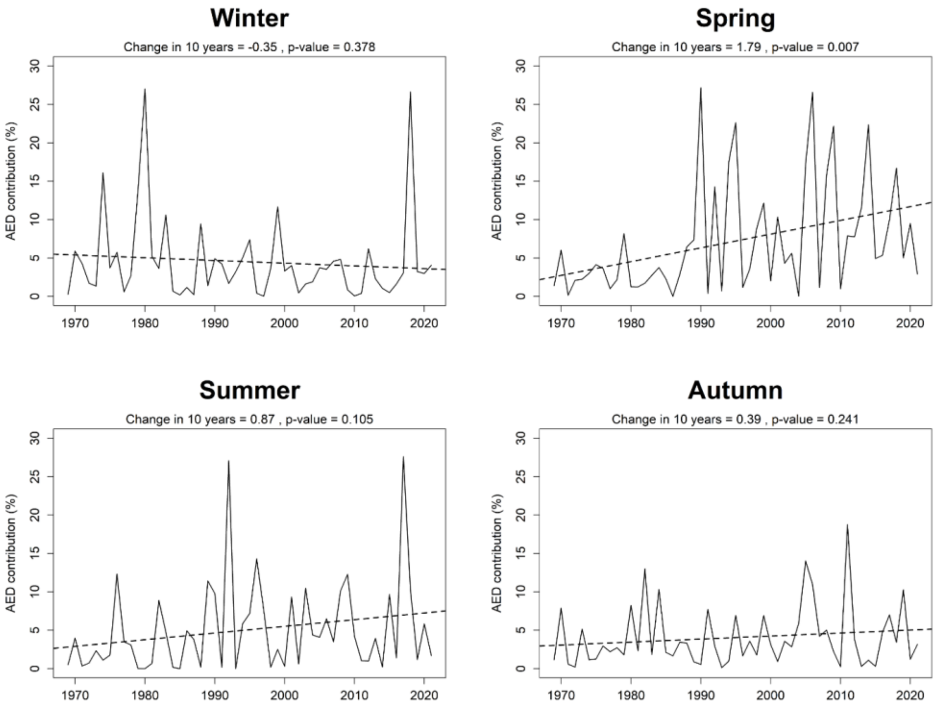

Figure 7. Seasonal evolution of the average contribution of AED to flash drought development in the United Kingdom for the period 1969-2021.

At regional scale, some relevant differences in the evolution of the AED contribution are noted (Figure A6~~5~~). A decrease in AED contribution is recorded in TRAN and SE region in winter, although only the SE region exhibits a significant trend. By contrast, all regions show an increase in AED contribution in spring, which is significant in NW and TRAN regions. In summer, a general increase in AED contribution is recorded, but this increase only is significant in SE region. In autumn, a significant decrease in AED contribution is recorded in NW region, while regions TRAN and SE show non-significant increases. In general, there is also a clear regional relationship between the evolution of AED contribution and precipitation and AED patterns in each region (Figure A7~~6~~ and A8~~S7~~).

3.3 Atmospheric and oceanic conditions during flash drought development

Figure 8 shows the seasonal composites of 500 hPa geopotential height (Z500) and sea level pressure (SLP) anomalies during the development of the top-10 flash droughts recorded in each season for the period 1969-2021. Overall, notable positive Z500 anomalies are recorded during flash droughts development over the UK and western Europe in all seasons, exceeding 50m in summer and spring, or even 100m in winter and autumn. Similarly, high SLP anomalies are recorded during flash droughts development in all seasons, although there are some seasonal variations. The highest anomalies in SLP are recorded in winter, with values higher than 10 hPa around the UK. Notable anomalies in SLP are also noted in spring and autumn, exceeding 6 hPa. In summer, the positive anomalies reach the lowest values (2-4 hPa).

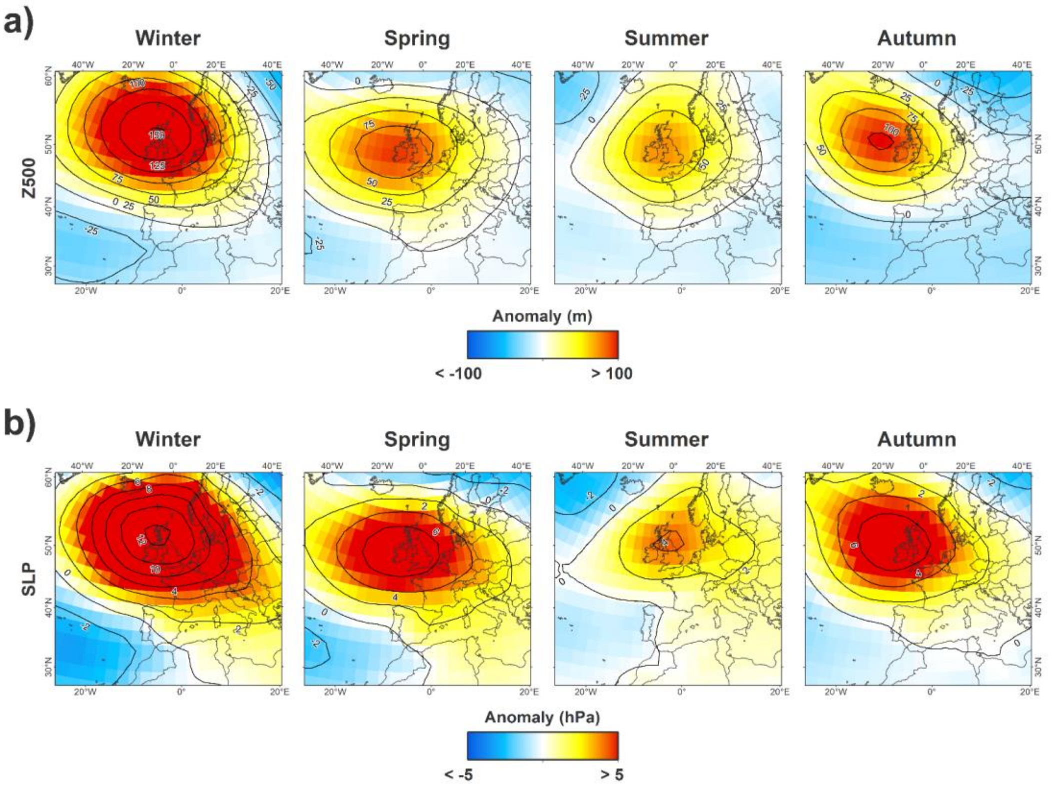

Figure 8. Seasonal composites of **(a)** Z500 and **(b)** SLP anomalies during the development of the top-10 flash droughts of each season over the United Kingdom for the period 1969-2021.

The average anomalies in the North Atlantic Oscillation index (NAOi) during the development of the top-10 flash droughts of each season are presented in Figure 9. Important seasonal differences were noted in NAO phase during the development of flash droughts, with a marked contrast between winter-autumn and summer-spring months. In winter and autumn, remarkable and negative anomalies in NAOi are recorded, with average values around -1, but in some cases are less than -2. By contrast, positive and moderate NAOi anomalies are dominant during the development of the flash droughts occurred in spring and summer months.

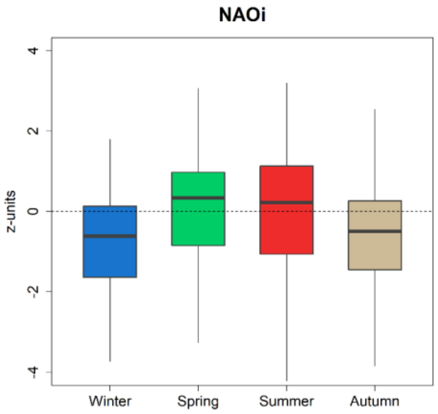

Figure 9. Seasonal North Atlantic Oscillation index (NAOi) values during the development of the top-10 flash droughts of each season over the United Kingdom for the period 1969-2021.

Finally, the seasonal anomalies in sea surface temperature (SST) were examined during the development of the top-10 flash droughts recorded in each season for the period 1982-2021 (Figure 10). Positive SST anomalies are generally recorded during the development of the flash drought in spring and summer over the Atlantic Ocean around the UK and western Europe coast, with anomalies that generally exceed 1ºC in summer months. By contrast, we found a higher spatial variability in SST during winter and autumn, with both positive and negative anomalies recorded during the development of flash drought in these seasons over the Atlantic Ocean around the UK. Positive and remarkable anomalies were also observed~~r~~ over some areas of the Arctic Ocean in all seasons, which exceed 1ºC.

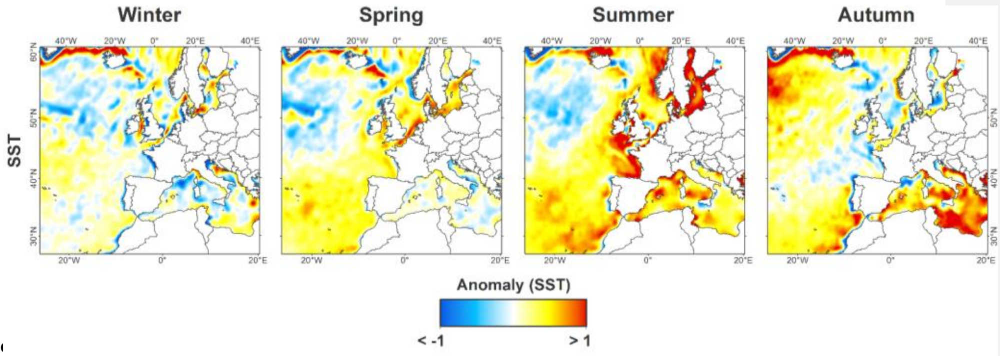

Figure 10. Seasonal anomalies (ºC) in sea surface temperature (SST) during the development of the top-10 flash droughts of each season over the United Kingdom for the period 1982-2021.

4. Discussion

4.1 Characteristics and trends of flash droughts in the UK

This study analysed the occurrence of flash droughts in the UK over a long-term period. The results ~~evidence~~ indicate that flash drought is characterised by a high variability, with important regional and seasonal differences. Droughts in the UK exhibits a great spatiotemporal variability (Tanguy et al., 2021) and, naturally, this complexity also extends to flash drought patterns. However, the patterns of these rapid-onset droughts occurring~~ed~~ at short times scales vary notably from those found by previous studies focused on long-term droughts (Burke and Brown, 2010; Dobson et al., 2020; Rahiz and New, 2012). Our finding shows that both the wetter regions of the North-West and the drier areas of the South-East were affected by flash drought in all seasons over the last five decades. Overall, the highest frequency of flash drought is reported in Wales and Northern Ireland, while the southeastern regions reported the lowest number of events. The high number of events recorded in some humid regions of the central and northern UK could be a response to the frequent occurrence of short dry periods compared to the southeastern regions, where rainfall is notably lower as well as less variable, so these rapid dry spells may be less frequent but more relevant in terms of impacts. For example, Tanguy et al. (2021) found that northwestern regions tend to be more frequently affected by short-term droughts, while the southeastern regions are affected by droughts less frequently but with greater severity. In late autumn and winter, it is expected that flash droughts have little environmental impact as deficits built up during short dry periods are quickly replenished by wet periods, although these dry spells may still be relevant from a hydrological point of view given the quick response (~1-month) of UK catchments to rainfall scarcity, especially in the north (Barker et al., 2016). Conversely, flash droughts occurring in spring, summer, and early autumn (i.e. growing-season), which affect central and western UK more frequently, are expected to have important environmental and agricultural implications. During this period vegetation demands more water and precipitation deficits associated with droughts are often accompanied by increased temperatures leading to vegetation stress (Pribyl, 2020), with ~~attendant~~ significant environmental and agricultural impacts, as apparent during recent summer half-year droughts (Barker et al., 2024; Turner et al., 2021).

In general, there are no compelling major increases in flash drought frequencies for the period 1969-2021. Previous studies focussing~~ed~~ on long-term drought (e.g. 3-, 6- and 12- months times scales) also reported few changes in drought occurrence over most of the UK (Tanguy et al., 2021; Vicente-Serrano et al., 2021). Nevertheless, we found a notable and significant increase in the number of flash droughts recorded in spring. Recent studies based on soil moisture data from reanalysis suggest an increase in flash drought frequency at European scale associated with the rise of evaporative demand in the last few years (Shah et al., 2022). In this case, we noted some parallels between the trends in flash droughts and the recent evolution of rainfall and AED over the UK at seasonal scale (see Figure A5~~4~~). Thus, the only season in which precipitation has not increased and AED has ~~raised~~ risen significantly (i.e., spring), is the only one that shows a general increase in flash drought frequency. On the contrary, the seasons in which the average precipitation has increased show generally negative and non-significant trends. Therefore, there is a seasonal consistency between flash drought frequencies and the spatiotemporal patterns noted in rainfall and AED over the UK. During the growing-season, when the impacts of this kind of events are expected to be greater, we observed significant increases in the eastern regions due to the increase in the number of events observed in spring and summer over these areas, although there is no clear trend for the whole of the UK as well as for each of the regions considered.

4.2 Meteorological drivers underlying flash droughts

Flash droughts in the UK are strongly driven by precipitation variability, particularly in winter and autumn. In these cold and wet months in which AED is very low (Mayes and Wheeler, 2013), drought triggering depends almost exclusively on the occurrence of deficits in rainfall and AED is irrelevant with a few exceptions. The results evidenced that AED role is ~~only relevant in~~mainly limited to the drier regions of the southeast in spring and summer, when rising temperature (e.g. associated with heat wave episodes) combined with precipitation deficit can exacerbate pressure on water resources, amplifying drought impacts (Turner et al., 2021). By contrasts, in humid regions such as northern UK, AED has a minor role in triggering droughts. In these regions characterised by energy-limited conditions, under normal (wet) conditions, an increase in AED would have no impact~~s~~ (Vicente-Serrano et al., 2020). Thus, it is expected that AED ~~is~~ only plays a relevant role in driving drought conditions during very dry periods as rainfall is a key factor determining the effect of AED on drought (Tomas-Burguera et al., 2020). Indeed, there is a clear spatial relationship between mean precipitation (e.g., Figure A4 b) and the AED contribution to flash drought (e.g., Figure 6), which shows the same northwest-southeast gradient observed in rainfall distribution.

Although rainfall is the primary factor controlling flash drought variability in the UK, we found that the role of AED is becoming more relevant in triggering summer and spring flash droughts. This is especially evidenced in spring, when a significant increase in AED was noted, but also in southeastern region in summer. Curiously, the maximum percentages of AED contribution to flash drought development were generally found in spring rather than in summer. This pattern may be explained by the notable increase in AED contribution in spring since late 1980s associated with the general rise of AED in this season (Blyth et al., 2019; Robinson et al., 2017), but also by the anomalous higher-than-average precipitation recorded during summer (Kendon et al., 2022) compared to spring over recent few years. In other words, spring was the driest season in the UK over the last five decades. The trends observed in AED contribution could be relevant to understand the recent trends observed in flash droughts occurrence in summer and, particularly, in spring. We found that those regions and seasons, in which AED contribution increased, generally show positive trends in flash drought frequency. Previous studies have linked the increase in the frequency and severity of flash droughts in some regions of the world to the growing relevance of AED as a driver of drought conditions under global warming (Mishra et al., 2021; Noguera et al., 2022; Yuan et al., 2018, 2019).

4.3 Atmospheric and oceanic conditions involved in flash drought development

The atmospheric and oceanic conditions preceding the onset of flash droughts in each season were examined in order to identify the possible mechanism behind the strong anomalies related with this kind of events (Figure A9). Typically, f~~F~~lash droughts develop~~ment is~~ under ~~strongly associated to~~ the presence of high-pressure systems over the UK. Remarkable anomalies in SLP and Z500 were noted during the development of flash droughts in all seasons, but particularly in winter. The patterns observed typically respond to the northward displacement of the Azores High, resulting in blocking situations that prevent the arrival of humid air masses and, consequently, inhibiting precipitation (Richardson et al., 2018). In winter and autumn, the location of the pressure fields corresponds to the typical patterns of the negative phase of the NAO. Thus, the development of flash droughts in autumn and particularly in winter, is commonly associated with strong negative anomalies in NAOi. Numerous studies have demonstrated the relationship between the negative phase of the NAO and the absence of precipitation during these seasons (Fowler and Kilsby, 2002; Murphy and Washington, 2001; West et al., 2021b), particularly in northwestern regions (West et al., 2019). In addition, the negative phase of the NAO in winter usually coincides with cold periods (Hall and Hanna, 2018), which would reinforce the negligible role of the AED compared to that of rainfall during these months as well as the negative anomalies observed in AED (Figure A9). On the contrary, positive anomalies in NAOi are generally recorded in spring and summer, although these anomalies are highly variable. During these months, there is not a strong relationship between precipitation variability and NAO phase (West et al., 2021b), which would explain why the anomalies recorded during these months are generally more variable. NAO is the main large-scale atmospheric circulation pattern that controls precipitation variability (West et al., 2021a), and its links with drought occurrence is well-know (West et al., 2022). The anomalies observed during the previous weeks to flash drought onset confirm that flash drought development is also closely connected with NAO phase, especially in winter.

Flash droughts usually develop during period of positive SST over the Atlantic Ocean around the UK and western Europe coast in spring and summer, while no clear patterns in SST anomalies are recorded in winter and autumn flash droughts. The influences of SST on drought are quite complex considering the strong oceanic-atmospheric interactions and its crucial role modulating large-scale atmospheric circulation patterns (Robertson et al., 2000). Several studies showed how SST anomalies over the Atlantic Ocean can have an important role driving precipitation and, consequently, drought variability over Europe ~~at~~ in the long-term (Ionita et al., 2015; Rimbu et al., 2001). Recent studies also noted that SST anomalies can play certain role driving drought events developing ~~at~~ in the short-term as flash droughts (Ma et al., 2024). In the case of the UK, SST patterns over the Atlantic Ocean are very important in promoting drought occurrence given their influence on atmospheric circulation, including the NAO (Kingston et al., 2013; Svensson and Hannaford, 2019). Here, we found some similarities with the patterns observed ~~for~~ in other studies that showed a connection between drought occurrence in UK and periods characterised by positive SST anomalies in eastern Atlantic Ocean and the Arctic Ocean prior to the onset of spring and summer drought (Kingston et al., 2013; McCarthy et al., 2019). This seems to suggest that these anomalies may have some relevance in favouring the development of flash drought events, although this issue requires further research.

4.4 Limitations and future work

Despite the consistency of the results with the meteorological observations as well as the ocean-atmospheric conditions, there are some issues that should be carefully considered in interpreting our findings. Firstly, adopting an approach for flash drought identification based exclusively on meteorological data does not provide a measure of drought impacts. In addition to meteorological data, a comprehensive assessment of drought conditions would ideally require the use of different source of data, including; data on vegetation activity, soil moisture and streamflow variability, or crop yield, among others (Otkin et al., 2022). Some of these datasets have constraints (e.g. relatively short records) so we focused our study on meteorological data that enabled us to carry out our study over the~~at~~ long-term. Future work could link flash drought occurrence, as reported here, with hydrological drought responses and agricultural or environmental impacts. Moreover, by applying a method focused ~~only~~ solely on the rate of intensification of the development phase to identify flash drought, it is expected that in some cases, short-term deficits could quickly be offset by wet periods, reducing their overall impact~~the strong deficits occurring in the short-term could be quickly replaced by wet periods and not have a great relevance in terms of impacts~~, especially if the development of the event was preceded by humid conditions. This issue is more likely to occur in late autumn and winter, when wet and cold conditions are dominant and vegetation activity is lower.

Another important point that should be considered is related to the complex dynamics of precipitation in the UK (Hulme and Barrow, 1997; Mayes and Wheeler, 1997), which is characterised by large variations. Given the great variability of precipitation in the UK, the period selected for the analysis had important implications on the trends observed. This is especially crucial in summer season when a high interdecadal variability is observed. For example, given the occurrence of unusual wet summers since 2007 (Kendon et al., 2022), positive trends in precipitation are recorded over the last decades, as well as increases in stream flows (Hannaford, 2015). By contrast, other studies focussing on very long records (i.e. period 1776-2002) found a decrease in summer precipitation over England and Wales (Mills, 2005). Therefore, although summer got wetter if we consider the last few decades, these trends are strongly determined by the period selected and could vary notably when considering longer records.

Future work should focus on addressing whether the observed trends are simply due to natural climate variability, or whether these increases could be attributed to anthropogenic forcing contributing to rising temperatures and the relevance of the AED on flash drought development. In this way, large ensembles could be considered in the future to examine possible trends according to natural variability (e,g. Deser and Phillips, 2023). Furthermore, it would be necessary to analyse future projections of these trends under different greenhouse emission scenarios to disentangle the possible effect of climate change on the occurrence of flash droughts in the UK. Another key issue that should be analysed in future studies is the response of the different systems affected by drought, as well as unravelling how flash drought conditions propagate through these systems in the UK. The response of crops, natural vegetation, soil moisture and river flows should be analysed to unravel how the meteorological anomalies identified in this study translate in terms of impact, given that the response of the different affected systems is expected to vary considerably over time and space. There are increasing efforts to establish databases of the environmental and social impacts of drought, which could also be linked to flash drought occurrence (e.g. building on previous approaches applied for droughts more generally, e.g. Bachmair et al. 2015, Parsons et al. 2019).

5. Conclusion

In this research, we present for the first time a climatology of flash droughts in UK, providing a detailed characterisation of their spatial and temporal patterns. Likewise, we analysed the trends in the seasonal occurrence of flash droughts ~~over the last five~~

~~decades~~for the period 1969-2021. We also show the role played by AED on flash drought triggering, as well as its evolution ~~under the currently process of global warming~~over the last five decades. Finally, we analysed the atmospheric and oceanic conditions recorded during flash droughts development, and their possible connections with large-scale atmospheric patterns such as NAO. The main conclusions from this study are as follows:

- Flash drought occurrence in the UK is characterised by a high spatial and seasonal variability, affecting both the wetter regions of the North-West and the drier regions of the South-East.
- There is a notable and significant increase of flash droughts in spring, but non-significant trends (positive/negative) noted in winter, summer and autumn.
- Flash droughts in the UK are mainly driven by rainfall variability, while the AED has a minor role triggering flash drought occurrence. In spring, there is a significant increase in AED contribution, which could explain the positive and significant trends reported in the number of events in this season.
- Positive and remarkable anomalies in SLP and Z500 were noted during the flash droughts development in all seasons. These anomalies are associated with the presence of high-pressure systems around the UK, which prevent the arrival of humid air masses and, consequently, inhibit precipitation.
- The North Atlantic Oscillation (NAO) strongly controls flash droughts occurrence over the UK, particularly in winter and autumn months.
- Positive anomalies in sea surface temperatures (SST) were seen over the Atlantic Ocean around the UK during flash drought development in spring and summer, while mixed anomalies were observed in winter and autumn.

Appendix A

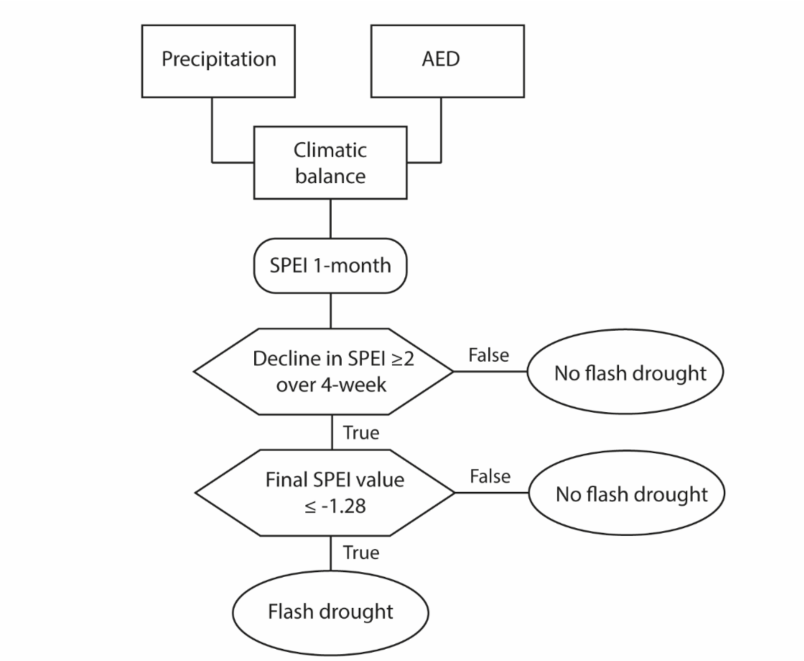

Figure A1. Diagram of the process followed for the identification of flash droughts.

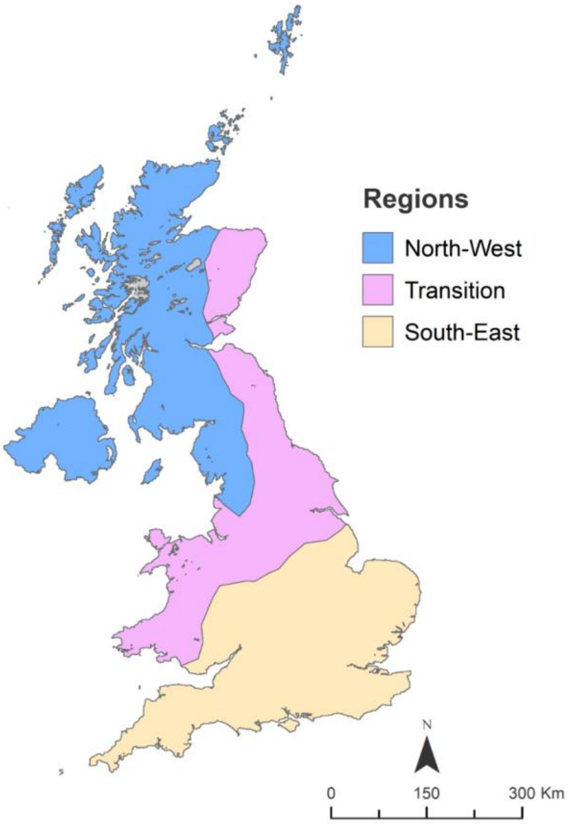

Figure A2~~1~~. Regional delimitation based on ~~Maliko~~ Tanguy et al. (2021).

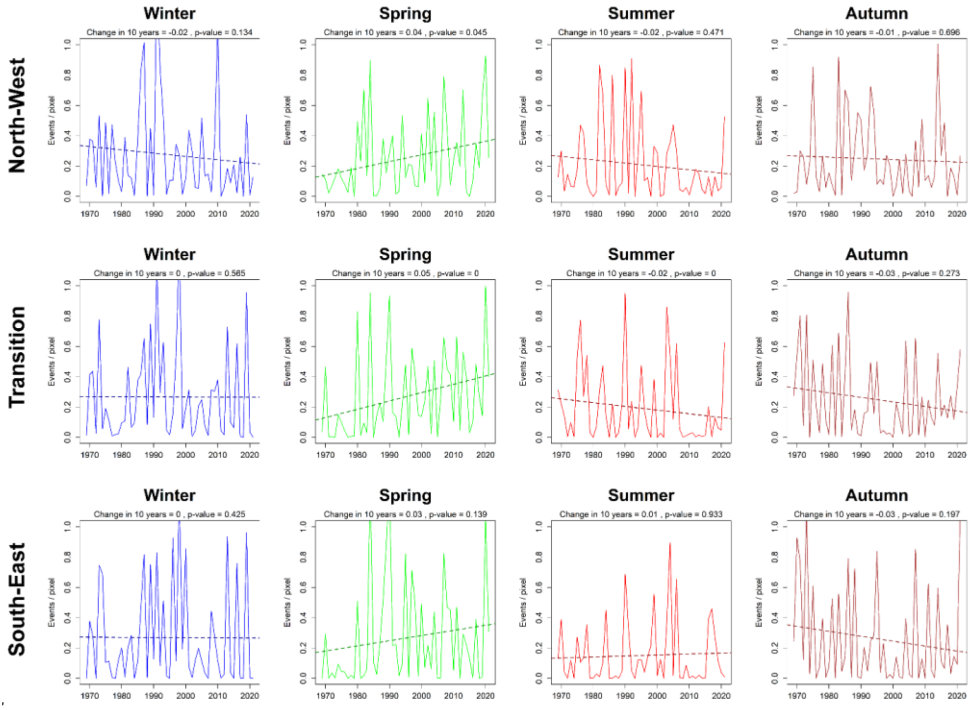

Figure A3~~2~~. Seasonal evolution of the number of flash droughts (events/pixel) in the United Kingdom for the period 1969-2021 by regions.

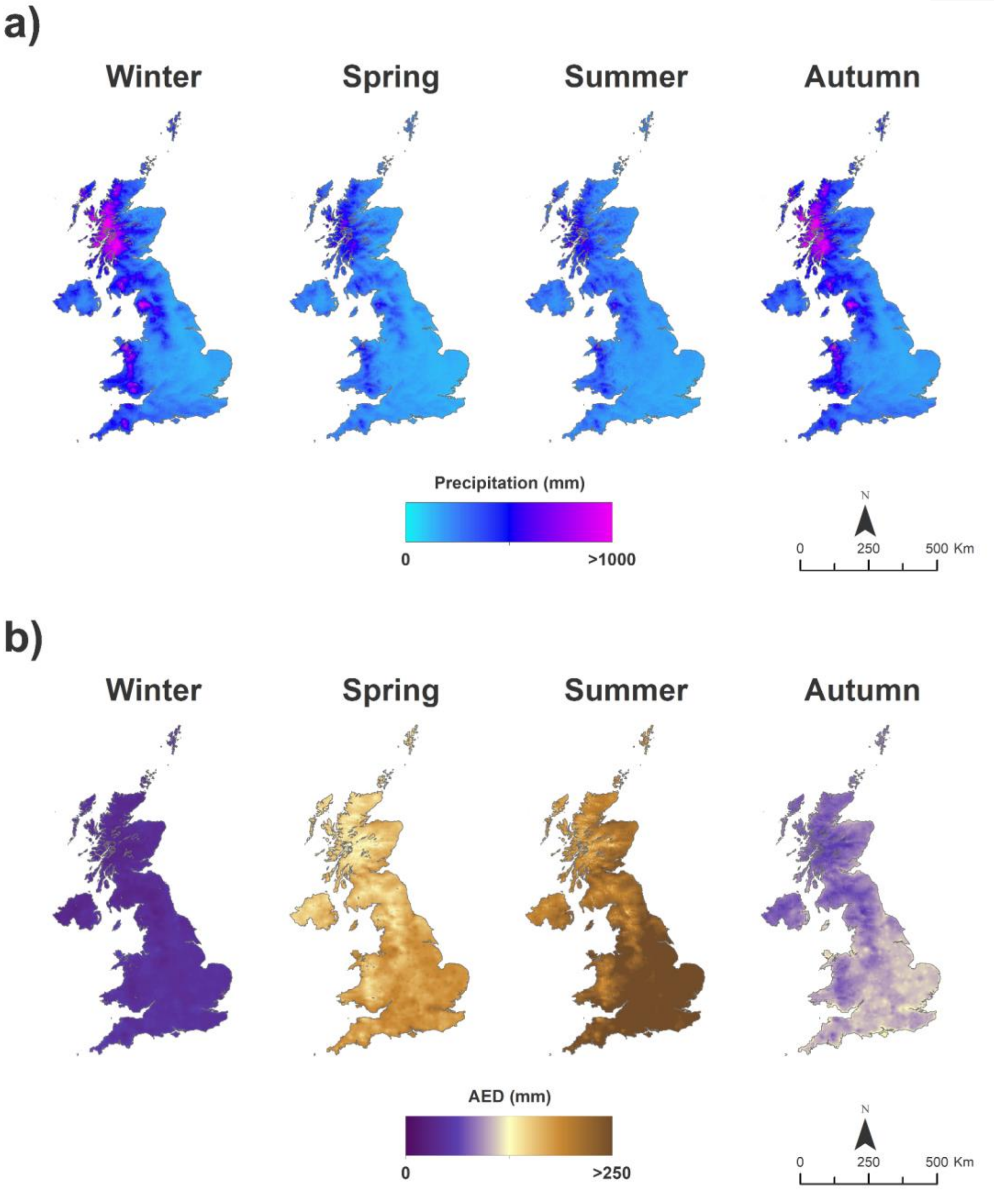

Figure A4~~3~~. Seasonal spatial distribution of the average **(a)** precipitation and **(b)** AED in the United Kingdom over the period 1969-2021.

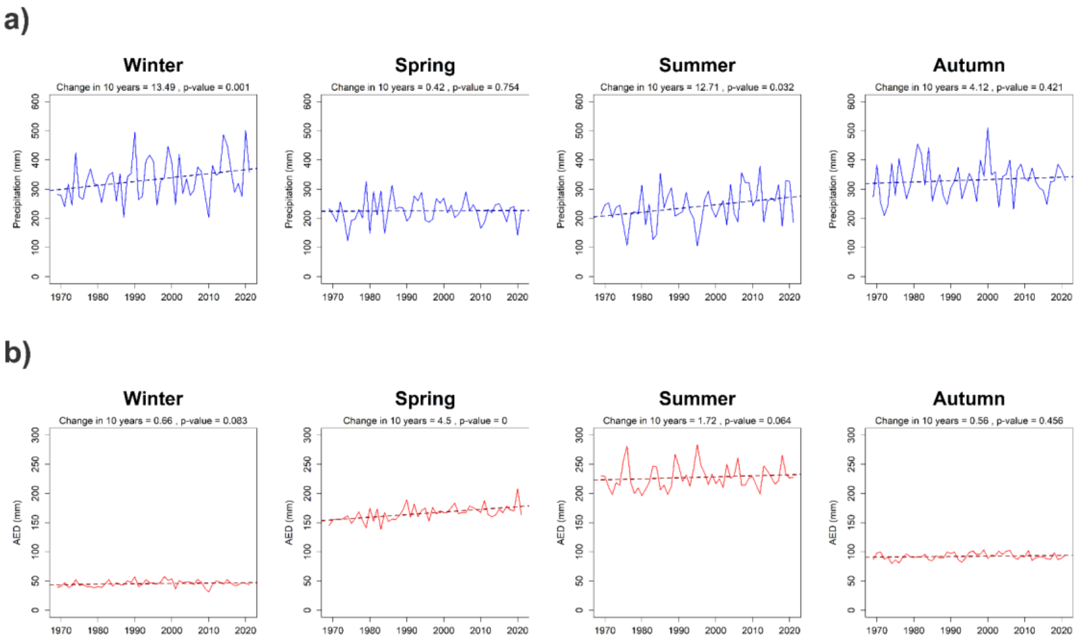

Figure A54. Seasonal evolution of the average **(a)** precipitation and **(b)** AED in the United Kingdom for the period 1969-2021.

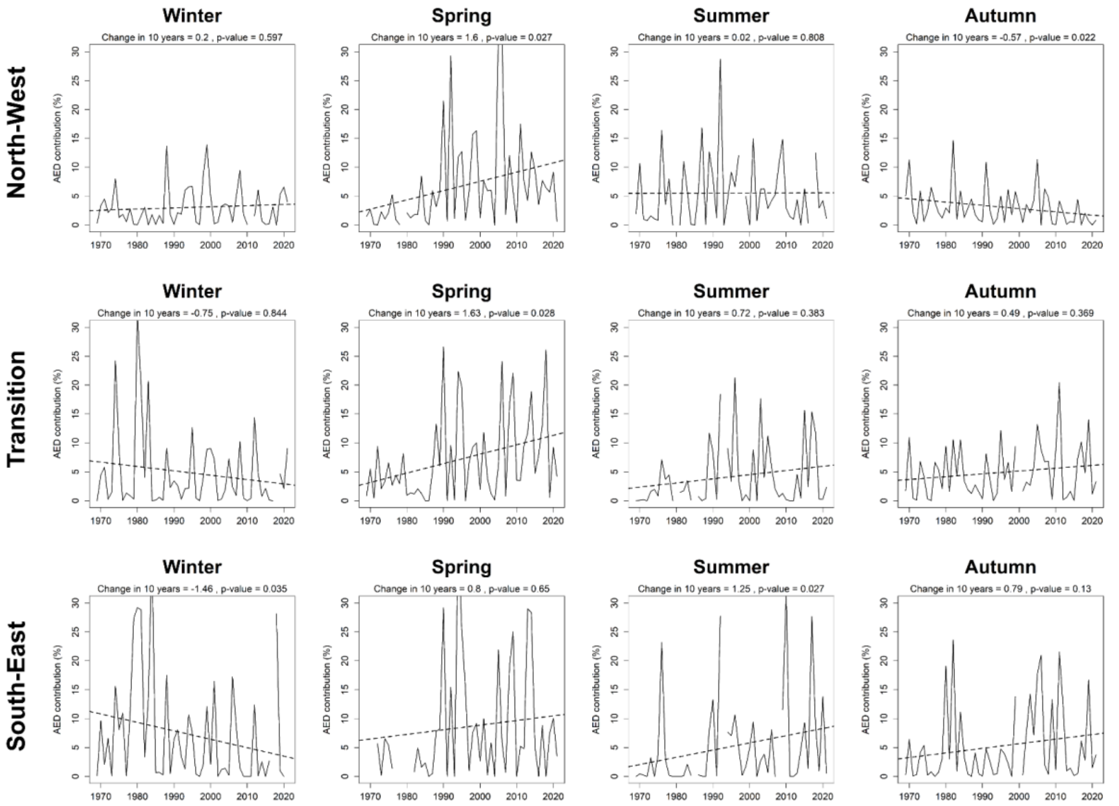

Figure A6~~5~~. Seasonal evolution of the average contribution of AED to flash drought development in the United Kingdom for the period 1969-2021 by regions.

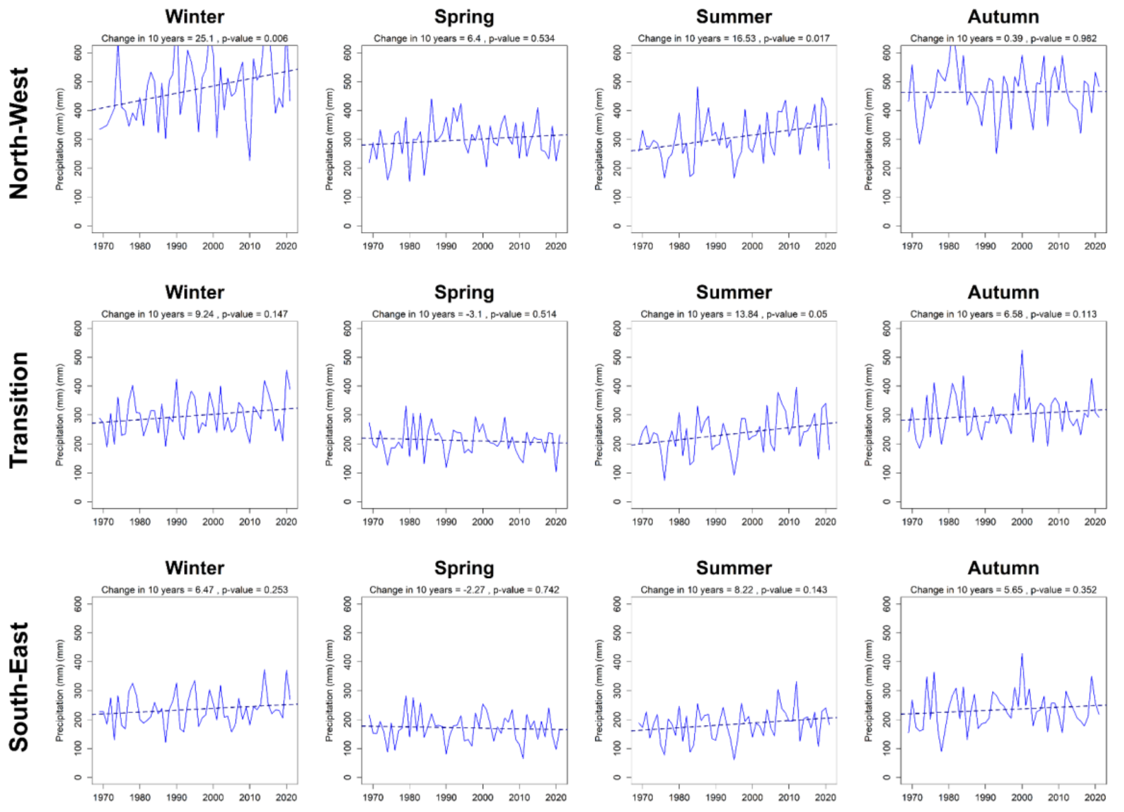

Figure A7~~6~~. Seasonal evolution of the average precipitation in the United Kingdom for the period 1969-2021 by regions.

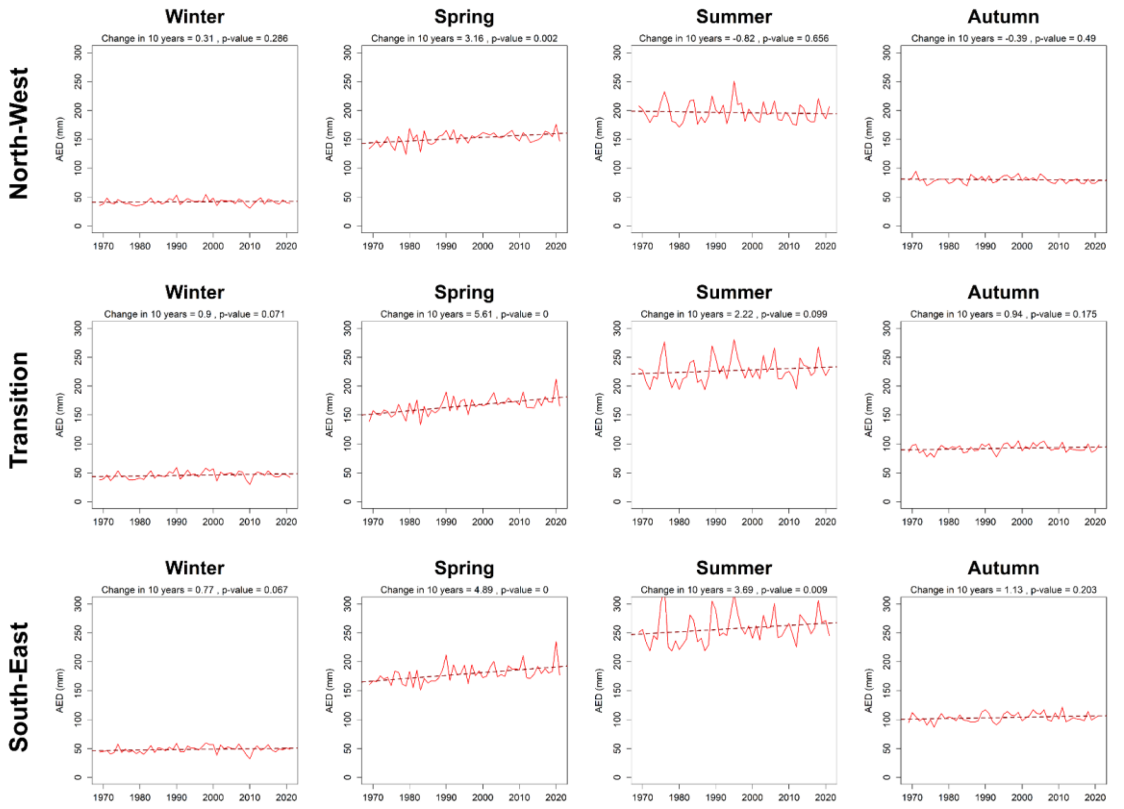

Figure A8~~7~~. Seasonal evolution of the average atmospheric evaporative demand (AED) in the United Kingdom for the period 1969-2021 by regions.

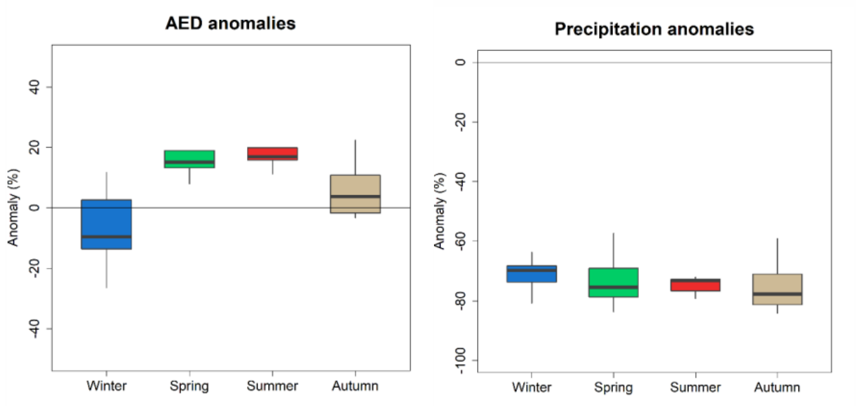

Figure A9. Seasonal anomalies in AED and precipitation (%) during the development of the top-10 flash droughts of each season over the United Kingdom for the period 1969-2021.

Author contribution

All authors contributed to the conceptualisation and design of the research, as well as to the preparation and revision of the manuscript. IN conducted the data processing, analysis, ~~and visualisation~~visualization and led the preparation of the manuscript.

Competing interests

The authors declared that there are no competing interests.

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Data availability

All information used in this study is open access. To calculate SPEI, we employed daily precipitation and AED data. Precipitation data was obtained from Met Office Hadley Centre for Climate Science and Services, which is available at https://catalogue.ceda.ac.uk/uuid/4dc8450d889a491ebb20e724debe2dfb. While AED data was obtained from Environmental Information Data Centre (EIDC), which is available at https://catalogue.ceh.ac.uk/documents/beb62085-ba81-480c-9ed0-2d31c27ff196. To analysed the atmospheric and oceanic conditions during flash drought development, we employed daily sea level pressure (SLP), 500 hPa geopotential height (Z500) and sea surface temperature (SST) from the National Centers for Environmental Prediction (NCEP)–National Center for Atmospheric Research (NCAR), which is available at https://psl.noaa.gov/data/.

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