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Iván Noguera Corral

Flash drought in Spain: from methods to early warning

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Geografía y Ordenación del Territorio

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GOBIERNO
DE ARAGON
Departamento de Ciencia, Universidad
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“Prometo estarte agradecido”

Rosendo Mercado (1985)

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Abstract

Flash drought is characterized by a rapid development and intensification, causing major agricultural and environmental impacts at short-term. In this research, we developed an objective method that focuses on rapid and abrupt changes in drought indices at a short time scale (i.e., 1-month) for the identification and monitoring of flash drought. This methodological approach was applied to characterize flash drought in mainland Spain and Balearic Island over the last decades. The results evidenced that flash drought is a common phenomenon in Spain, with almost of 40% of all droughts developing as flash droughts. The spatio-temporal distribution of flash drought exhibits a high variability, finding important differences between regions and seasons. In the last six decades, the higher number of flash droughts was recorded in northern and northwestern Spain compared to central and southern regions. Flash drought was more frequent in summer and spring months, affecting large areas over northern and southern regions, whereas its occurrence in winter and autumn mainly affected northern Spain. The triggering of this type of drought events responds both to strong precipitation deficits and to anomalous increases in atmospheric evaporative demand (AED), although their role varies notably spatially and seasonally. In humid (energy-limited) regions of the north, flash drought development is almost exclusively driven by precipitation deficits in all season, while in dry (water-limited) regions of the central and southern Spain, AED plays an essential role in flash drought triggering during warm season. The total number of flash droughts shows no relevant change for the whole of Spain, although the trends observed vary considerably between regions. Negative and non-significant trends were mainly reported over central and northern regions, while positive trends were generally recorded in south and Mediterranean coast, with significant and notable increases in large areas of southeastern. In summer, there is a general and significant increase in flash droughts, especially marked in southern and southeastern Spain. The increase in flash droughts in summer is related with the increase of AED reported in Spain over the last decades, which has resulted in a higher contribution of AED to flash drought development. A general increase in AED contribution to flash drought development was noted in all season and particularly, in water-limited regions, where the role of AED is more relevant to trigger and intensify

flash drought conditions. In order to provide useful information for preparedness and mitigation of flash droughts, we developed the Flash Drought Monitor (FDM). This monitoring system enables near real-time tracking of flash drought conditions in Spain at high temporal and spatial resolution. The data provided by FDM could be employed for decision-making by land and water managers, as well as for the development of future research related with flash drought in Spain.

Resumen

La sequía repentina se caracteriza por un rápido desarrollo e intensificación, causando importantes impactos agrícolas y medioambientales a corto plazo. En esta investigación, desarrollamos un método objetivo centrado en los cambios rápidos y bruscos en los valores de los índices de sequía a una escala temporal corta (1-mes) para la identificación y monitorización de la sequía repentina. Este enfoque metodológico se aplicó para caracterizar la sequía repentina en la España peninsular y en las Islas Baleares durante las últimas décadas. Los resultados evidenciaron que la sequía repentina es un fenómeno común en España, con casi un 40% de todas las sequías desarrollándose como sequía repentina. La distribución espacio-temporal de la sequía repentina muestra una alta variabilidad, encontrando importantes diferencias entre regiones y estaciones. En las últimas seis décadas, el mayor número de sequías repentinas se registró en el norte y noroeste de España en comparación con las regiones del centro y sur. La sequía repentina fue más frecuente en los meses de verano y primavera, afectando amplias zonas de las regiones del norte y sur, mientras que su ocurrencia en invierno y otoño afectó principalmente al norte de España. El desencadenamiento de este tipo de eventos de sequía responde tanto a fuertes déficits de precipitación como a incrementos anómalos de la demanda evaporativa por parte de la atmósfera (AED), aunque su papel varía notablemente espacial y estacionalmente. En las regiones húmedas (limitadas en energía) del norte, el desarrollo de la sequía repentina está impulsado casi exclusivamente por los déficits de precipitación en todas las estaciones, mientras que en las regiones secas (limitadas en agua) del centro y sur de España, la AED desempeña un papel esencial en el desencadenamiento de la sequía repentina durante la estación cálida. El número total de sequías repentinas no muestra un cambio relevante para el conjunto de España, aunque las tendencias observadas varían considerablemente entre regiones. Tendencias negativas y no significativas fueron registradas en las regiones centrales y septentrionales, mientras que en el sur y la costa mediterránea se registraron tendencias positivas, con aumentos significativos y notables en amplias zonas del sureste de España. En verano, se observa un aumento generalizado y significativo de las sequías repentinas, especialmente marcado

en el sur y sureste de España. El aumento de las sequías repentinas en verano está estrechamente relacionado con el notable aumento de la AED registrado en España en las últimas décadas, lo que se ha traducido en una mayor contribución de las AED al desarrollo de las sequías repentinas. Se observó un aumento general de la contribución de los AED al desarrollo de sequías repentinas en todas las estaciones, especialmente en regiones con limitaciones de agua, donde el papel de los AED es más relevante para desencadenar e intensificar las condiciones de sequía repentina. Con el fin de proporcionar información útil para la preparación y mitigación de las sequías repentinas, desarrollamos el llamado Monitor de Sequía Repentina (FDM). Este sistema de monitorización permite realizar un seguimiento casi en tiempo real de las condiciones de sequía repentina en España con una alta resolución temporal y espacial. Los datos proporcionados por el FDM podrían emplearse para la toma de decisiones por parte de los gestores del territorio y el agua, así como para el desarrollo de futuras investigaciones relacionadas con la sequía repentina.

List of articles

Making use of the possibility offered by the University of Zaragoza, this PhD dissertation is presented as compendium of scientist articles, being the PhD student Iván Noguera Corral the main author of all of them:

1. **Noguera, I.**, Domínguez-Castro, F., & Vicente-Serrano, S. M. (2020). Characteristics and trends of flash droughts in Spain, 1961–2018. *Annals of the New York Academy of Sciences*, *1472*(1), 155–172. https://doi.org/10.1111/nyas.14365

2. **Noguera, I.**, Domínguez-Castro, F., & Vicente-Serrano, S. M. (2021). Flash Drought Response to Precipitation and Atmospheric Evaporative Demand in Spain. *Atmosphere*, *12*(2), 165. https://doi.org/10.3390/atmos12020165

3. **Noguera, I.**, Vicente-Serrano, S. M., & Domínguez-Castro, F. (2022). The Rise of Atmospheric Evaporative Demand Is Increasing Flash Droughts in Spain During the Warm Season. *Geophysical Research Letters*, *49*(11). https://doi.org/10.1029/2021GL097703

4. **Noguera, I.**, Domínguez-Castro, F., Vicente-Serrano, S. M., & Reig, F. (2023). Near-real time flash drought monitoring system and dataset for Spain. *Data in Brief*, *47*, 108908. https://doi.org/10.1016/J.DIB.2023.108908

5. **Noguera, I.**, Vicente-Serrano, S. M., Domínguez-Castro, F., & Reig, F. (2022). Assessment of parametric approaches to calculate the Evaporative Demand Drought Index. *International Journal of Climatology*, *42*(2), 834–849. https://doi.org/10.1002/JOC.7275

Chapter 1

Introduction

1. The complexity of the drought phenomenon

Drought is one of the most serious natural hazards for ecosystems and socioeconomic sectors worldwide (Wilhite et al., 2007; Wilhite & Pulwarty, 2017). It is a very complex phenomenon, affecting a wide variety of systems driven by both natural and human-induced processes (Van Loon et al., 2016). An estimated 55 million people are affected by droughts every year at global scale, representing the major risk to livestock and crops in almost all regions of the world (WHO, 2021). Likewise, drought causes a large number of impacts in non-agricultural systems (Ding et al., 2011); with notable effects on water availability and quality (Calow et al., 2010; Feyen & Dankers, 2009; Mosley, 2015), soil degradation and carbon storage (Robinson et al., 2016; van der Molen et al., 2011), net primary production (M. Zhao & Running, 2010), forest growth and decay (Allen et al., 2010; Linares et al., 2010), wildfires (Piñol et al., 1998; Russo et al., 2017), land degradation (Lal, 2003), wildlife (Bodmer et al., 2018; Sinclair et al., 2007), economic activities (Naumann et al., 2021; Pandey & Bhandari, 2009) or human health (Smith et al., 2014; Yusa et al., 2015). Usually, its development is slow over the time and space, spreading in a cascading way at long-term (Wilhite et al., 2007). Thus, drought is typically recognized when impacts are identified throughout different sectors and systems.

Drought is difficult to quantify in terms of duration, magnitude and spatial extent (Keyantash & Dracup, 2002). There is not an instrument for measuring it directly, and neither a variable that provides a complete and precise assessment of drought severity (Vicente-Serrano, 2016). Moreover, drought is a multidimensional phenomenon and can be recorded on different time scales (Edwards & Mckee, 1997; McKee et al., 1993), as the time lapse from water deficit to impact emergence in each of the systems may vary notably. In this way, several studies showed the great differences between response of agricultural (Huang et al., 2015; Peña-Gallardo, Vicente-Serrano, Quiring, et al., 2019; Vergni & Todisco, 2011), environmental (Lotsch et al., 2003; Vicente-Serrano et al., 2013; Q. Zhang et al., 2017) and hydrological (Barker et al., 2016; Peña-Angulo et al., 2021; Vicente-Serrano & López-Moreno, 2005) systems to drought time scales. Even in a particular region, large variations in response time can been found according to lithology, land cover, water management etc. Therefore, the use of multiple drought time scales is essential for an accurate assessment and monitoring of drought.

Drought mostly responds to natural climate variability (Wilhite & Glantz, 1985). For this reason, and given the spatial and temporal availability of climate data in most of the world regions, drought assessment is normally based on climatic information (A. K. Mishra & Singh, 2010). In recent decades, many drought indices based on time series of different meteorological variables (e.g., precipitation, temperature, evapotranspiration etc.) have been developed for drought quantification and monitoring (Zargar et al., 2011). Some of these indices have been used extensively [e.g., Standardized Precipitation Index (SPI; McKee et al. 1993), Standardized Precipitation Evapotranspiration Index (SPEI; (Vicente-Serrano et al. 2010), Palmer Drought Severity Index (PDSI; Palmer, 1965) etc.] (Kim et al., 2022), showing good performance in identifying drought conditions in diverse environmental systems (Vicente-Serrano, Beguería, et al., 2012). Thus, drought indices based on widely available meteorological data have become the most used metrics for drought assessment and monitoring worldwide (Hayes et al., 2011; Heim, 2002).

A critical issue that hinders a precise assessment of drought is the impossibility of establishing a universal definition of drought that covers the diversity of drought dimensions (Lloyd-Hughes, 2014). For this reason, several drought types are usually defined based on the environmental system or socioeconomic sector affected (Wilhite, 2000). Typically, droughts are classified into meteorological, agricultural, hydrological, environmental and socioeconomic (**Figure 1**). Meteorological drought is normally referring to precipitation deficits over a given period of time (McKee et al., 1993), which can be aggravated by other factors that control the atmospheric evaporative demand (AED) such as high temperature, strong wind, low relative humidity and high solar radiation. This lack in rainfall results in a progressive decline in soil moisture, which causes plant water stress and if this condition persists it generates agricultural and environmental droughts (Crausbay et al., 2017; Geng et al., 2016; Vicente-Serrano, Quiring, et al., 2020). If precipitation deficit is maintained over time, both inflows and water reservoirs are gradually reduced, causing hydrological drought (Van Loon, 2015). Therefore, drought types are closely connected to each other and can even occur at the same time (Wilhite, 2000; Wilhite & Glantz, 1985). Nevertheless, drought processes can be strongly complex and diverse as droughts may differ according to the system affected, the drivers involved, as well as the possible effects associated with the occurrence of each drought type.

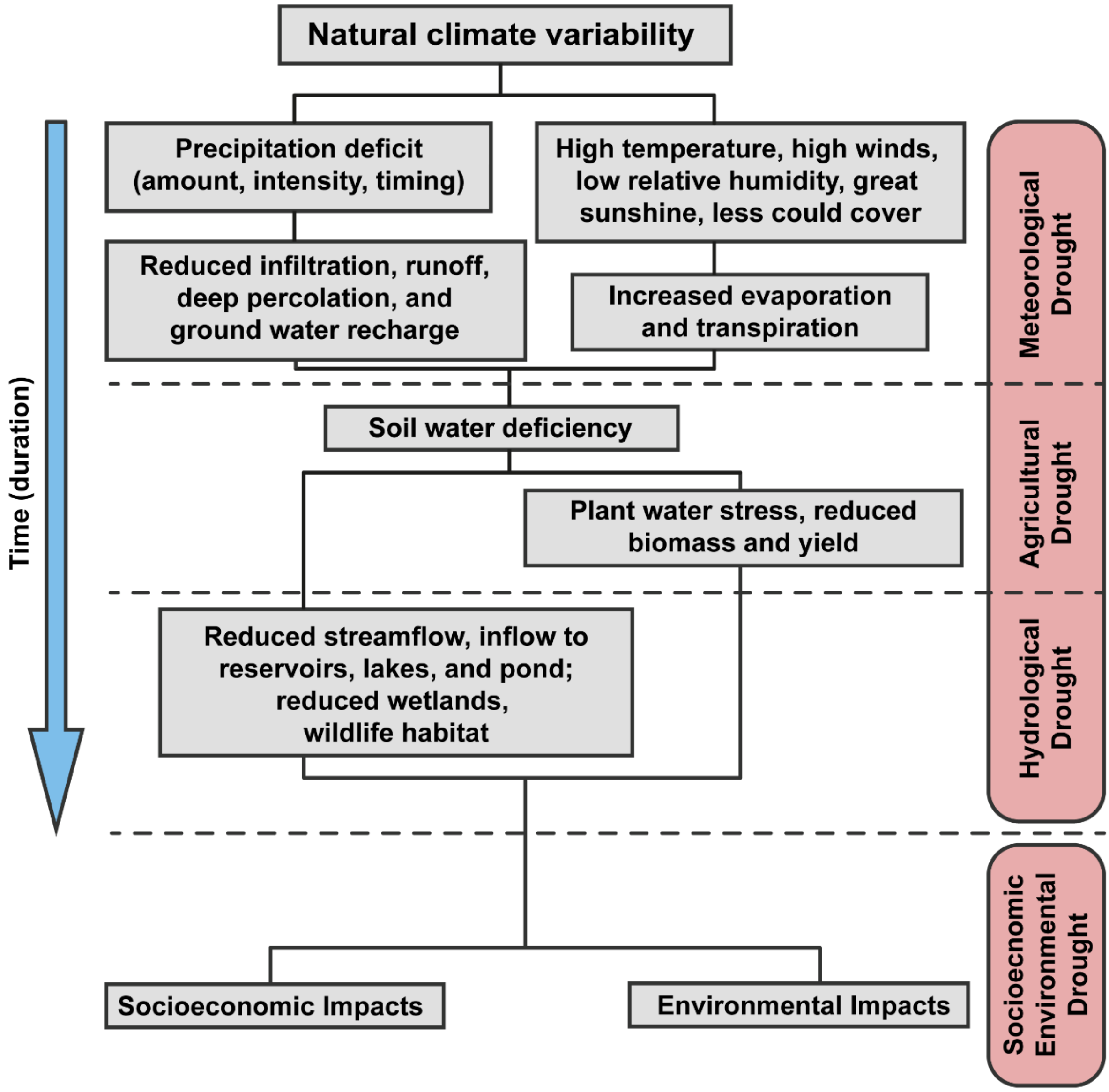

Figure 1. Relationship between climate and hydrological variables, drought types and impacts. Adapted from Wilhite (2000).

2. Flash drought: definitions, metrics and methodological approaches

In 2002, Svoboda et al. (2002) introduced for the first time the term “flash drought” to refer to drought events characterized by a rapid development and intensification. These events were associated with heat waves episodes occurred over United States, which caused an abrupt soil moisture decline and a crop failure in few weeks. Thus, they distinguished flash drought based on the velocity of development of drought events. Likewise, the study by Svoboda et al. (2002) stressed the possible drought development for the short-term, as opposed to the common drought understanding, related to a slow development given the need to long-term precipitation deficits to trigger a drought event. The concept of flash drought did not become popular until 2012, when a severe drought episode characterized by a fast onset affected large areas of the Midwest of United States (Otkin et al., 2018). The 2012 flash drought caused economic losses that excess $30 billion (NCEI, 2017), with large impact on vegetation and crops (Basara et al., 2019; Jin et al., 2019; Otkin et al., 2016). This extreme flash drought event highlighted for the first time the relevance of this phenomenon, attracting the interest of the scientific community.

In the last decade a growing number of studies have focused on flash droughts in order to characterize these events and understand the determining mechanisms in different regions of the world (Christian et al., 2019; Mo & Lettenmaier, 2015, 2016; Nguyen et al., 2019; L. Wang et al., 2016; Yuan et al., 2018, 2019). Usually, flash drought is associated with anomalous precipitation deficits and/or increases in AED that results in a rapid decline in humidity conditions over a short period (typically a few weeks). However, the existing ambiguity on the concept of flash drought makes it difficult to identify, quantify and monitor this phenomenon (Otkin et al., 2018). In addition, the rapid development makes the detection of flash droughts even more difficult than conventional slow-developing droughts (Chen et al., 2020) because the time elapsed from meteorological anomalies to impacts emergence is short, which reduces the time to establish measures for early warning (Otkin et al., 2022). In order to identify and characterize flash droughts, several authors have proposed different methodological approaches.

The first approaches used to define flash drought was focused on the occurrence of rapid changes in soil moisture for the short-term. For example, Hunt et al. (2009) defined flash drought as a period of no less than 3-week in which soil moisture decrease more than 50% to describe their occurrence in Nebraska (United States). Mozny et al. (2012) employed the Soil Moisture Index (SMI; Hunt et al., 2009) to analyzed flash droughts occurrence in the Czech Republic, and defined flash drought as a decrease of more than five units of SMI over a period of no less than three weeks. Likewise, Ford & Labosier (2017) used soil moisture data for flash drought identification in United States, defining a flash drought event as a period in which soil moisture in a given pentad (5-

days) declines from at least the 40th percentile to below the 20th percentile over 4 pentads or less. Further studies evidenced the usefulness of soil moisture data to establish an early warning of flash drought onset (Ford et al., 2015).

In addition to soil moisture, other studies used metrics derived from satellite information, such as the Evaporative Stress Index (ESI; Anderson et al. 2007), which is based on the difference between the evapotranspiration (ET) and AED. This metric provides a good assessment of the plant water stress and it is an effective metric to detect flash drought conditions in crop areas (Anderson et al., 2013, 2015; Nguyen et al., 2019, 2021; Otkin et al., 2013, 2016). For example, Otkin et al. (2014) proposed a Rapid Change Index (RCI), based on the variations of the standardized values of a given variable over a determined time interval, to evaluate fast changes in weekly ESI anomalies in order to capture flash drought onset. Subsequently, Otkin et al. (2015) also employed this methodological approach to examined rapid changes in soil moisture in response to flash droughts onset in the United States.

Other authors recognized different flash droughts types based on the meteorological drivers that trigger drought conditions and their duration. Mo & Lettenmaier (2015, 2016) distinguished between “heat waves” flash droughts, which are driven by anomalous increases in temperature, and “precipitation deficit” flash droughts, primarily related to strong lack in rainfall. Heat wave flash droughts were defined as a pentad with air temperature anomalies higher than one standard deviation, positive anomalies in ET and a soil moisture content less than 40%. On the contrary, precipitation deficit flash droughts were defined as a pentad with air temperature anomalies greater than one standard deviation, negative ET anomalies and a precipitation anomaly below than 40% of the probability distribution. Subsequent studies adopted a similar methodological approach based on drivers and duration of events to defined flash droughts associated with high temperatures and/or precipitation deficits in China (L. Wang et al., 2016; L. Wang & Yuan, 2018; Y. Zhang et al., 2017) and Africa (Yuan et al., 2018).

In 2018, there was already an important body of scientific studies on flash droughts and Otkin et al. (2018) reviewed the existing literature on the topic in order to provide a comprehensive definition and understanding of flash drought. They stressed the need of defining flash drought based on the speed of development and intensification instead of drought duration. Thus, they emphasized the importance of focusing on the development phase to distinguish flash droughts from other drought episodes. Although flash droughts could be related to any drought type (agricultural, hydrological, environmental, socioeconomic), they pointed out that flash drought has a primary agricultural and environmental dimension, as these are the main systems affected by short-term water deficits. Likewise, they stressed the importance of using methodological approaches that include both precipitation and AED anomalies to identify and quantify flash drought events, as assessing each component separately may provide an incomplete picture of flash drought.

After one decade of studies focusing of flash droughts (Lisonbee et al., 2021), nowadays, it is generally accepted that the existing methodological approaches for flash drought identification should mostly focus on the rapid onset of drought conditions (Y. Liu et al., 2020), which is the main characteristic of these drought events. However, there are still divergences on the use of different metrics for the assessment of flash droughts. Although several studies evidenced that precipitation deficit is the main driver controlling flash drought variability (Hoffmann et al., 2021; Koster et al., 2019; Parker et al., 2021; Y. Wang & Yuan, 2022b), most of the authors point out that metrics based exclusively on precipitation do not allow to detect properly flash drought, since they have been identified even in periods characterized by normal precipitation. Thus, few studies used metrics based exclusively on precipitation, such as SPI, to identify flash droughts (Hoffmann et al., 2021; Hunt et al., 2014). By contrast, numerous studies focused on evapotranspiration data to define and identify flash drought, associating primarily its occurrence with periods characterized by high temperature and ET (Anderson et al., 2011, 2013; Mo & Lettenmaier, 2015; Nguyen et al., 2019; Otkin et al., 2013, 2014). Other studies showed the usefulness of the metric such as Evaporative Drought Demand Index (EDDI; Hobbins et al. 2016), based exclusively on AED, for flash drought identification and quantification in United States (McEvoy et al., 2016). Recently, Pendergrass et al. (2020) defined flash drought as a 50% increase in EDDI over two weeks, sustained for at least another two weeks. Further studies adopted this approach based on EDDI to define flash drought events (Parker et al., 2021), showing that AED plays a crucial role triggering the rapid onset of drought conditions.

3. The influence of AED on flash drought

Atmospheric evaporative demand (AED) refers to the potential from atmosphere to evaporate (demand) water, which is given by a radiative component, determined by net radiation, and an aerodynamic component, determined by air temperature, relative humidity and wind speed (Hobbins et al., 2017). The influence of AED on drought is complex and varies according to the drought type (e.g., agricultural, environmental, hydrological). AED affects soil moisture and the variations of AED can be both a cause and a consequence of the increased land-atmosphere feedbacks (Seneviratne et al., 2010) and reinforce drought severity (Miralles et al., 2019). The effect of AED is more relevant during dry periods, when an increase in AED reduces water resources available for vegetation by enhanced ET (Teuling et al., 2013), affecting plant transpiration, hydraulic, photosynthesis and carbon uptake (Breshears et al., 2013; Grossiord et al., 2020). Even with water available in the soil, the increase in AED can reduce carbon uptake and photosynthesis from plants (Donohue et al., 2010). Several studies showed that an increase in AED can trigger droughts by means of its effects on ET, soil moisture, leaf stomatal conductance, photosynthesis and hydraulic embolism (Brodribb et al., 2020; Choat et al., 2018; McDowell, 2011). All these processes can cause a decline in vegetation growth or even a plant failure at short-term (Hunt et al., 2021; Otkin et al., 2016, 2019). Therefore, AED has important agricultural and environmental implications (K. Wang & Dickinson, 2012) and may play an important role in aggravating the severity of flash drought.

Some authors highlighted the crucial role of AED in triggering flash droughts, pointing that this type of events typically occur at the transition from energy-limited to water-limited conditions in which, under increased AED, different land-atmosphere processes may reactivate (**Figure 2**) (Hobbins et al., 2016; Pendergrass et al., 2020). The rationale is that land-atmospheric feedbacks are the main drivers of AED variability so an increase of AED would be connected with soil water conditions. Under water-limited conditions, ET would not enable to produce an accurately assessment of flash drought severity because ET is limited by water availability, so ET decreases as the water availability became insufficient to maintain the water supply that the atmosphere demands by means of evaporation processes. In that case, an increase in AED would not increase ET, but it would notably enhance vegetation stress. Therefore, AED is a better proxy of plant stress than ET under dry conditions and, consequently, it would provide a more precise detection of flash droughts associated with rapid increases in temperature and AED.

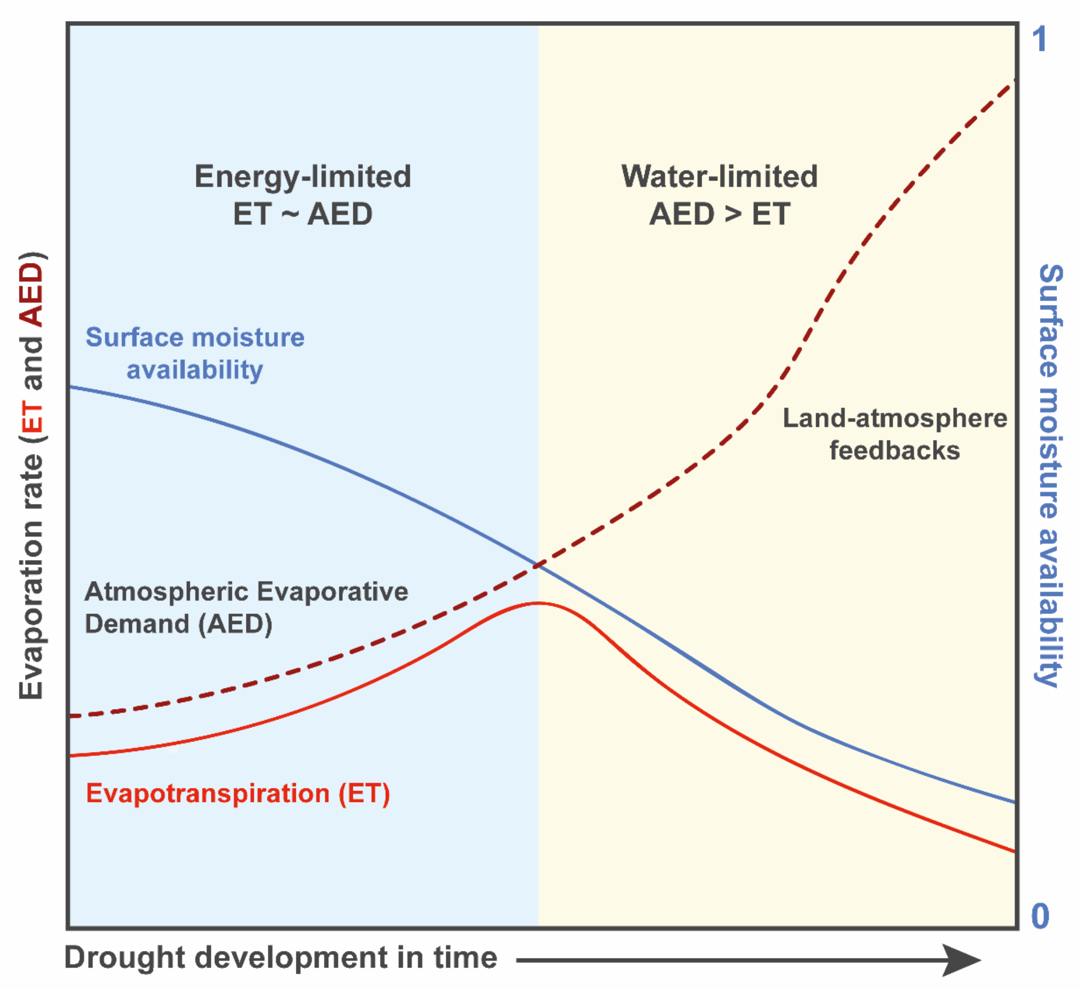

Figure 2. Evolution of atmospheric evaporative demand (AED), evapotranspiration (ET) and surface moisture availability over the transition from energy-limited to water-limited conditions. Adapted from Pendergrass et al. (2020).

However, unraveling the role played by the AED in triggering and aggravating drought conditions is not an easy task. Several studies demonstrated that the increase in AED may cause major impacts on vegetation and crops (Ciais et al., 2005), but the influence of AED on drought strongly depending on the water availability (Vicente-Serrano, McVicar, et al., 2020). Thus, the effect of AED varies notably according to climatic characteristics, finding remarkable differences between humid (i.e., energy-limited) and dry (i.e., water-limited) regions (Tomas-Burguera et al., 2020). In humid regions, in which vegetation and crops growth is limited by radiation and temperature, the increase in AED is not cause a negative effect on vegetation since water losses from ET would not exceed water availability. In fact, under normal conditions (i.e., average precipitation values), an increase in AED could result in higher vegetation activity and growth given high correlation with temperature and radiation, which affect photosynthesis. Thus, in these humid regions characterized by energy-limited conditions, the negative effects of AED would be only expected during periods of precipitation deficits. By contrast, in dry regions characterized by water-limited conditions, AED may have important effects on agricultural and environmental drought severity. In these regions, in which water availability is usually low, an anomalous increase in AED results in a depletion of water resources and soil moisture, which would notably increase vegetation stress, causing in some cases plant mortality episodes (Breshears et al., 2005; Williams et al., 2013).

Therefore, the influence of AED on flash drought development could vary considerably spatially and seasonally. For example, it would be expected that precipitation variability mainly controls flash droughts occurrence in energy-limited regions, playing AED a secondary role. In these regions, where water availability is not usually a constraint, strong precipitation deficits during short periods would be required to trigger flash drought conditions even during warm periods (**Figure 3**). In water-limited regions, where precipitation and water availability are low, AED is likely to play a major role in triggering flash drought conditions. The role of AED on flash drought could be particularly relevant during warm and dry periods, when precipitation reaches its minimum values and enhanced AED may increase notably vegetation stress, aggravating the impacts on agricultural and environmental systems. Although the responses described here may be the most general for flash drought development given deficits of precipitation and increased AED, it seems reasonable to expect important differences between events as these may develop under very diverse conditions worldwide. Some flash droughts could be related to precipitation deficits, others to an increase in AED and, in other cases, flash droughts triggering can be related to both precipitation deficits and an anomalous increase in AED.

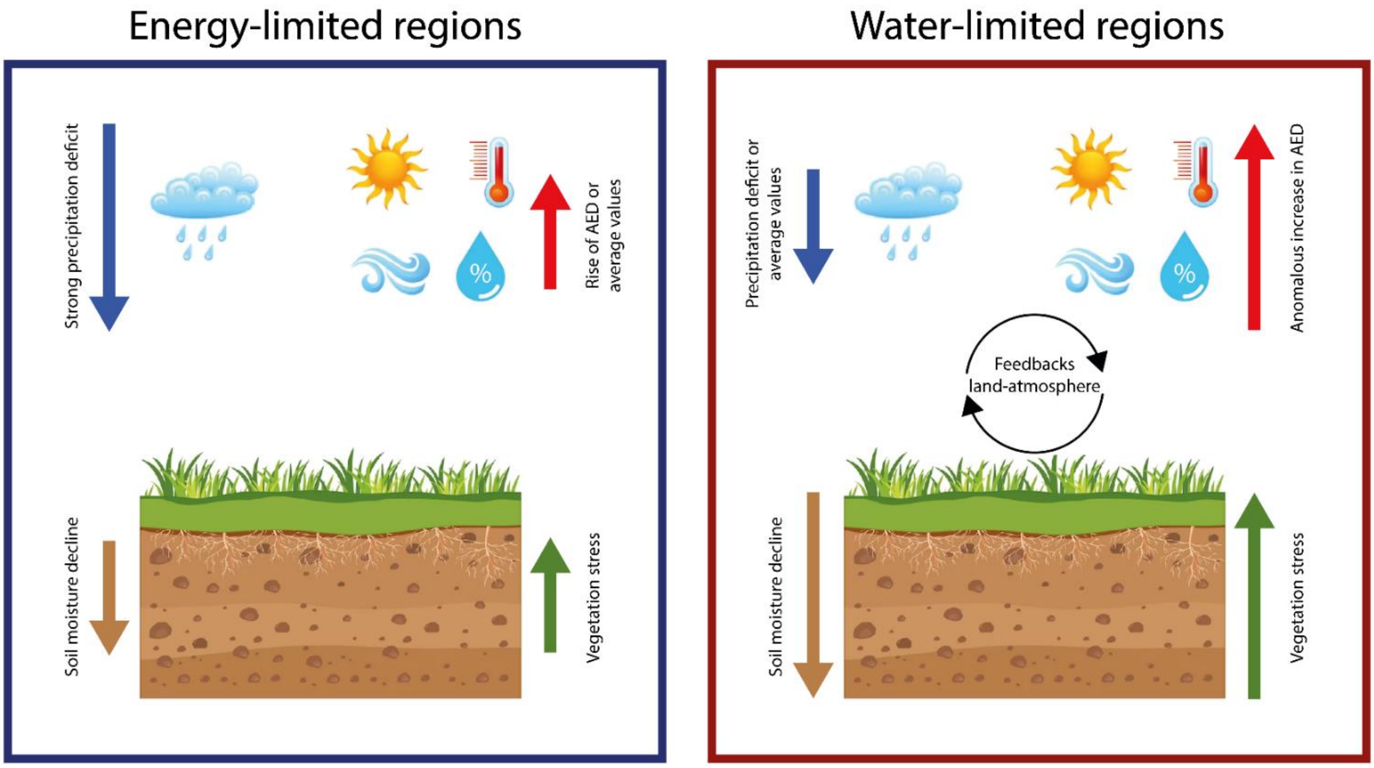

Figure 3. Potential drivers of flash drought triggering in energy-limited and water-limited regions.

In addition, the influence of AED on flash drought may also exhibit important variations over time. In the currently context of climate change, different studies pointed that drought severity is increasing due to the rise of AED (Dai, 2011, 2012; Dai et al., 2018; M. Zhao et al., 2017). This increase in AED, mainly driven by rising temperature associated with greenhouse emissions (Scheff & Frierson, 2014), results in major agricultural and environmental impacts (Allen et al., 2015; Asseng et al., 2014; Lobell et al., 2011; McDowell, 2011). Thus, it is expected that AED will become more important in the future to trigger and aggravate flash drought conditions (Y. Wang & Yuan, 2021, 2022a; Yuan et al., 2019). In fact, some studies have associated the observed increase of AED with the increase of the frequency and severity of flash droughts in some world regions (Christian et al., 2021; L. Wang et al., 2016; L. Wang & Yuan, 2018; Yuan et al., 2018, 2019). However, given that the AED influence varies notably over the time and space, the possible implication on flash drought frequency and severity could be very different, and it needs to be evaluated in depth.

4. The importance of droughts in Spain

Drought is one of main climate risk affecting Spain, with important economic and environmental consequences (Pita, 1989). Given the large interannual variability of precipitation (Serrano et al., 1999), as well as the dominance of semi-arid and subhumid conditions (Molina, 1981), drought occurs frequently and severely in Spain. Drought is a major driver of vegetation activity in Spain, controlling crop yield production and forest growth (Vicente-Serrano et al., 2019). Likewise, drought highly impact hydrological systems, with important effects in streamflows, reservoirs and groundwater (Lorenzo-Lacruz et al., 2017; Lorenzo-Lacruz, Morán-Tejeda, et al., 2013). Thus, drought is probably the most relevant climatic phenomena for water and land management in Spain (Estrela & Vargas, 2012; Hervás-Gámez & Delgado-Ramos, 2019; Paneque, 2015), especially in regions usually affected by water scarcity. In Spain, drought has been analyzed from different perspectives (see review in Vicente-Serrano, 2021) using meteorological records (Vicente-Serrano, 2006a, 2006b), documentary sources (Domínguez-Castro et al., 2008, 2012; Tejedor et al., 2019), dendrochronological data (Camarero et al., 2018; Pasho et al., 2011a), remote sensing (Ribeiro et al., 2019; Vicente-Serrano et al., 2019) or model outputs (Dutra et al., 2008; Quintana-Seguí et al., 2020).

Drought is characterized by a complex spatio-temporal behavior in Spain, exhibiting a high variability in terms of frequency, duration and magnitude (Domínguez-Castro et al., 2019). This complexity is given by the topography and the variety of atmospheric mechanisms that affect the Iberian Peninsula (Martín Vide & Fernández Belmonte, 2001; Rodríguez-Puebla et al., 2001; Trigo et al., 2004), resulting in notable differences in precipitation (Cortesi et al., 2014; Serrano et al., 1999) and AED (Tomas-Burguera et al., 2021) (**Figure 4**). Thus, spatio-temporal drought occurrence responds to different atmospheric dynamics in Spain (Manzano et al., 2019; Russo et al., 2015), including; large-scale atmosphere circulation patterns such as North Atlantic Oscillation (NAO) (Vicente-Serrano et al., 2011), Mediterranean Oscillation (MO) (Conte et al., 1989), Western Mediterranean Oscillation (WeMO) (Martin-Vide & Lopez-Bustins, 2006) and other specific mechanisms that may drive extreme temperature (Sahsamanoglou, 1990; Serrano-Notivoli et al., 2022; Sousa et al., 2019). Although major drought event can impact most of Spain, it is common that drought conditions affect a given region driven by a specific mechanism (Vicente-Serrano, 2006a).

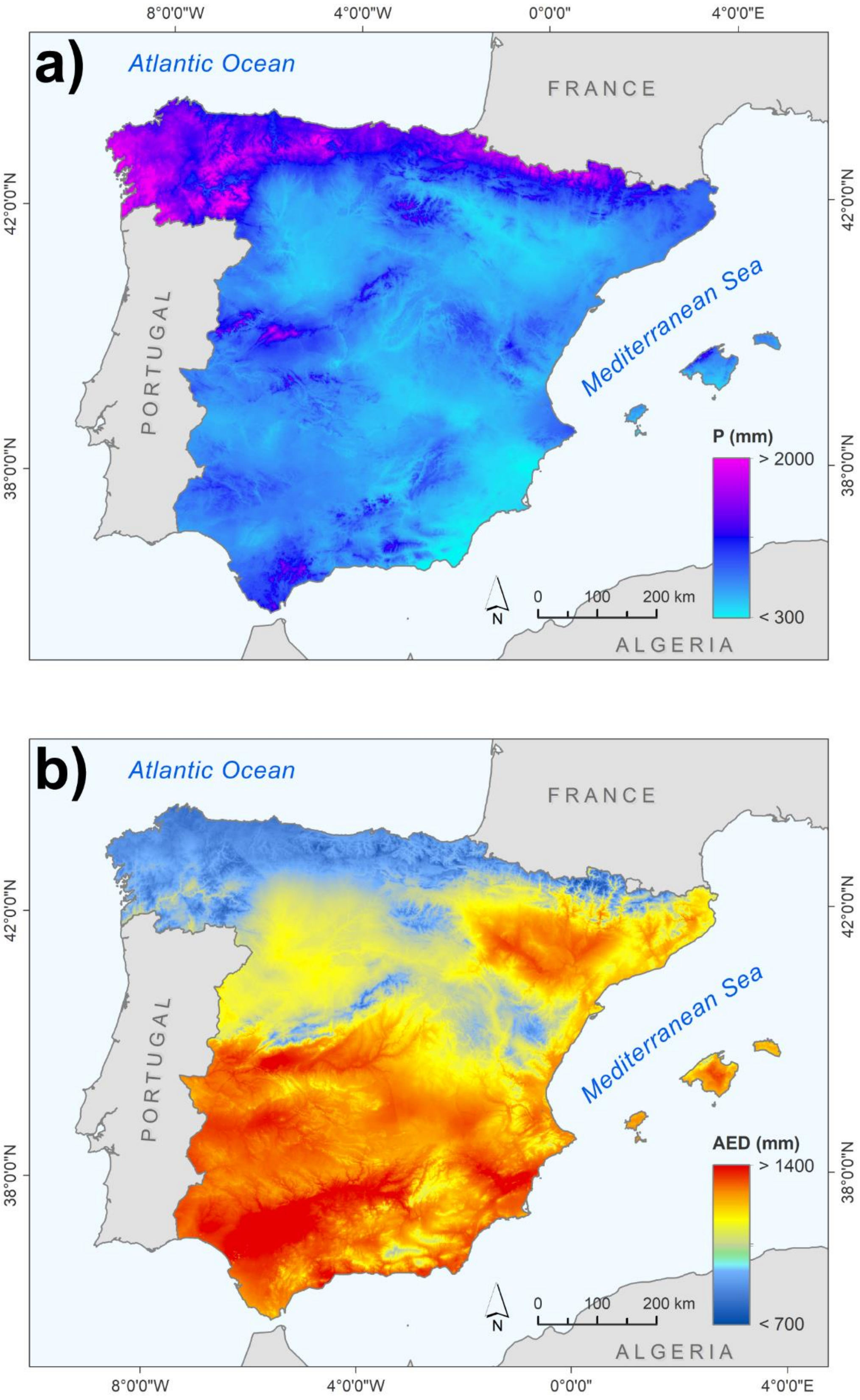

Figure 4. Annual **a)** precipitation (P) and **b)** atmospheric evaporative demand (AED) in mainland Spain and Balearic Island over the period 1961-2018. Data obtained from Vicente-Serrano et al. (2017).

In Spain, many studies analyzed the response of different systems (e.g., agricultural, environmental and hydrological) to drought at different time scales. Focusing on agricultural systems, some authors have shown the strong influence of drought on crop yield, evidencing that some of the main crop's types (e.g., wheat, barley) respond to drought at short and medium (1-6 months) time scales in Spain (Páscoa et al., 2017; Peña-Gallardo, Vicente-Serrano, Domínguez-Castro, et al., 2019; Ribeiro et al., 2019). Moreover, numerous studies have analyzed the important environmental implications of drought in Spain, including the effects on forest growth and mortality (Gazol et al., 2022; Manrique-Alba et al., 2020; Sánchez-Salguero et al., 2010, 2012), wildfire (Rodrigues et al., 2018) or shrubs damage and land degradation in semi-arid regions (Peñuelas et al., 2001; Vicente-Serrano, Zouber, et al., 2012), among others. In general, forest growth responds to short time scales (1-3 months) in Spain (Camarero et al., 2018; Peña-Gallardo, Vicente-Serrano, Camarero, et al., 2018), although this response varies notably among species and site at regional scale (Pasho et al., 2011b). Also, wildfire exhibits a strong relationship with drought frequency occurrence at short time scales (2-months) in Spain (Russo et al., 2017). Since a hydrological point of view, drought also has significant impacts in the Spanish water basins (Lorenzo-Lacruz et al., 2010), affecting streamflows (Lorenzo-Lacruz, Morán-Tejeda, et al., 2013) and groundwater reservoirs (Lorenzo-Lacruz et al., 2017). Small basins with a dominance of permeable lithology usually respond to short time scales (2-3 months), while larger basins with groundwater reserves respond to long time scales (Lorenzo-Lacruz, Vicente-Serrano, et al., 2013). Other studies focused on the propagation of drought conditions over hydrological systems also showed a strong response at short-term (~ 3-months) (Peña-Angulo et al., 2021). All these studies stress the major response of different systems to drought at short-term, so it is expected that flash drought occurrence may have important agricultural, environmental and hydrological implications in Spain

Moreover, there are some uncertainties related to the effect of global warming on droughts frequency and severity in Spain (Vicente-Serrano, 2021). Although generally non-significant trends in the frequency and duration of droughts was found over the last few decades (Domínguez-Castro et al., 2019), some studies evidenced an increase in drought severity associated with increases in AED (Vicente-Serrano, Lopez-Moreno, et al., 2014). Thus, the general increase in AED over Spain (Tomas-Burguera et al., 2021), which is driven by temperature increase (Brunet et al., 2007; del Río et al., 2011) and relative humidity decline (Vicente-Serrano, Azorín-Molina, et al., 2014), could also play a key role in triggering flash drought events, an interesting topic that is necessary to analyze in depth.

5. PhD motivation and objectives

Flash drought has attracted a great interest in the scientific community over the last few years (Lisonbee et al., 2021). Numerous authors have proposed diverse methodological approaches to establish an objective definition of flash drought. Despite efforts of the scientific community, there is not a widely accepted method for quantification and analysis (Otkin et al., 2018). The existing discrepancies are given by both criteria (e.g., definition based on duration versus velocity of development) and metrics (e.g., soil moisture, precipitation, evapotranspiration, AED etc.) adopted by the different methodological approaches to define flash droughts. In addition, the rapid development characteristic of flash drought makes more difficult its quantification and monitoring. The lack of a clear definition and uncertainty in the role played by the drivers involved in the flash drought development makes difficult to determine the suitability of the different metrics. Moreover, it is necessary to consider the possible effects of climate change on the occurrence and severity of flash droughts, especially in regions in which water stress is increasing. Thus, at the star of this dissertation, there are still many knowledge gaps related the study of flash drought.

There is a need to establish methodological approaches to define flash drought in an objective manner, improving the capacity to identify, quantify and monitor it. Many of the methodological approaches for flash drought identification are based on information usually constrained in time and space (e.g., soil moisture, satellite-derived information), making it difficult to apply the methods in most of world regions and to assess flash drought variability at long-term. Therefore, the implementation of methodological approaches based on widely available meteorological data would provide several advantages for flash drought analysis compared to these approaches. Most of the existing studies focus on ET, assuming a minor role of precipitation deficits in the development and intensification of flash droughts. However, different studies have evidenced that precipitation has a major role to drive flash drought conditions in different world regions (Hoffmann et al., 2021; Koster et al., 2019; Parker et al., 2021; Y. Wang & Yuan, 2022b). Consequently, it seems essential to include the role of precipitation in the methodological approaches used for flash drought assessment. In this way, some authors highlighted the potential use of drought indices such as the Standardized Precipitation Evapotranspiration Index (SPEI), based on a climatic balance (i.e., precipitation minus AED), for the assessment of flash droughts (Hunt et al., 2014; Otkin et al., 2018). Thus, we believe that the development of a methodology based on the SPEI, which provides comparable information over time and space, could be one of the best ways to identify and monitoring flash droughts.

Also, it is essential to unravel the role played by the drivers underlying flash drought development. Some studies evidenced that the influence AED on drought severity varies notably over the time and space (Tomas-Burguera et al., 2020; Vicente-Serrano, McVicar, et al., 2020), so it seems reasonable to consider that this complexity is also reflected on the development of flash droughts. Therefore, the use of different metrics based on precipitation (e.g., SPI), AED (e.g., EDDI) or both (e.g., SPEI) may provide different results, as it is expected that the identified events are driven by different divers. Thus, and considering that there is no single metric/variable that allows an overall assessment of drought severity (Lloyd-Hughes, 2014), the implementation of different metrics could allow a better assessment and understanding of flash drought events. Likewise, this would also make possible to recognize some of the limitations and benefits of using different metrics. In addition, it is necessary to find out whether the role of the AED in flash drought triggering shows a temporal evolution to determine the possible effects of global warming processes.

In Spain, in which drought is a frequent phenomenon (Domínguez-Castro et al., 2019), flash drought could represent a major risk for agricultural and environmental systems. However, there are not studies that have analyzed flash droughts. For this reason, it necessary to provide the first spatial and seasonal characterization of the flash drought events in Spain, as well as to determine their trends over the last decades. Moreover, considering the climatic complexity of Spain and its variability in terms of precipitation and AED (including humid regions and dry regions), this could be an excellent case of study to analyze the occurrence of flash drought in a region with very different climatic characteristic, where the frequent occurrence of drought has important agricultural, hydrological, environmental and socioeconomic implications, which may be amplified under global warming.

Given the existing uncertainties for flash drought, as well as the potential agricultural and environmental implications of these events in Spain, it is need to unravel some key issues underlying flash droughts. The main objective of this research is to characterize the flash drought phenomenon in Spain during the last decades and for this purpose, we define different specific objectives:

1) To develop an objective methodology for the identification of flash droughts based on standardized drought indices, allowing the results obtained to be comparable over time and space.

2) To analyze the spatial and seasonal patterns of flash drought in Spain, comparing them with those observed in other drought events.

3) To determine possible trends in the frequency of flash drought spatially and seasonally in Spain over the last few decades compared to other drought events.

4) To evaluate the spatio-temporal patterns and trends of flash droughts reported by means different metrics (i.e., SPI, EDDI and SPEI), unraveling the possible influence of precipitation deficits and AED increase on flash drought.

5) To determine the contribution of AED to the development of flash droughts spatially and seasonally, as well as the possible temporal evolution over the last few decades.

6) To create a user-friendly monitoring system for early warning of flash drought in Spain. This should allow the operational tracking of flash drought at near-real time.

6. PhD dissertation outline

The PhD dissertation is organized into 7 chapters. The Chapter 1 includes a general description of the scientific context in which the research was developed, as well as some of the key issues that motivated the objectives of this PhD dissertation. In Chapter 2, we introduce the methodological approach proposed for flash drought identification in the context of this research. In this chapter we also described the spatio-temporal patterns and trends observed in Spain over the last six decades by means the application of the proposed methodology. Chapter 3 focuses on the analysis of the role played by the main climate drivers involved in flash drought development and intensification. For this purpose, we analyzed and compared spatially and seasonally the flash drought patterns obtained by means of the implementation of different metrics (SPI, EDDI and SPEI) to explain the main meteorological drivers that control flash drought occurrence (i.e., precipitation deficit and anomalous AED increase). Chapter 4 provides a detailed analysis of the contribution of AED to the development of flash drought, as well as its evolution over the time. Chapter 5 presents the first available flash drought monitoring system for Spain, which allows a precise and operational tracking of flash drought at near-real time. In this chapter, we illustrate some of the capabilities of this monitoring system and its possible uses for preparedness and mitigation of flash droughts. In Chapter 6, we discuss the results obtained in this research. Finally, we summarize the main findings of this PhD dissertation in the Chapter 7.

To support some of the issues addressed in the chapters, we included two annexes. In Annex 1, we present a study developed to improve the Evaporative Drought Demand Index (EDDI) computation through the implementation of a parametric approach. This research was crucial for improving the performance of EDDI in the identification of flash drought, as well as for the evaluation and comparison of EDDI (originally based on a non-parametric approach) with parametric indices such as SPI and SPEI shown in the Chapter 3. The Annex 2 includes supporting information on the different research addressed in this PhD dissertation.

Chapter 2

Characteristics and trends of flash droughts in Spain, 1961–2018

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ORIGINAL ARTICLE

Characteristics and trends of flash droughts in Spain, 1961–2018

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Flash droughts are characterized by rapid onset and intensification, as well as major environmental and agricultural impacts. In this study, we developed an objective method for identifying flash droughts using the standardized evaporation precipitation index (SPEI) based on a short time scale (1-month) and high-frequency data (weekly). The identification of flash droughts was focused on the development phase, anomalous decreases in index values in a short time period (4 weeks), and the magnitude of the events. The method was applied to mainland Spain and the Balearic Islands using a high spatial resolution gridded dataset for the period 1961–2018. For this period of 58 years, we characterized the occurrence of flash droughts and showed that for Spain, there was a large spatial and temporal variability in their frequency, with more occurring in the northwest than in the central and southern regions. The northern regions, where a higher frequency of flash droughts was found, showed negative trends in the frequency of flash droughts, while the regions subject to fewer flash drought events showed generally positive trends. We investigated the relative frequency of flash droughts affecting the study regions and found that they are a common phenomenon, as 40% of all droughts were characterized by rapid development. The findings of this study have important implications for drought assessment, monitoring, and mitigation.

Keywords: flash drought; atmospheric evaporative demand; SPEI; time scale; Spain

Introduction

Drought is one of the main natural hazards affecting society and the environment.[1] Since 1900, more than 11 million people have died as a consequence of drought, and in excess of 2 billion people have been affected by droughts, more than by any other physical hazard.[2] Although droughts are usually associated with a decline in precipitation relative to normal levels over a defined period, there is no broadly accepted definition.[3–5] Drought is difficult to identify in time and space, and difficult to quantify in terms of magnitude and duration.[6–8] Furthermore, droughts are multidimensional phenomena and can occur on differing time scales.[9,10]

The development and spatial propagation of drought is usually slow,[11,12] and typically a drought takes many months to reach maximum intensity.[13] Because of the lag between a decline in precipitation and a decrease in water resources, the impacts of meteorological droughts on agriculture, the environment, and hydrological processes usually occur over long periods.[9,14–17] Nevertheless, drought impacts on agriculture and ecological systems are usually not entirely dependent on long-term dry conditions. Short periods characterized by low levels of precipitation and/or increased atmospheric evaporative demand (AED) can have marked negative impacts on plant physiology,[18,19] which explains why natural vegetation and crops usually respond to short time scales of meteorological drought.[20–22]

Recent studies have reported that droughts can develop very rapidly as a consequence of severe precipitation anomalies during humid periods and/or as a consequence of an anomalous increase in the AED, usually during the warm season.[18,23] The rapid onset observed in some drought events has

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resulted in coining of the term *flash drought*. This concept was first applied by Svoboda *et al.*,[24] who used the U.S. Drought Monitor and identified some events in which the drought magnitude increased rapidly. Several studies have subsequently identified the occurrence of flash droughts in various regions worldwide. Anderson *et al.*,[25] Otkin *et al.*,[26] and Ford *et al.*[27] identified drought events characterized by rapid development in the United States since the year 2000, Yuan *et al.*[28] reported the occurrence of a flash drought in southern Africa in December–January 2015–2016, and Nguyen *et al.*[29] recently recorded a flash drought event in Australia in early 2018.

Although various studies have tried to describe the characteristics of flash droughts, there is no widely accepted definition.[23] The main feature of a flash drought is its rapid onset and intensification. Consequently, all meteorological droughts could be classified as flash droughts if the onset is rapid. Flash drought characteristics are related to a rapid decrease in soil moisture and/or an increase in the AED, which are well-known drivers of vegetation stress.[30–34] Flash droughts usually begin as meteorological droughts that rapidly become agricultural droughts because of the rapid depletion in soil moisture,[35] but land–atmosphere feedbacks and/or unusually warm air masses[36–38] can also trigger or reinforce these drought conditions.

Various approaches have been used to identify flash droughts. Anderson *et al.*,[25] Otkin *et al.*,[26] and Nguyen *et al.*[29] suggested that anomalous changes in the satellite-derived evaporative stress index (ESI; see Anderson *et al.*[39]) can be an early signal of flash droughts. Similarly, Otkin *et al.*[13] reported that standardized change anomalies in the ESI and the rapid change index (see Otkin *et al.*[40]) can provide valuable information enabling rapid identification of soil moisture depletion. Mozny *et al.*[33] used the soil moisture index (see Hun *et al.*[41]) to detect flash droughts in the Czech Republic. Likewise, Ford and Labosier[30] identified several flash drought events in the United States using soil moisture data. Christian *et al.*[35] recently proposed a method based on the standardized evaporative stress ratio. Nevertheless, there is no widely accepted method for the identification of flash droughts, and the cited approaches are affected by problems of applicability, as some of the drought metrics used are not widely available (e.g., soil moisture measurements) or are based on unverified remote sensing data (e.g., evapotranspiration (ETo) and soil moisture).

Because of the constraints associated with most soil moisture and ETo data worldwide, it is necessary to develop objective and comprehensive methods for identifying drought events characterized by rapid development, preferably on the basis of widely available information (e.g., meteorological observations) and comprehensive drought indices. Standardized drought indices calculated using meteorological information are widely accepted and used for drought quantification and monitoring, and these could be used to identify flash droughts.[31] In this study, we used this methodological approach to identify drought episodes characterized by rapid onset.

Our study was conducted in Spain because of data availability at high temporal frequency and spatial resolution, but also because droughts have major impacts in this region. Droughts show high recurrence in Spain,[12] and have important agricultural[21,42] and ecological impacts, including decreased plant activity and gross primary production,[43,44] decreased forest growth,[45–47] forest fires,[48,49] and local land degradation processes in particularly vulnerable areas.[50] Various atmospheric mechanisms determine the occurrence of droughts,[51,52] and in Spain these show great spatial complexity[53] and remarkable variation in frequency, duration, and magnitude.[54] Although there have been no generalized trends in drought severity in Spain over the last six decades,[54] an increase in the severity of drought events, related to enhanced AED, has been identified.[12,55]

Despite advances in the knowledge of droughts in Spain, nothing is known about the characteristics and temporal behavior of flash droughts in the country. For this reason, the general objectives of this study were twofold: (1) to develop a simple method for identifying flash droughts, on the basis of a comprehensive and widely used climate drought index; and (2) to describe the long-term variability and trends in flash droughts in Spain, on the basis of a high spatial resolution and temporal frequency dataset.

Data and methods

Climate dataset

The study was based on a high spatial resolution (1.21 km^2) gridded climate dataset for the

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period 1961–2018. This dataset comprised weekly data on precipitation, maximum and minimum air temperature, relative humidity, sunshine duration, and wind speed. The gridded dataset was created using all daily observational information from the National Spanish Meteorological Service (AEMET) by means of an interpolation scheme of universal kriging using as input the meteorological data measured in the different meteorological stations and the terrain elevation. The climate series were subjected to a careful quality control and homogenization process.[56] Details of the dataset development, including interpolation methodology, and validation have been described by Vicente-Serrano *et al.*[57] On the basis of the data for maximum and minimum temperature, relative humidity, wind speed, and sunshine duration, we used the FAO-56 Penman–Monteith equation[58] to calculate the reference ETo, which is a metric of the AED.

Methods

Flash drought identification. Standardized drought indices are widely used to analyze droughts. Among these, one of the most widely used is the standardized evaporation precipitation index (SPEI; see Vicente-Serrano *et al.*[59]), which is based on standardization of the difference between precipitation and the AED. This drought index can be calculated on various temporal scales to enable adaptation of the times of response of hydrological, agricultural, and environmental variables to the climate variability.[17,20,22,60,61] The use of long time scales of drought indices prevents the detection of the rapid onset of drought because of the influence of cumulative past climate conditions on the current values of the indices. For this reason, we used the SPEI at a short time scale (1-month), and made calculations based on a temporal frequency of 1 week (four per month). The selected time scale identifies rapid changes in the general humidity conditions.[23,24,26,35]

To identify rapid onset in a drought event, we calculated the change in the SPEI (ΔSPEI) in periods of 4 weeks for each week at each cell by grid point. After several tests of various thresholds, the onset of a flash drought was defined as involving a ΔSPEI equal to or less than –2 SPEI units (z-values), which reflected a very rapid decrease in the SPEI values in a short period of time (4 weeks). The frequency of events recorded varied considerably as a function of the thresholds, decreasing the number of events as the absolute value of ΔSPEI value increased (Fig. S1, online only). We sought a balance in choice of the threshold, as higher ΔSPEI threshold greatly increased the recorded occurrence of flash drought events, while lower thresholds resulted in the identification of very few events. Although subjective, in various tests, the selected threshold identified flash droughts consistent with the expected spatial and temporal frequency of drought events in the region. Moreover, given the comparability of the SPEI across regions and periods, the selected threshold enabled identification of spatial patterns and possible changes in the flash drought frequency. Not all events identified on the basis of the selected ΔSPEI threshold were considered flash droughts because the absolute value of this index had to be taken into account; a rapid decline in the SPEI value is not necessarily indicative of drought conditions (e.g., a drop from 2 to 0 SPEI units in 4 weeks). Therefore, in addition to the ΔSPEI threshold, we included a third criterion to be met in identifying flash drought events, whereby final SPEI values had to be equal to or less than –1.28 SPEI units. This value corresponds to moderate drought conditions (the maximum drought severity expected in a 10-year period, according to the standard normal distribution of SPEI values). In summary, the criteria selected to record the occurrence of a flash drought were:

1. A minimum length of 4 weeks in the development phase.
2. A ΔSPEI value equal to or less than –2 z-units.
3. A final SPEI value equal to or less than –1.28 z-units.

The methodology and criteria described above were applied to the complete SPEI gridded series to identify flash droughts affecting Spain in the period 1961–2018. Figure 1 shows examples of flash droughts identified in the dataset. Note that the flash drought events were assigned to the week in which the SPEI was ≤ -1.28 z-units and the ΔSPEI value was ≤ -2 z-units.

Comparisons among all drought events. To characterize the frequency and spatial and temporal patterns of flash droughts identified using the developed methodology, we compared the occurrence of flash droughts with all drought events

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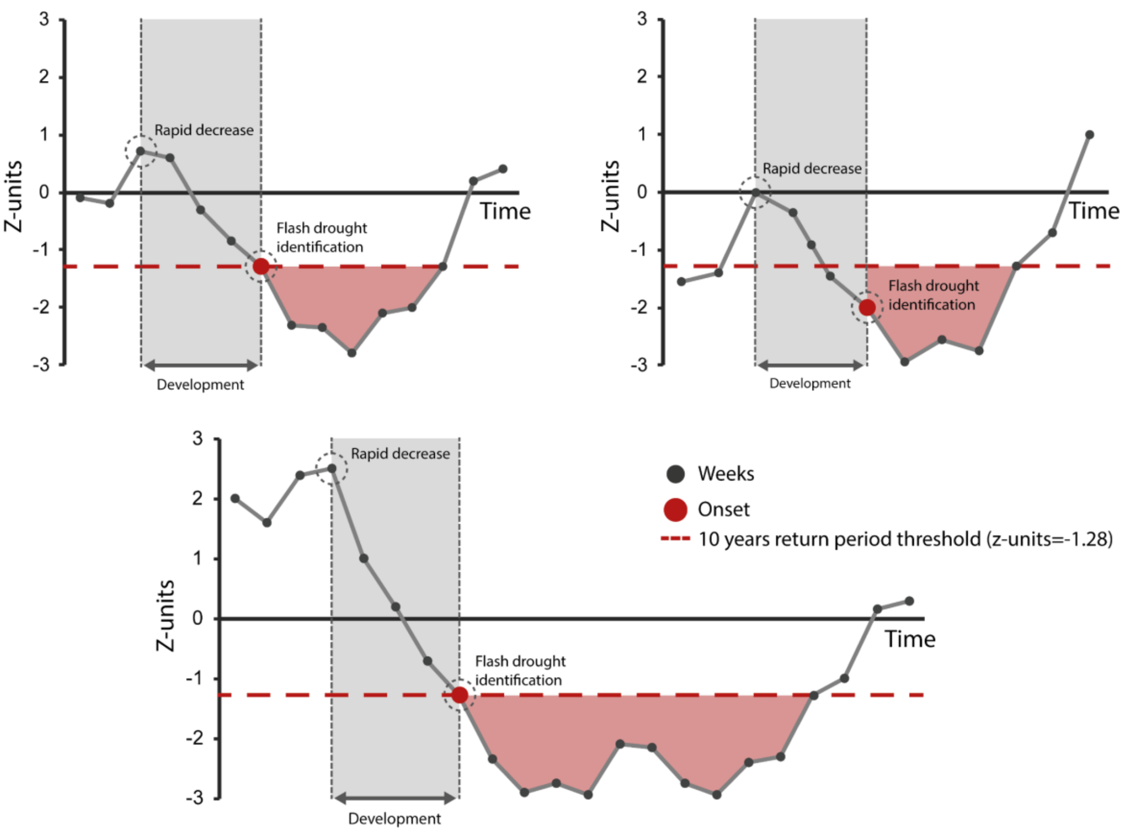

Figure 1. Examples of flash drought identification using the developed methodology.

in the dataset that met a threshold of −1.28 SPEI z-units, regardless of whether they showed a rapid onset. In this process, we compared spatial and temporal differences in the number of flash droughts and all drought events that were quantified seasonally and annually. The temporal relationship between annual and seasonal series of flash droughts and all drought events was analyzed using Pearson's correlation coefficient. This analysis was applied to each cell by grid point, but also to specific Spanish regions. These regions were selected according to homogeneous behavior in the temporal variability of drought events at the 1-month time scale (methodology described by Vicente-Serrano[53]) (Fig. S2, online only).

Trend analysis. Changes in the frequencies of flash droughts and all drought events were analyzed for each cell by grid point at the annual and seasonal scales. Our analysis used the nonparametric Mann–Kendall statistic, which measures the degree to which a trend is consistently increasing or decreasing. Its advantage compared with parametric tests is that it is robust to outliers and does not assume any underlying probability distribution of the data.[62] Autocorrelation was considered in the trend analysis using the modified Mann–Kendall trend test, which returned corrected P values after accounting for temporal pseudoreplication.[63,64] To assess the magnitude of change in the frequencies of flash droughts and all drought events, we used a linear regression analysis between the series of time (independent variable) and the seasonal and annual series of drought frequencies (dependent variable). The slope of the regression indicated the amount of change (change in the number of events per year), with greater slope values indicating greater change. We used crosstab analysis to investigate the spatial relationship between the significance (negative: $P < 0.05$; negative: $P > 0.05$; positive: $P < 0.05$; positive: $P > 0.05$) of trends found in flash droughts and all droughts. The degree of spatial consistency

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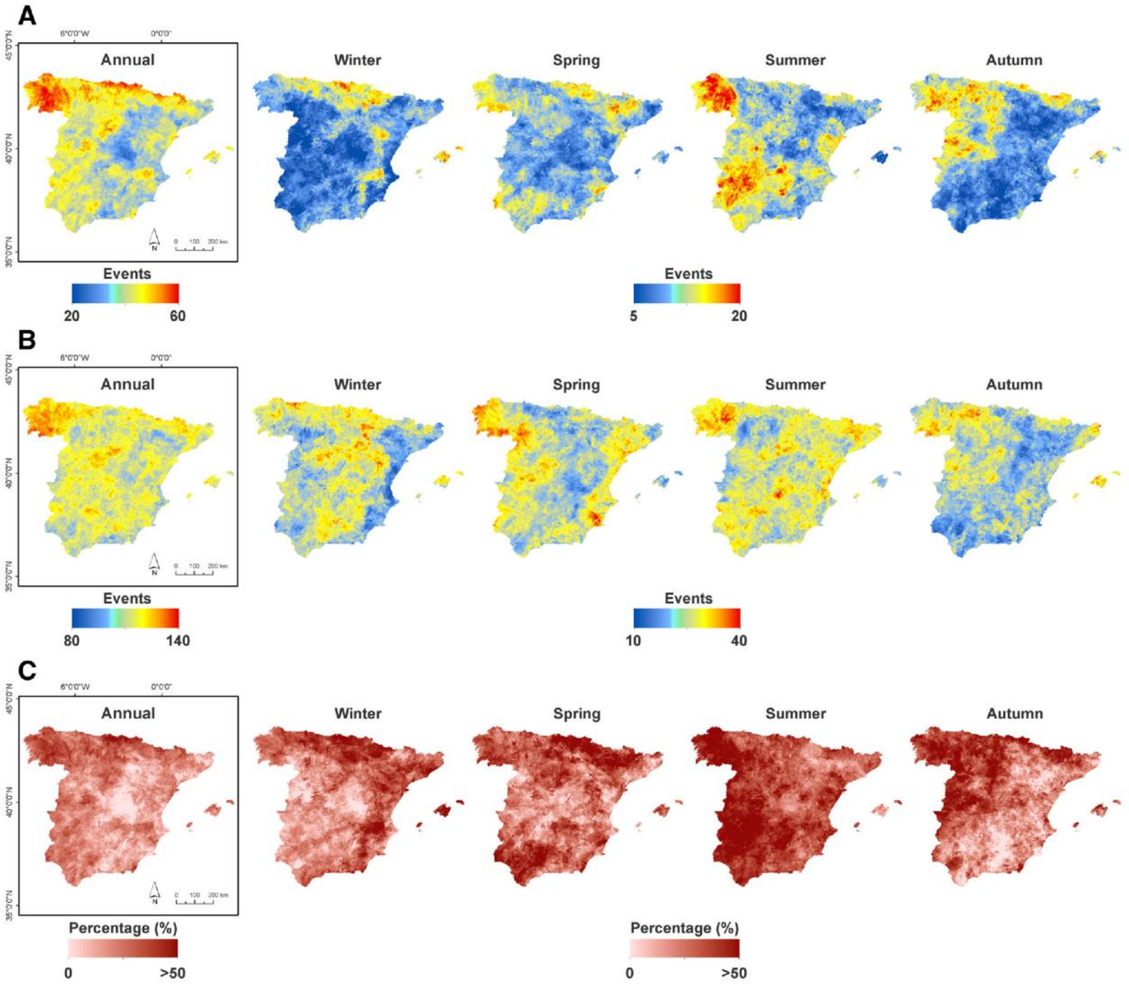

Figure 2. Annual and seasonal spatial distribution of the total frequency of: (A) flash droughts; (B) all drought events; and (C) the percentage of flash droughts relative to all drought events.

of the significance in trends was investigated using the contingency coefficient (CC).[65]

Results

Spatial distribution of flash droughts

Figure 2 shows the spatial distribution of the total number of flash droughts and all drought events for mainland Spain and the Balearic Islands from 1961 to 2018 at the annual and seasonal scales. There was remarkably contrasting and high spatial variability in the number of flash droughts recorded at the annual scale across the entire study domain (Fig. 2A). Northern and northwestern Spain had the highest number of flash droughts, with some areas exceeding 60 events during the study period, while fewer flash droughts occurred in the central and southeastern regions; the total frequency of all drought events was also highest in northwestern Spain (Fig. 2B). As expected, the average occurrence of all droughts at the annual scale and for all of Spain was markedly higher than that for flash drought events (114 and 42 events/cell by grid point from 1961 to 2018, respectively). However, there were some similar spatial patterns for both drought categories. Thus, northern and northwestern Spain had high numbers of both types of drought event, but flash drought events comprised a very high percentage (>40%) relative to the total of all droughts recorded in this region (Fig. 2C). The average percentage of flash droughts for the entire

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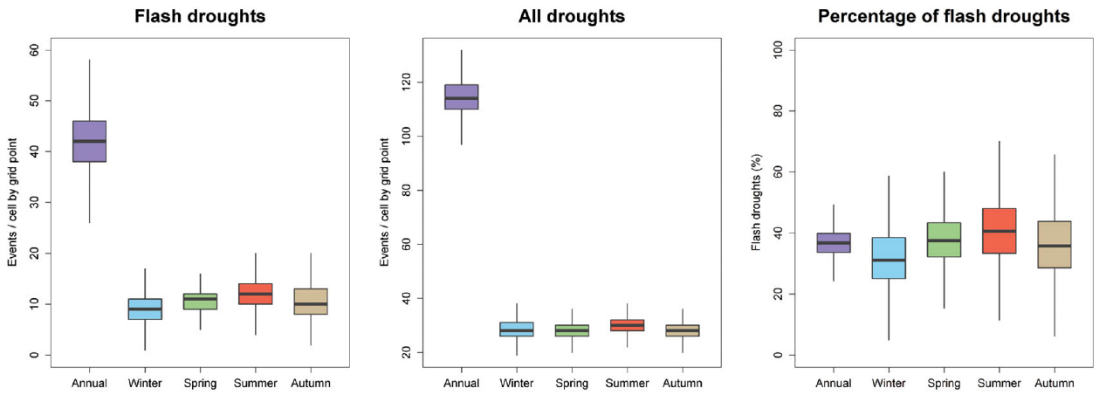

Figure 3. Annual and seasonal frequency of flash droughts, all drought events/cell by grid point, and the percentage of flash droughts relative to all drought events during the period 1961–2018.

study area was approximately 39%, indicating that almost 4 in every 10 drought events developed as flash droughts.

At the seasonal scale, the spatial patterns change markedly. In general, there were greater seasonal differences in the spatial patterns of flash droughts than there were for all drought events (Fig. 2). There average number of all drought events/cell by grid point was similar in winter, spring, and autumn (approximately 28 events). Winter had the lowest average frequency of flash droughts (approximately 9 events/cell by grid point), but a high frequency of flash droughts was found for the north and the Balearic Islands. In these regions, flash droughts represented a high proportion of all drought events. Unlike the spatial distribution of flash droughts, all drought events also occurred at high frequency in large areas of central Spain in winter. The maximum average frequency of flash droughts and all droughts occurred in summer (12 and 30 events/cell by grid point, respectively). In this season, a high frequency of flash droughts occurred in the northwest and large areas of southern Spain, while the frequency of all droughts was high in the majority of the study area, including the northeast. Thus, compared with the northwest and southwest Spain, lower percentages of flash droughts occurred in the northeast; although on average, the maximum percentage of flash droughts occurred during summer (Fig. 3). In spring, the average number of flash droughts was approximately 11 events/cell by grid point, although the spatial distribution of the frequency of events was variable, with areas in the south, northwest, and the Pyrenees subject to a high frequency of flash droughts. By contrast, the Mediterranean coast and eastern Spain had the highest frequency of all drought events in spring. In autumn, there was a northwest—southeast gradient in the frequency of flash droughts. Although the highest number of all droughts occurred in the northwest, there was a high frequency of events in areas of the Mediterranean coast and the Balearic Islands. Thus, the northwest—southeast gradient in the spatial distribution of flash droughts in autumn resembled the pattern of percentage of flash droughts relative to all drought events.

The differences in the frequency of flash droughts recorded annually and seasonally for the entire study area were also evident regionally (Fig. 4). Thus, the total frequency of flash droughts in the period analyzed was markedly higher in the northwestern and northern regions, with averages of approximately 54 and 49 drought events, respectively. The frequency of flash drought events in the other regions (northeastern, Iberian Peninsula, southern, and southeastern) was lower, with averages of approximately 40 events. These differences were also noted at the seasonal scale, with the highest frequency of drought events occurring in autumn in the northwestern and northern regions. In winter, and to a lesser extent in spring, there was a higher frequency of flash droughts in the northwestern, northern, and northeastern regions compared with central and southern Spain. In summer, the highest frequency of flash droughts occurred in the NW region (average, approximately 16 events).

Figure 5 shows the spatial relationship between the total number of flash droughts and all drought

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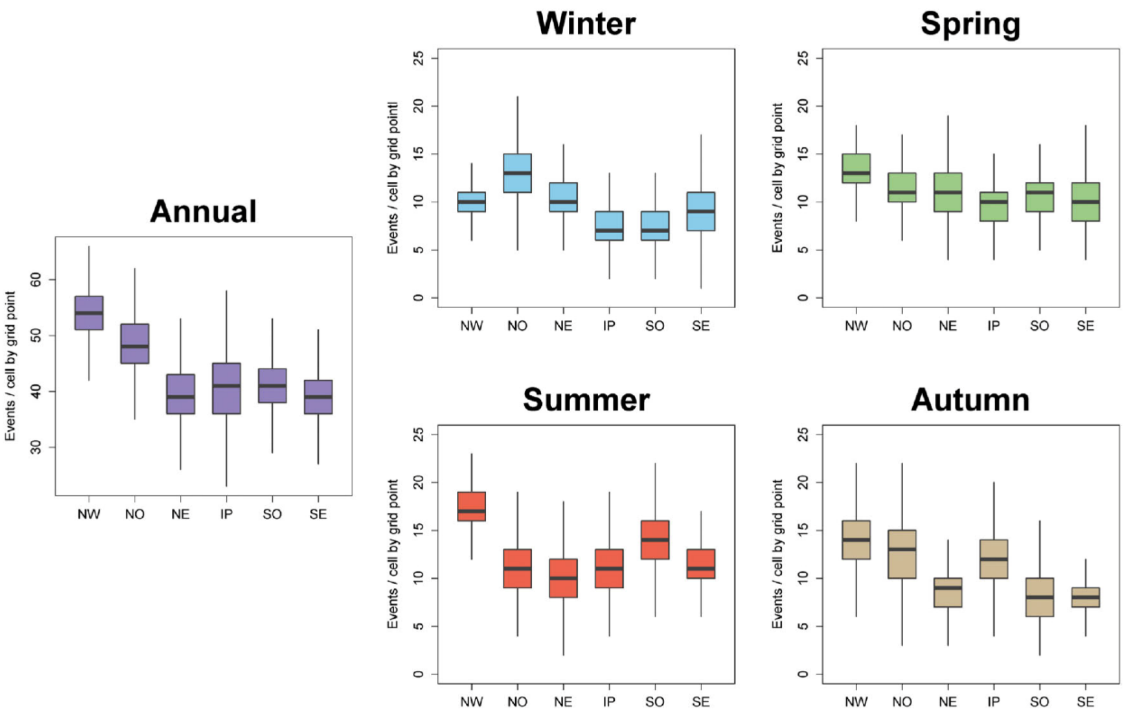

Figure 4. Annual and seasonal frequency of flash drought events in various drought regions for the period 1961–2018. IP, Iberian Peninsula; NO, northern; NE, northeastern; NW, northwestern; SE, southeastern; SO, southern.

events recorded annually and seasonally. At the annual scale, there was a significant and positive relationship between the absolute frequency of flash droughts and all drought events (Pearson's $r = 0.58$). Similarly, the seasonal series showed a positive correlation, but this was only statistically significant for autumn. These findings indicated important spatial differences between the frequencies of flash droughts and all drought events. Thus, the shared variance was very small, which suggests differing spatial behavior, and possibly different drivers for each drought category event in the region. At the regional level, there were some differences in the relationship (Fig. S3, online only), with positive and significant correlations in the northwestern, northern, northeastern, and southeastern regions in winter; the northwestern, northeastern, and southeastern regions in spring; the northern and southern regions in summer; and the northwestern, northern, and northeastern regions and the Iberian Peninsula in autumn. At the annual scale, all regions showed a positive correlation, but this was only statistically significant for the northeastern region.

Temporal variability and trends of flash droughts

We analyzed the changes in the occurrence of flash droughts in Spain in absolute terms, but also as a percentage of all drought events. Figure 6A summarizes the annual and seasonal evolution of the frequencies of flash droughts and all drought events on mainland Spain and the Balearic Islands over the period 1961–2018. The annual series shows high interannual variability in the occurrence of flash droughts and no significant trend over the entire period. All drought events were also characterized by high interannual variability and showed a positive and not statistically significant trend. At the annual scale, the temporal evolution of the frequencies of flash droughts and all drought events was positive and significantly correlated (Pearson's $r = 0.67$). Figure 6B shows the temporal evolution of the percentage of flash droughts relative to all drought events. The trend in the temporal evolution of the percentage of flash droughts was negative, but was not statistically significant.

Similarly, the seasonal series of average frequencies of flash droughts and all drought events showed

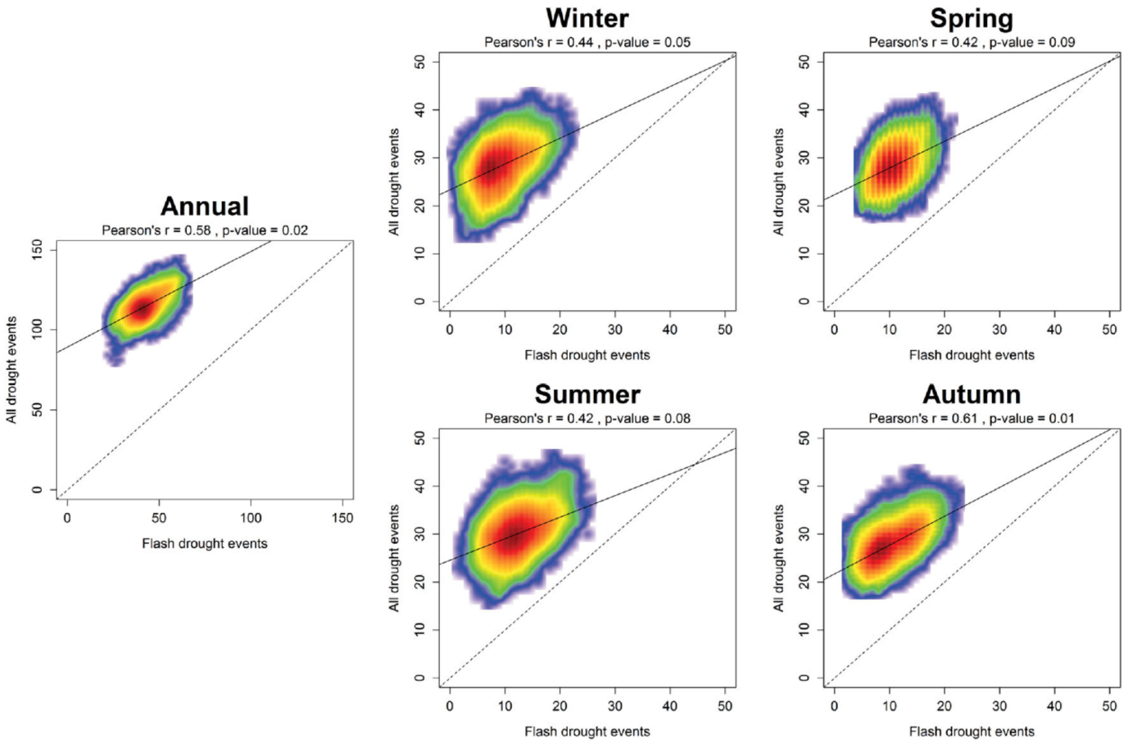

Figure 5. Scatterplots showing the annual and seasonal relationship between the number of flash droughts and all drought events. The colors represent the density of points, with red denoting the highest density. The significance of Pearson's *r* coefficients was estimated using a Monte Carlo approach based on 1000 random samples of 30 points.

high interannual variability, and there was a positive and significant correlation between the two drought categories. A negative trend was noted in the frequency of flash droughts and all droughts in winter, although this was only significant for the frequency of flash droughts. By contrast, there was a positive and significant trend in the frequency of flash droughts and all drought events in summer. In spring and autumn, there was no significant trend in the frequency of flash droughts and all drought events. The percentage of flash droughts relative to all drought events showed nonsignificant trend over the entire period in all seasons, although there was an increase in the percentage of flash droughts in summer and spring in the last two decades.

For different regions, the annual series of drought occurrence showed no significant trends (Fig. S4, online only), except in the northwestern region where a negative and significant trend was evident in the frequency of flash droughts, and the southeastern region, where there was a positive and significant trend in the frequency of flash droughts and all drought events. In all analyzed regions, there was a positive and statistically significant correlation between the series of flash droughts and all drought events over the period 1961–2018. The temporal evolution of the percentage of flash droughts relative to all drought events in general showed not statistically significant trends (Fig. S5, online only), and the trend was only significant for the northwestern region. At the seasonal scale, there was no significant trend in spring and autumn, with the exception of the negative and significant trend noted in the flash drought series in autumn in the northern region. In general, positive trends in the frequency of flash droughts and all droughts were evident in summer, but the increase of flash droughts was only statistically significant in the southern and southeastern regions. Furthermore, there was high variability in the seasonal percentage of flash droughts relative to all drought events, but only in the Iberian Peninsula and southern region in spring and northeastern region in winter was there a significant (negative) trend.

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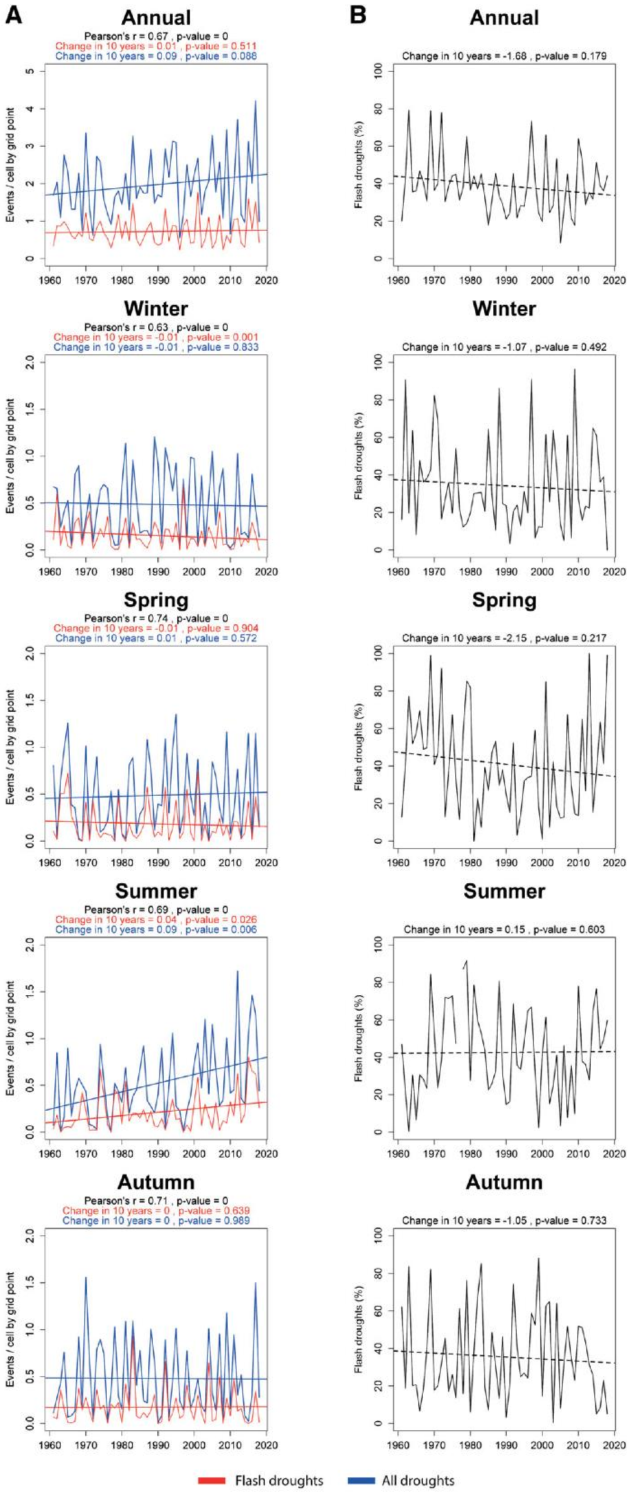

Figure 6. Temporal evolution of the annual and seasonal frequencies of: (A) flash droughts and all drought events; and (B) percentage of flash droughts relative to all drought events over the period 1961–2018. The data represent a regional average based on all the grid cells for Spain. In panel B, the years having no records correspond to those in which no drought events were recorded.

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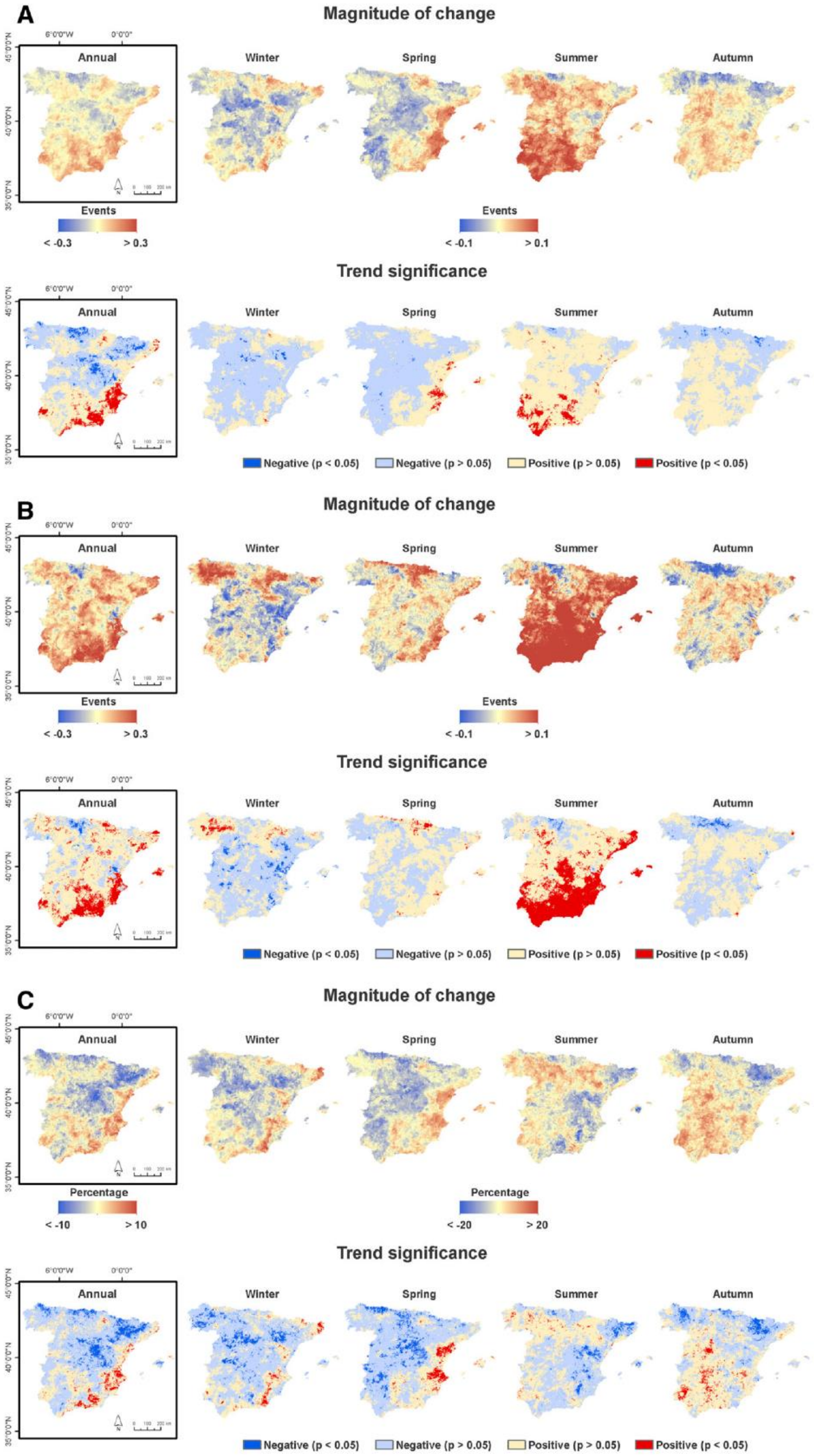

Figure 7. Spatial distribution of the annual and seasonal magnitudes of change per decade and the significance of trends for: (A) flash droughts; (B) all drought events; and (C) the percentage of flash droughts relative to all drought events for the period 1961–2018.

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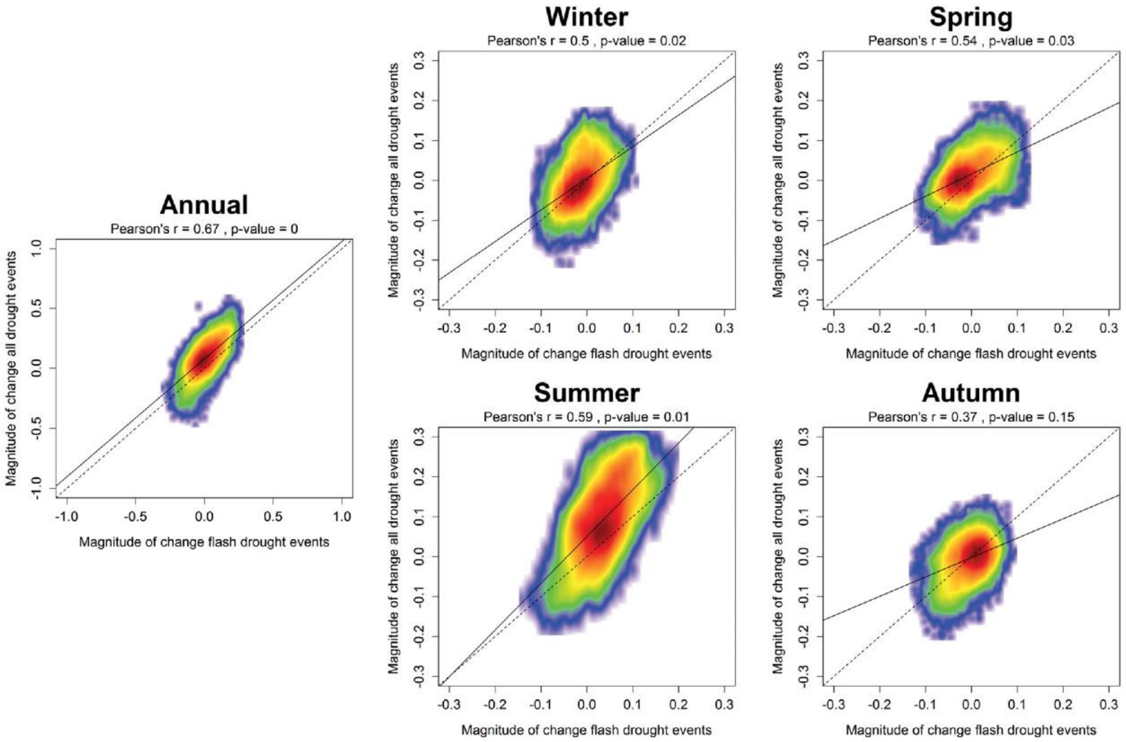

Figure 8. Scatterplots showing the annual and seasonal relationships between the spatial distribution of the magnitude of change per decade in flash droughts and all drought events. The colors represent the density of points, with red denoting the highest density. The significance of Pearson's *r* coefficients was estimated using a Monte Carlo approach based on 1000 random samples of 30 points.

Figure 7 shows the spatial distribution of the magnitude of change and the significance of trends in the annual and seasonal series of the frequency of flash droughts and all drought events over the period 1961–2018. At the annual scale, the greatest increase in the frequency of flash droughts occurred in areas of the Mediterranean coast and southern Spain, where the positive trends were statistically significant. Some regions of central and northern Spain showed negative and statistically significant trends. In general, areas showing an increase in the frequency of flash droughts coincided with areas showing the greatest increase in the frequency of all drought events (south and southwest Spain). These areas of the Mediterranean coast and southern Spain showed an increase in the number of flash droughts and a significant trend in the percentage of flash droughts relative to all drought events, while the central and northern regions showed generally negative trends. Figure 8 shows the spatial relationship between the magnitude of change in the frequency of flash droughts and all drought events. At the annual scale, there was a positive and significant relationship between the spatial pattern of the magnitude of change in the frequency of flash droughts and that for all drought events. Nevertheless, the shared variance was not high (<50%; Fig. 8). A positive and significant relationship was also noted at the regional scale, except in the northwestern region and Iberian Peninsula (Fig. S6, online only). In general, the areas having positive trends in the frequency of flash drought events had a high degree of consistency with areas that showed positive trends in all drought events, but there were major disparities in the areas showing negative trends. Thus, the CC for the spatial patterns in the sign and signification of the trends in the frequency of between flash droughts and all drought events was 0.53 at the annual scale, indicating that the degree of spatial consistency was not high.

At the seasonal scale, there were marked differences in the spatial patterns of the magnitude

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of change in the frequency of flash droughts and all drought events, and in the significance of the trends. Summer showed the highest spatial consistency between the patterns of trend significance for flash droughts and all drought events (CC = 0.45), while the major differences occurred in autumn (CC = 0.25). For spring and winter, the CC values were also low (0.33 and 0.36, respectively). With the exception of summer, the trend in the frequency of flash droughts and all drought events was not statistically significant for most of the study area, and the spatial relationship was smaller than at the annual scale. The trend in the frequency of flash droughts and all drought events in summer was generally positive, especially in the south of Spain, and more pronounced considering all drought events. However, there was no significant trend in the percentage of flash droughts in these areas. It is noteworthy that in spring, there was a significant increase in flash droughts and their occurrence relative to all droughts in some areas of the Mediterranean coast.

Discussion

This study focused on the identification and characterization of flash droughts over mainland Spain and the Balearic Islands since the 1960s. A simple and objective methodology was developed, on the basis of one of the most widely used standardized indices in drought studies: the SPEI.

Method to characterize flash droughts over the long term

The majority of previous studies focused on the analysis of flash droughts using satellite data and/or observations/models of soil moisture,[13,18,26,27,29,30,32,33] but the availability of these data is limited, and usually only short time series are available. We adopted a method based on widely available meteorological information, from which it was possible to assess the long-term spatial and statistical characteristics of flash droughts, and potentially changes in the frequency of this phenomenon. In addition, this approach enabled comparison with other droughts characterized by slower development. Standardized drought indices based on meteorological information are the most widely used tools to quantify drought severity, as recommended by the World Meteorological Organization.[66,67] Furthermore, the use of a standardized drought index will enable application of the developed methodological approach to other regions worldwide, and results that are comparable in time and space.

The implications of flash droughts are mostly related to environmental and agricultural impacts.[13,23,68] Empirical studies have shown a strong relationship between standardized drought indices, including the SPEI and various types of impact, including on forest growth,[46,47,69] vegetation activity,[20,60,70] and crop yields.[21,71,72] Therefore, it is likely that the environmental and agricultural impacts of flash droughts can also be identified using standardized drought indices.

As the main characteristics of flash droughts are rapid onset and intensification,[23,24] the method that was developed enabled identification of drought events with these characteristics; from this, it was possible to characterize flash droughts over the long term, including the analysis of long-term temporal trends. We used the SPEI rather than the standardized precipitation index (SPI; see McKee *et al.*[9]). This is because several studies have shown that the SPEI is better for identifying environmental and agricultural impacts than the SPI,[73–76] as inclusion of the AED in the calculation facilitates the identification of added vegetation stress, mostly in periods of low precipitation.[77] In addition, using the SPEI made it possible to identify the greater severity of recent drought events associated with higher levels of the AED.[12,78,79] The inclusion of the AED in the quantification of flash droughts seems necessary as several studies suggest that flash droughts are commonly enhanced by heat waves characterized by high AED,[23,25,26,32] which would cause more rapid depletion of soil moisture[27,33] and greater vegetation stress.[80–82] Thus, the SPEI ensures that the AED anomalies that drive the rapid onset of flash droughts are taken into account, in addition to the decrease in precipitation that must occur for the development of any drought event.

The most extreme droughts having the largest environmental, agricultural, and hydrological impacts typically occur on long time scales of meteorological drought indices.[1,12] Nevertheless, flash droughts have the particularity of rapid onset. Therefore, we focused on high-frequency data (weekly) and a very short time scale (1-month) of the SPEI. Short time scales have not previously been considered in analyzing the severity of drought episodes, but doing so enables the

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detection of the rapid climate anomalies that give rise to flash droughts (see also Hunt *et al.*[31]). Our approach was based on specific thresholds reflecting the speed of drought onset and the severity of the drought index, including a minimum length of 4 weeks in the development phase, a change in the SPEI equal to or less than −2 z-units during that period, and a final SPEI value equal to or less than −1.28 z-units (corresponding to a return period of 1 in 10 years). These criteria emphasize on drought events that can generate anomalously stress conditions in natural vegetation and produce drought, mostly in summer. The selected thresholds used to identify flash droughts in this study were subjective. However, no objective criteria were available, given uncertainties in the concept of flash droughts[23] and the scarcity of studies focused on their identification. While other thresholds could have been used to identify flash droughts, those chosen enabled the identification of events characterized by very rapid onset and a major change in humidity conditions from humid or normal conditions to severe drought. We believe that this approach is an improvement on recent attempts to identify flash droughts based on the duration of the events.[28,32,83–85] This is because methodological approaches intended to identify flash drought events must be focused on the velocity of drought onset as the main component differentiating these from other drought events characterized by slower development. Because of the common availability of the necessary meteorological information, the method we developed can be applied worldwide to characterize flash drought over the long term, and to establish spatial comparisons among regions having different climate characteristics.

Spatial characteristic of flash droughts in Spain

Flash droughts in Spain show substantial spatial and seasonal complexity, which is a feature of droughts generally in Spain that has been stressed in previous studies.[12,53,54,86] However, none of the previous approaches has focused on the developmental phase and the rapid onset of flash droughts. We focused on drought spatial patterns on a very short time scale, which was necessary for characterizing the rapid onset of the droughts. The focus on a 1-month time scale enabled the identification of regions and seasons in which flash droughts are more frequent and representative relative to all drought events. The spatial patterns of the frequency of all drought events varied from those recently identified by Domínguez-Castro *et al.*,[54] given the use of a different threshold (−1.28 in the present study versus 0 in the noted study), but in both cases, the higher frequency of dry events was recorded in the north and northwest of Spain. This pattern was reinforced in analysis of the frequency of flash drought events, which were much more frequent in these regions and markedly in contrast with the regions in central Spain. In the humid northern area, periods characterized by precipitation levels below the average would cause a rapid drop in the drought index values, which would explain the higher frequency of flash droughts found in this area. By contrast, in central and southern Spain, periods characterized by several weeks of low precipitation are common in all seasons, and the conjunction of other factors (e.g., extreme high temperatures and AED in summer) is probably necessary to trigger flash drought events. This hypothesis seems to be reinforced by the spatial and seasonal patterns in the frequency of flash droughts relative to all drought events. At the annual scale, but also during wet periods, the percentage of flash droughts was greater in the north than in central and southern Spain. Nevertheless, in summer, the pattern was more homogeneous, and large areas of western and southern Spain were also characterized by a high percentage of flash droughts. In these areas, the precipitation during summer was almost zero,[87,88] so the occurrence of heat waves that dramatically enhance the AED would probably be important in triggering flash drought events; recent studies have suggested that during the last decade, there has been a large increase in the frequency and severity of these events.[89,90]

It is notable that although the spatial pattern in the frequency of flash droughts showed some relationship to the frequency of all drought events at the annual and seasonal scales, the shared variance between these droughts was small, and particularly low in winter, spring, and summer. This suggests that the mechanisms that trigger flash droughts may be different from those that control the majority of drought events in Spain. This issue should be investigated in depth in the future, but it is possible that the AED may be much more important in explaining the development of flash drought events than

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it is for other drought events, where the predominant role of precipitation is undisputed.[77] Previous studies have stressed the importance of the AED in explaining the occurrence of flash drought events in various regions of the world.[18,23,26,28,30,32] However, although this could explain the differences in summer, when the AED is strong in Spain,[91,92] the divergence between the spatial patterns for flash droughts and all drought events is probably explained by precipitation, which shows strong interannual variability.

Temporal trends in flash droughts in Spain

There were no clear drought trends for Spain since the 1960s. Only during summer has there been some increase in the frequency of drought events in southern Spain. This finding is consistent with studies that analyzed trends based on the SPEI in Spain. For example, using 3-month standardized drought indices, Domínguez-Castro *et al.*[54] found a decrease in southern Spain, mostly related to the level of precipitation, as the SPI also decreased. Nevertheless, in this study, we found that the magnitude of the trend for all drought events in summer was stronger than that found for flash droughts. This seems to be contradictory given the possible role of heat waves in the development of flash drought events, as noted above. Nevertheless, as observed in the United States,[93–95] other studies have shown that under a scenario of increased frequency and severity of heat waves, there is a decrease in the number of flash drought events linked with heat waves.[32] In Spain, the frequency of extreme temperature events has increased[96,97] in recent decades, with heat waves associated with various mechanisms, including air stagnation,[90,98] and possibly land−atmosphere feedbacks associated with soil moisture deficits.[99] This seems to have contributed to reduced relative humidity[100] and an increase in the AED,[91,92] which has contributed to more severe drought events in recent decades.[12,54,55,78] Nevertheless, this does not seem to explain the increase in flash droughts. The strong temporal and spatial variability in summer precipitation[88,101] may have had a role, although for further research it is necessary to understand the contribution of precipitation and AED anomalies to the development of flash droughts in Spain, and to explain the recently observed trends.

Conclusions

We developed an objective and comprehensive method for identifying flash droughts on the basis of the SPEI. This method focuses specifically on the rapid onset of droughts and on the magnitude of the events. It enables flash droughts to be identified objectively in time and space, and in a way that is spatially and temporally comparable. The main findings of the first characterization of flash droughts in Spain are that:

(1) Flash droughts in Spain are complex phenomena having great spatial and temporal variability. The northern and northwestern regions showed a higher frequency of flash drought events compared with central and southern Spain.
(2) Flash droughts are common in Spain, with almost 40% of all drought events (considering a return period of 1 in 10 years) developing as flash droughts.
(3) There was a higher average number and percentage of flash droughts in summer and spring.
(4) There has been a general and significant increase in the number and percentage of flash droughts in southeastern Spain. Only in summer has there been a generalized increase in flash droughts, notably and significantly in the southern regions.

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Author contributions

I.N., F.D.C., and S.M.V.S. designed and performed the research. I.N., F.D.C., and S.M.V.S. were involved in developing the methodology. I.N. worked in data processing and figure creation. I.N., F.D.C., and S.M.V.S. drafted the paper and contributed to revising the content of the final version of the manuscript.

Supporting information

Additional supporting information may be found in the online version of this article.

Figure S1. Flash drought events/cell by grid point recorded based on various ΔSPEI thresholds.

Figure S2. Regional classification of mainland Spain and the Balearic Islands based on the temporal evolution of droughts at a 1-month time scale (based on Vicente-Serrano[53]).

Figure S3. Scatterplots showing the annual and seasonal relationship between the absolute frequency of flash droughts and all drought events in the various homogeneous drought regions during the period 1961–2018.

Figure S4. Temporal evolution of the average annual and seasonal frequency of flash droughts and all drought events in the various drought regions.

Figure S5. Temporal evolution of the annual and seasonal percentage of flash droughts relative to all droughts in the various homogeneous drought regions during the period 1961–2018, where the years having no records correspond to those in which no drought events were recorded.

Figure S6. Scatterplots showing the annual and seasonal relationship between the magnitude of change per decade in flash droughts and all drought events in the various homogeneous drought regions during the period 1961–2018.

Competing interests

The authors declare no competing interests.

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Chapter 3

Flash drought response to precipitation and atmospheric evaporative demand in Spain

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Flash Drought Response to Precipitation and Atmospheric Evaporative Demand in Spain

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Abstract: Flash drought is the result of strong precipitation deficits and/or anomalous increases in atmospheric evaporative demand (AED), which triggers a rapid decline in soil moisture and stresses vegetation over short periods of time. However, little is known about the role of precipitation and AED in the development of flash droughts. For this paper, we compared the standardized precipitation index (SPI) based on precipitation, the evaporative demand drought index (EDDI) based on AED, and the standardized evaporation precipitation index (SPEI) based on the differences between precipitation and AED as flash drought indicators for mainland Spain and the Balearic Islands for 1961–2018. The results show large differences in the spatial and temporal patterns of flash droughts between indices. In general, there was a high degree of consistency between the flash drought patterns identified by the SPI and SPEI, with the exception of southern Spain in the summer. The EDDI showed notable spatial and temporal differences from the SPI in winter and summer, while it exhibited great coherence with the SPEI in summer. We also examined the sensitivity of the SPEI to AED in each month of the year to explain its contribution to the possible development of flash droughts. Our findings showed that precipitation is the main driver of flash droughts in Spain, although AED can play a key role in the development of these during periods of low precipitation, especially in the driest areas and in summer.

Keywords: flash drought; sensitivity; atmospheric evaporative demand; precipitation; standardized drought indices; SPEI; Spain

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1. Introduction

Drought is one of the most complex natural hazards affecting natural and human systems [1–3]. Typically, drought is considered to be a meteorological phenomenon that is slow to develop, taking many months or even years to reach maximum intensity [4,5]. However, recent studies have proved that drought may also develop in the short-term as a result of large precipitation deficits and/or anomalous increases in atmospheric evaporative demand (AED) [6]. The term "flash drought" has become popular in the scientific literature to describe these drought episodes characterized by rapid onset and intensification. Flash droughts usually begin as a meteorological drought that becomes an agricultural drought within a short time, due to a decline in soil moisture and an increase in vegetation stress [7], with a strong potential impact on agriculture and the environment [8].

Precipitation is the most important factor in the development of droughts [9]. However, the occurrence of flash droughts has been commonly related to drastic increases in AED and the associated land–atmosphere feedbacks (e.g., increased land evapotranspiration) that can trigger or reinforce drought conditions [10]. Numerous studies have evidenced that AED can play a key role in the development and intensification of certain drought episodes [11–13]. Therefore, the AED can be a crucial variable in explaining the rapid depletion of soil moisture and vegetation stress caused by flash droughts [12,14–16].

However, given complex land–atmosphere feedbacks involving drought [10], the role of AED in the development of flash droughts could be very complex and variable in time and space [17].

Efforts to develop objective methodologies and early warning systems to identify flash droughts have increased in recent years [7,14–16,18–26], but none is widely acceptable [6]. Most methods proposed for identifying flash droughts mainly focus on rapid changes in reference evapotranspiration (ET_o) or soil moisture [7,19,23,24], without including precipitation as an input variable. Other authors, such as Mo and Lettenmaier [16,22] or Zhang et al. [27] suggested differentiating two types of flash droughts: "heat wave flash droughts" linked to high temperatures and "precipitation deficit flash droughts" linked to anomalously low rainfall.

In this work, we studied the role of precipitation deficit and atmospheric evaporative demand increase on flash droughts in Spain, where flash droughts are a frequent phenomenon with approximately four in every 10 drought events (i.e., a return period of 1 in 10 years) resulting in a flash drought [18]. Several studies showed the high occurrence of severe droughts episodes in Spain through historical [28–30] and instrumental records [31]. Spain has strong climatic contrasts with marked spatial and seasonal differences in precipitation [32–35] and AED [36–39]. Northern Spain is characterized by its humid oceanic climate with abundant precipitation over the year, while northeastern and southeastern regions are mainly characterized by semiarid conditions with annual precipitation generally below 300 mm [40]. On the other hand, the complex topography given by the presence of numerous mountain chains results in a strong continental features in central Spain. This climatic complexity is also reflected in the spatial and temporal variation of droughts [41,42] and the variety of atmospheric mechanisms triggering them [43–45], which enable an evaluation of the role of precipitation deficits and AED in the development of flash droughts over a wide range of climate conditions.

For this purpose, we compared three standardized drought indices based on different climate variables for flash drought analysis. The objectives of this study were twofold: (i) to compare the spatial and temporal patterns of flash droughts identified by three robust standardized drought indices based on different climatic variables: the standardized precipitation index (SPI), evaporative demand drought index (EDDI), and standardized evaporation precipitation index (SPEI); and (ii) to analyze the role of precipitation deficits and AED excess in flash droughts in Spain over the period 1961–2018.

2. Methods

2.1. Data

This research used a high spatial resolution (1.21 km^2) gridded climate dataset with coverage for mainland Spain and the Balearic Islands from 1961 to 2018 at weekly frequency. The climate dataset included data on precipitation, maximum and minimum air temperature, relative humidity, sunshine duration, and wind speed. The gridded dataset was created based on all daily observational information from the National Spanish Meteorological Service (AEMET) by means of an interpolation scheme of universal kriging using as input the meteorological data measured in the different meteorological stations and the terrain elevation. The climate series were subjected to a homogenization process and a careful quality control (see details in Tomas-Burguera et al. [46]). Additional information about the dataset development, interpolation methodology, and validation are available in Vicente-Serrano et al. [47]. The reference evapotranspiration (ET_o), as a metric of the AED, was calculated from the maximum and minimum temperature, relative humidity, wind speed, and sunshine duration, using the FAO-56 Penman–Monteith equation [48].

2.2. Computing the Drought Indices: SPI, EDDI, and SPEI

Standardized drought indices are commonly used in drought analysis and monitoring across the world. Among these, some of the most widely used for drought analysis are the standardized precipitation index (SPI; see Mckee et al. [49]) based on precipitation and the standardized evaporation precipitation index (SPEI; see Vicente-Serrano et al. [50]) based on the difference between precipitation and AED. In particular, the SPI and SPEI also proved to be robust metrics for identifying flash droughts [51]. Recently, other standardized drought indices, such as the evaporative demand drought index (EDDI; see Hobbins et al. [52]) based exclusively on AED, was developed and recommended for flash drought analysis [19]. The EDDI quantify drought severity as AED increases under water-limited conditions, which is very useful during periods of low precipitation or soil moisture and important land–atmosphere coupling [17].

The SPI and SPEI were calculated using parametric approaches, fitting the data to Gamma and Log-logistic distributions, respectively. Moreover, the EDDI was calculated by a parametric approach based on Log-logistic distribution [53]. The SPI, EDDI, and SPEI are comparable in time and space and can be calculated on different time scales to adapt the response of hydrological, agricultural, and environmental systems to the climate variability [54]. However, the shorter scales better capture the rapid variations in precipitation and/or atmospheric evaporative demand that can trigger a flash drought, since the anomalies accumulated over past climate conditions do not affect the index values. Therefore, we calculated the SPI, EDDI, and SPEI at a short time scale (1-month) and a weekly frequency for each grid point of the climate dataset from 1961 to 2018 (see details in Noguera et al. [18]).

2.3. Identifying Flash Droughts Based on Standardized Drought Indices: SPI, EDDI, and SPEI

Flash drought events were identified following the methodology proposed by Noguera et al. [18]. The original approach was based on the SPEI at a short time scale (1-month) and high-frequency data (weekly) to identify the onset of flash drought episodes. This method focuses on the rapid development characteristic of flash droughts, which results in a sudden, very sharp drop in the index values. Thus, flash drought is defined as: (i) a minimum length of four weeks in the development phase; (ii) an ΔSPEI (in 4 weeks) equal to or less than -2 z-units; and (iii) a final SPEI value equal to or less than -1.28 z-units (i.e., a 10-year return period). This method was used here to identify flash droughts based on the three standardized drought indices: SPI, EDDI, and SPEI.

2.4. Comparison of the SPI, EDDI, and SPEI

We analyzed the spatial and temporal variability of the SPI, EDDI, and SPEI by comparing the spatial and temporal behavior of the values of each index in each month of the year. Pearson's correlation coefficient (95% confidence level) was used to examine the relationship between SPI, EDDI, and SPEI series over time and space. Given that each weekly data is calculated based on the precipitation, AED, or climate balance ($D = P - AED$) data accumulated over four weeks (corresponding to a 1-month time scale), we used the weekly data for the last week of each month to calculate the correlation between the indices in order to reflect the variability over the whole month. The relationship between the frequency of annual and seasonal flash drought series recorded by the SPI, EDDI, and SPEI for each grid point from 1961 to 2018 was also examined by means of Pearson's correlation coefficient (95% confidence level). In addition, we analyzed the relationship between the total frequency of flash droughts identified by each index and the associated significance. The significance of Pearson's r coefficients was estimated using a Monte Carlo approach, in which the total number of flash droughts recorded by SPI, EDDI, and SPEI was correlated in 1000 random samples of 30 points from the entire dataset at annual and seasonal scales. We also examined the trend of annual and seasonal flash drought series recorded by the non-parametric Mann–Kendall statistic. Autocorrelation was included in the trend analysis by the modified Mann–Kendall trend test, which returned corrected p-values after accounting for temporal pseudoreplication [55,56]. To assess the magnitude of change in the frequencies of flash droughts, we used a linear regression analysis between the series of time (independent variable) and the seasonal and annual series of drought frequencies (dependent variable). The slope of the regression indicated the amount of change in the number of events per year, with higher slope values indicating greater variation. In order to identify changes between the frequencies of flash droughts recorded for each index, we also calculated the differences (events/for each grid point) between the flash drought series obtained through the SPI, EDDI, and SPEI annually and seasonally and also examined their trends using the non-parametric Mann–Kendall statistic.

2.5. Evaluation of Sensitivity of Flash Droughts to AED

To analyze the role of precipitation deficits and atmospheric evaporative demand (AED) positive anomalies in the development of flash drought events in Spain, we calculated the sensitivity of SPEI to the AED at a short time scale (1-month) and compared it with the total frequency of flash drought events recorded in each month of the year in the period from 1961 to 2018. The sensitivity of SPEI to AED differs between climate conditions [9,17]. The SPEI is based on standardization of the climate balance (D) resulting from differences between precipitation and AED ($D = P - AED$), making it possible to quantify the contribution of precipitation and AED to the variability of SPEI values, following the methodology proposed by Tomas-Burguera et al. [9]. Thus, using the precipitation and AED series employed to compute SPEI, we calculated the partial derivatives of the climate balance (D) to determinate the relative contribution of both variables in each month over the period 1961–2018. The series of precipitation and AED were detrended prior to making the analysis to avoid the possible effects of trends on the results (see more details in Tomas-Burguera et al. [9]).

3. Results

3.1. Spatial and Temporal Variability of the SPI, EDDI, and SPEI

In general, the indices present high interannual variability in all months (Figure 1). The SPI and EDDI show non-significant correlation from November to January. On the contrary, there is a significant correlation between the SPI and EDDI from March to June and September–October (Pearson's $r > 0.7$). February, July, and August returned lower correlation values, although there was a significant correlation. Correlation between the EDDI and SPEI was also low from November to February, although with slightly higher correlation values than those found between the SPI and EDDI. From March to October, there was a high correlation between EDDI and SPEI, reaching a maximum in May, June, and July (Pearson's $r \geq 0.9$). Correlation between the SPI and SPEI was very high and significant in all months of the year, although it was slightly lower in July and August.

The spatial pattern of the correlation and associated significance between monthly series of the SPI, EDDI, and SPEI over the period 1961–2018 also show some relevant differences (Figure 2). In general, there is a low, non-significant correlation between the SPI and EDDI in northwestern regions from November to January, while it is high and significant in the Mediterranean coastland and southern Spain. From February to June, also in September and October, there is a high, significant correlation between SPI and EDDI. In contrast, correlation between the SPI and EDDI was low and non-significant in July and August in large areas of southern Spain. Correlation between the EDDI and SPEI was also low and non-significant in northwestern regions, but it was high and significant in southern and eastern Spain from November to January. From February to October, there was a significant correlation between the EDDI and SPEI over most of the study area, reaching a maximum from May to July. As expected, there was very high and significant correlation between the SPI and SPEI in every month over almost all of the study area, with only some areas in southern Spain, where precipitation is very low in summer, returning low values in July and August.

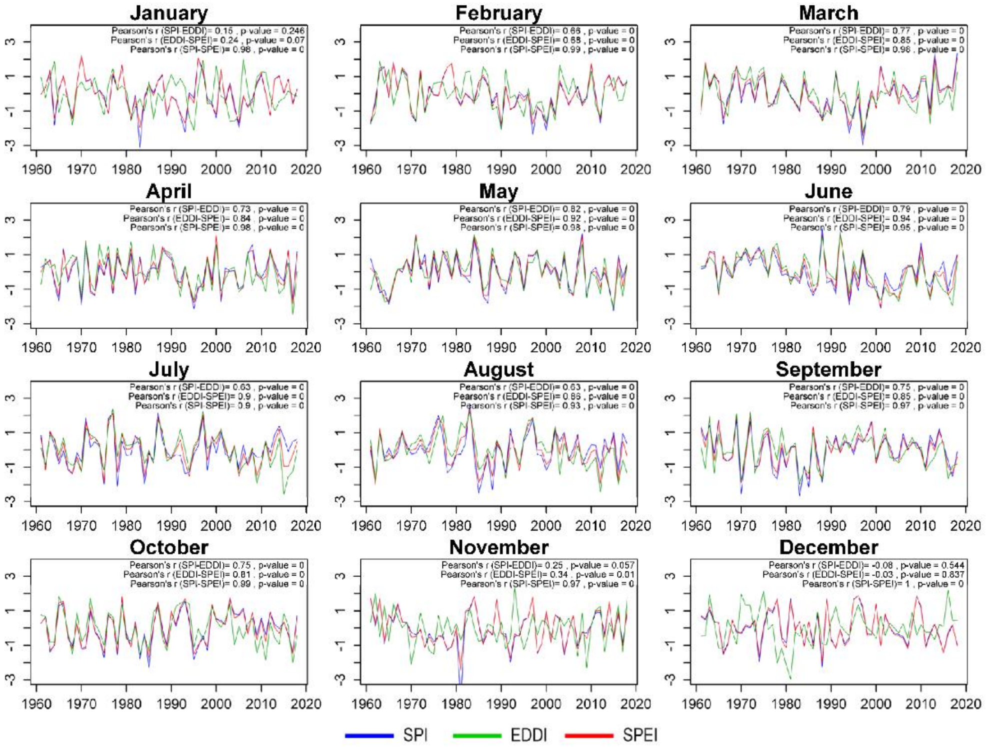

Figure 1. Temporal evolution of monthly series of the standardized precipitation index (SPI), evaporative demand drought index (EDDI), and standardized evaporation precipitation index (SPEI) based on average data on mainland Spain and the Balearic Islands over the period 1961–2018 at a short time scale (1-month). The monthly series includes the weekly data for the last week of each month in each year.

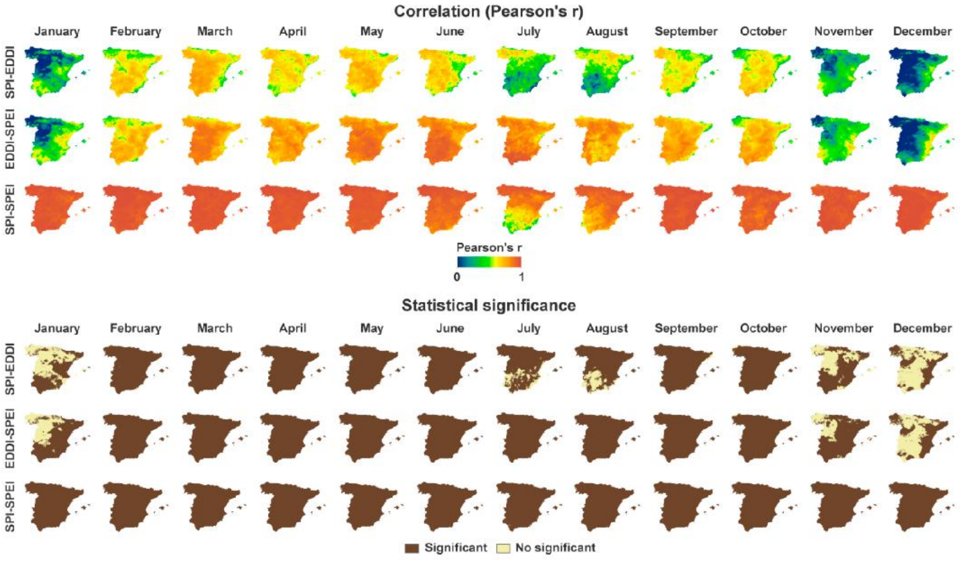

Figure 2. Spatial pattern of the correlation (Pearson's r) and associated significance between monthly series of the SPI, EDDI, and SPEI over the period 1961–2018. The monthly series include the weekly data for the last week of each month in each year.

3.2. Spatial Distribution and Trends in Flash Drought

Figure 3 shows the spatial distribution and frequency of flash droughts (events/for each grid point) identified by the SPI, EDDI, and SPEI from 1961 to 2018 at annual and seasonal scales. There were notable differences in the spatial distribution of flash droughts identified by the SPI, EDDI, and SPEI (Figure 3a), as well as in the average frequency of events recorded for each index (Figure 3b). The average frequency of flash droughts obtained by the SPI (≈70 events/for each grid point) was considerably higher than for the EDDI and SPEI (≈40 events/for each grid point) at an annual scale. In general, the SPI identified a high occurrence of flash droughts in most of the study area at an annual scale, which was also noted in some areas of central and northeastern Spain, while the Mediterranean coastland recorded the lowest number of events. The EDDI and SPEI recorded the highest number of flash drought events in northern and northwestern Spain, although the EDDI also recorded a great many in some areas of the Mediterranean coastland.

At a seasonal scale, there were also spatial differences between patterns of the average frequency of flash droughts recorded by the SPI, EDDI, and SPEI. In winter, similar spatial patterns were found for SPI and SPEI, with the highest occurrence found in the northern and eastern regions of the Iberian Peninsula and in the Balearic Islands. However, the average frequency of flash droughts identified by the SPI (≈16 events/for each grid point) was substantially higher than by the SPEI, which recorded the lowest average frequency in this season (≈9 events/for each grid point). On the other hand, the EDDI recorded a great many flash droughts in large areas of central Spain in winter, reaching its maximum average frequency for the season, with approximately 13 events/for each grid point. In spring, the spatial distribution and average frequency of flash droughts recorded by the SPI showed great disparities with the EDDI and SPEI. The average frequency of the flash droughts recorded by the SPI (≈17 events/for each grid point) was considerably higher than by the EDDI and SPEI (≈10 events/for each grid point). The SPI recorded a high incidence of flash droughts in spring in most of central and western Spain, and also in some areas of the Pyrenees. In contrast, the EDDI recorded a low number of flash droughts in those regions, and more events were found in certain areas of the Mediterranean coastland and northern and northwestern Spain. Similarly, the SPEI identified a high occurrence of flash drought events in northern and northwestern regions but also in large areas of southern Spain. In summer, the SPI and EDDI recorded their lowest average frequency, while the SPEI reached its maximum average frequency (≈12 events/for each grid point). There is no clear spatial pattern of flash drought identified by the SPI in summer, with a high number of flash droughts occurring in central, northwestern, and northeastern Spain. The EDDI identified the highest number of flash droughts in northern and western regions, while central and eastern Spain had few events. In general, the SPEI recorded a high frequency of flash drought events in summer, with wide areas of the south and northwest exceeding 15 events/for each grid point. In autumn, the pattern of spatial distribution of flash droughts identified by the SPI and SPEI was similar in northern Spain, and both recorded a low number of events in the Mediterranean coastland. However, the SPI also identified a high number of events in large areas of central Spain, reaching its maximum average frequency in this season with approximately 19 events/for each grid point. Unlike the SPI and SPEI, the EDDI recorded the highest incidence of flash droughts in the Mediterranean coastland in autumn, but it only recorded a few in western Spain.

In general, there was non-significant spatial correlation between the total number of events identified for each index and the shared variance was not high, due to notable spatial differences annually and seasonally (Figure 4). At an annual scale, there was a negative and non-significant correlation between the spatial distribution of the total number of flash droughts recorded by the SPI and EDDI. The highest correlation was found between the EDDI and SPEI at annual scale, although it was non-significant. The SPI and SPEI also returned a positive, but non-significant, correlation annually.

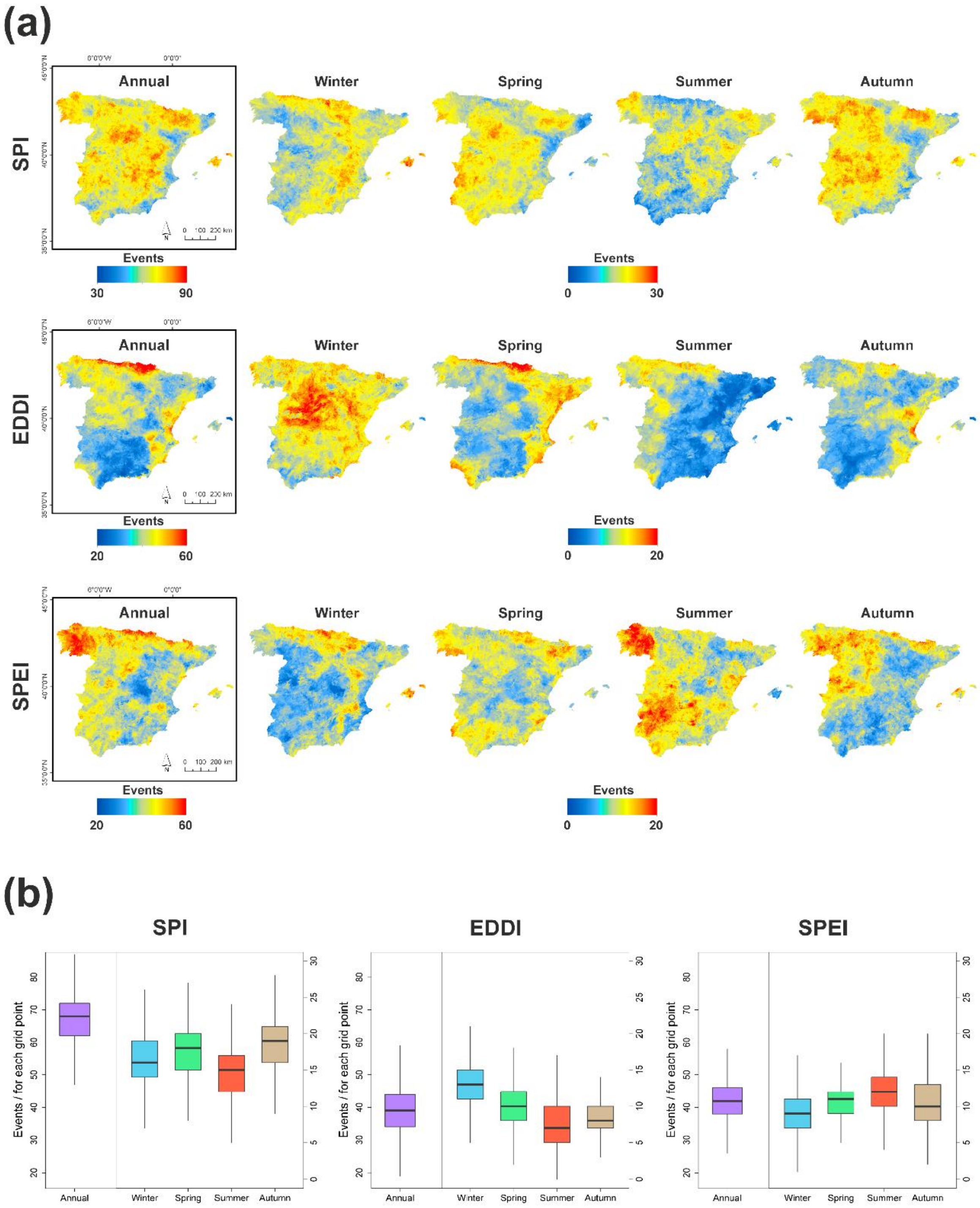

Figure 3. Annual and seasonal (**a**) spatial distribution for the frequency of flash droughts (events/for each grid point) identified by the SPI, EDDI, and SPEI over the period 1961–2018, (**b**) box plots summarizing the annual and seasonal frequencies obtained with the different indices. In the box plot, the left axis represents the annual data and the right axis represents the seasonal data.

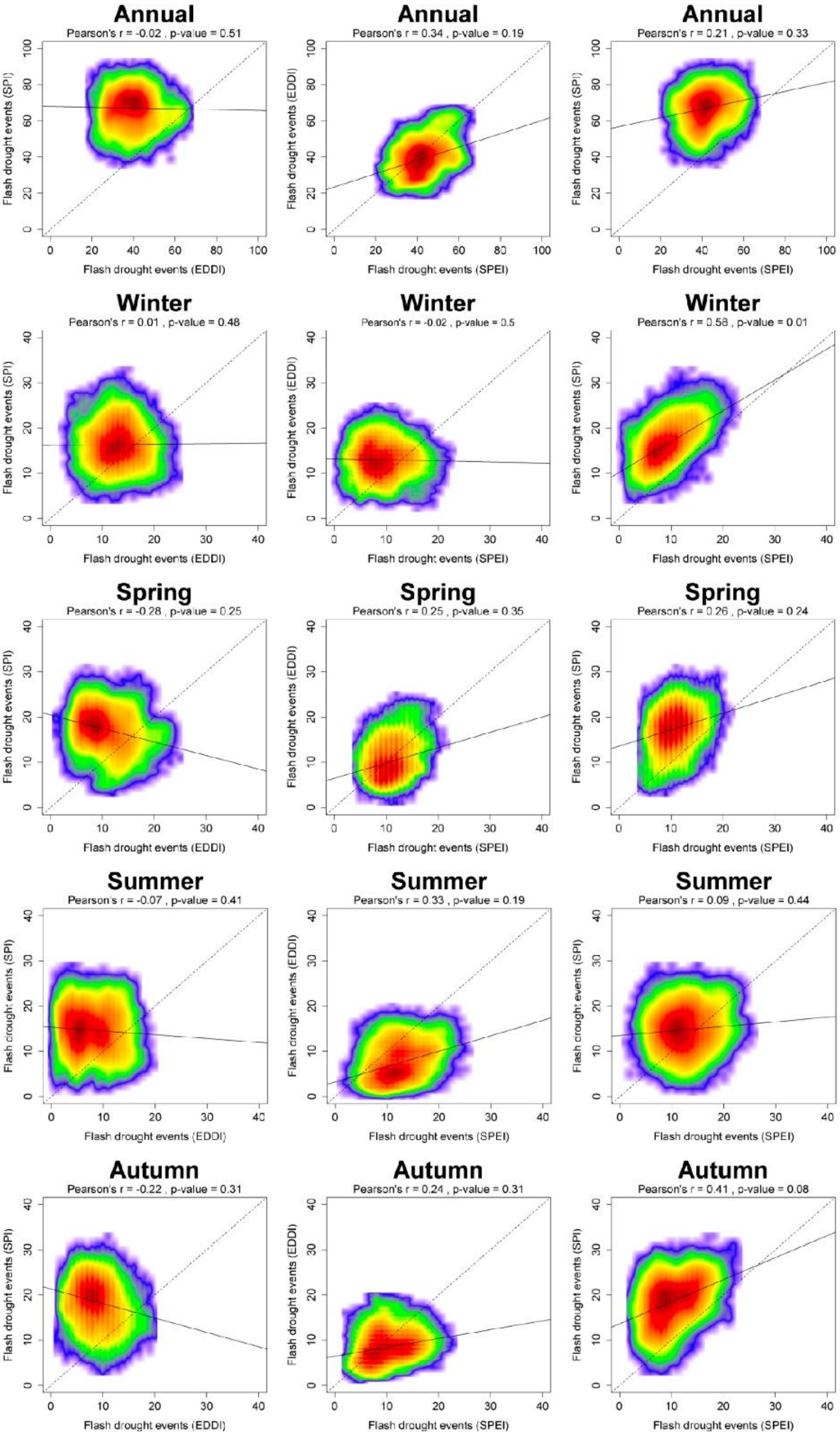

Figure 4. Scatterplots showing the annual and seasonal relationship between the total number of flash drought events recorded by the SPI, EDDI, and SPEI. The colors represent the density of points, with red denoting the highest density.

At a seasonal scale, there was a negative and non-significant correlation between the spatial distribution of the total number of flash droughts recorded by the SPI and the EDDI in all seasons, except in winter. Correlation between the EDDI and SPEI in winter was negative and non-significant, while it was positive and non-significant in spring, summer, and autumn. The highest correlation between the EDDI and SPEI was found in summer (Pearson's r = 0.33). The spatial distribution of the total number of flash droughts recorded by the SPI and SPEI showed a positive correlation in all seasons, reaching the maximum values in winter (Pearson's r = 0.58) and autumn (Pearson's r = 0.41), although it was only significant in winter.

Figure 5 depicts the spatial distribution of the magnitude of change and significance of trends in annual and seasonal frequency of flash droughts recorded by the SPI, EDDI, and SPEI over the period 1961–2018. At an annual scale, there was a significant decline in the number of flash droughts identified by the SPI across wide areas of central Spain, and only small areas of the Mediterranean coast and northern Spain showed significant increases in flash droughts. The EDDI also recorded a decrease in flash droughts in some areas of central Spain, but this decline was generally non-significant. In contrast, there was a significant increase in the frequency of flash drought events identified by the EDDI in some areas of southern and northwestern Spain. The SPEI also identified significant increases in flash droughts in southern Spain annually, as well as in some areas of the Mediterranean coastland. Similar to the SPI and EDDI, the SPEI also recorded a general decrease in flash droughts in central and northern Spain, although this was only statistically significant in a few areas.

At a seasonal scale, most of the study area showed non-significant trends in the occurrence of flash droughts recorded by the SPI, EDDI, and SPEI over the period 1961–2018. The three indices identified a general decline in flash drought events in central Spain in winter, although only the SPI and EDDI found statistically significant decreases in some of these areas. In spring, similar trends were found by the SPI, EDDI, and SPEI, with negative and non-significant trends in most of the study area. Furthermore, the three indices recorded increases in the frequency of flash droughts in the Mediterranean coastland and Balearic Islands in this season, but only the SPEI and the SPI showed positive and statistically significant trends. In summer, there were notable differences in flash drought trends recorded by the SPI, EDDI, and SPEI. The SPI identified negative, non-significant trends in most of the study area, while the EDDI and SPEI showed a general increase in flash droughts. The SPEI identified some significant increases in flash droughts in southern regions in summer, while the EDDI recorded statistically significant increases in a few small areas of western Spain. In autumn, the SPI returned a general decrease in flash droughts in most of the study area, although this was only significant in northeastern Spain. On the contrary, the EDDI and SPEI identified positive, non-significant trends in the occurrence of flash drought in most of the study area, with the exception of northern regions, where negative, non-significant trends were noted.

The temporal evolution of the average frequency of flash drought events identified by the SPI, EDDI, and SPEI on mainland Spain and the Balearic Islands over the period 1961–2018 showed a high variability at annual and seasonal scales (Figure 6). The annual series of flash droughts recorded by the SPI, EDDI, and SPEI exhibited statistically significant correlations among them, although the average frequency of flash droughts identified by the SPI was substantially higher until the year 2000. There was a significant decline in flash droughts recorded by the SPI annually, while the annual series obtained by the SPEI and EDDI showed non-significant trends.

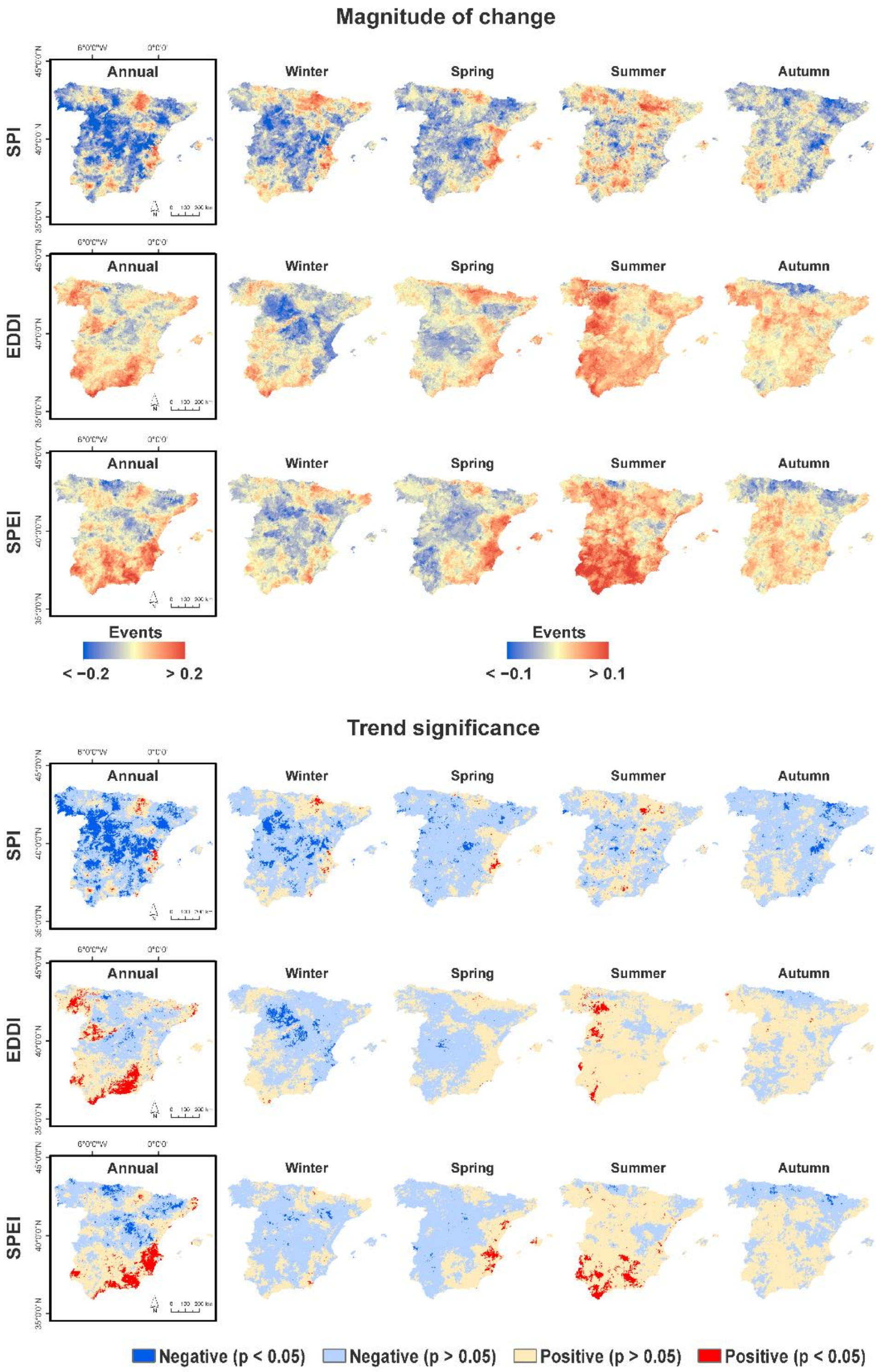

Figure 5. Spatial distribution of the annual and seasonal magnitudes of change per decade and the significance of trends of flash drought events identified by the SPI, EDDI, and SPEI over the period 1961–2018.

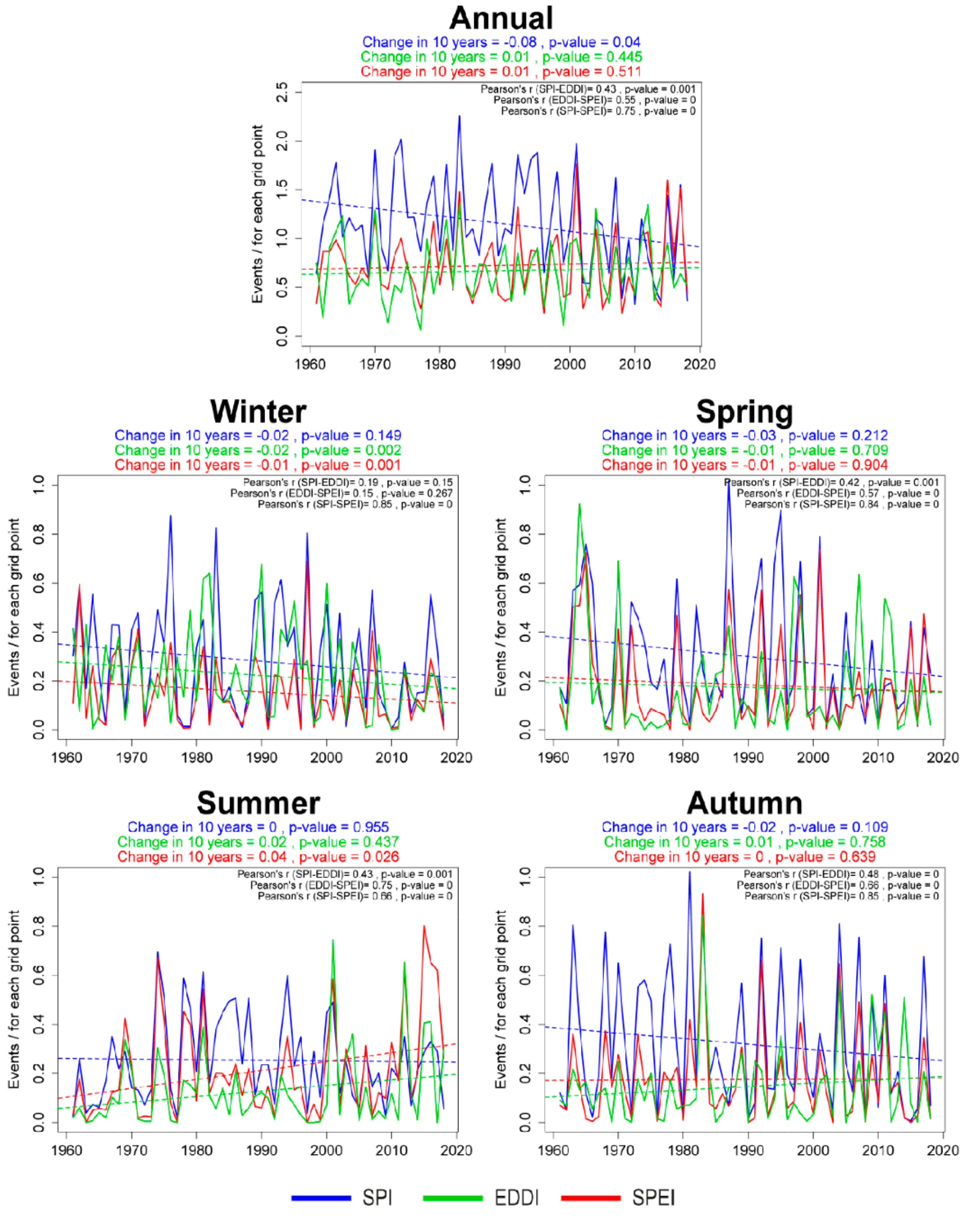

Figure 6. Temporal evolution of the average frequency of flash droughts identified by the SPI, SPEI, and EDDI on mainland Spain and the Balearic Islands over the period 1961–2018 at an annual and seasonal scale.

At a seasonal scale, the flash drought series recorded by the SPI, EDDI, and SPEI from 1961 to 2018 also exhibited high interannual variability. In winter, the flash drought series returned by the three indices showed negative trends, although this was only statistically significant for the EDDI and SPEI. The flash drought series recorded by the EDDI showed a low, non-significant correlation with the SPI and SPEI in this season, while there was a significant correlation between the SPI and SPEI (Pearson's r = 0.85). In spring, a negative, non-significant trend was noted in the series from the SPI, EDDI, and SPEI. The flash drought series also showed significant correlation in this season; the highest correlation was found between the SPI and SPEI (Pearson's r = 0.84). In summer, there was a positive trend in flash droughts recorded by the EDDI and SPEI, but it was only statistically significant for the SPEI. The flash droughts series obtained with the SPI showed a non-significant trend. Summer also returned a significant correlation between the flash drought series recorded by the SPI, EDDI, and SPEI, although in this case, higher correlation was noted between the EDDI and SPEI. In autumn, the series recorded by the SPI, EDDI, and SPEI showed non-significant trends. There was a significant correlation between the series obtained by the three indices, with the highest found between the SPI and SPEI (Pearson's r = 0.85).

The difference in the number of flash droughts recorded between the SPI and SPEI, and also between the SPI and EDDI, showed a significant decrease over the period 1961–2018 at an annual scale (Supplementary Materials Figure S1). This is a result of the decline in the number of flash droughts recorded by the SPI over the last two decades, which explains why the average frequency events/for each grid point reported by the three indices was very similar in recent years. On the other hand, the differences between the series of flash drought frequency recorded by the EDDI and SPEI annually did not show a significant trend over the study period.

At a seasonal scale, the differences among series obtained by the SPI, EDDI, and SPEI also exhibited some notable changes over the period 1961–2018 (Supplementary Materials Figure S1). For example, spring exhibited a significant decrease in the difference in events identified by the SPI and the SPEI. In summer, non-significant trends were found, although there was a decrease in the difference in events identified by the SPI and SPEI as a result of the increase in flash drought events recorded by the SPEI over the last few years. In autumn, the difference between the flash drought series identified by the SPI and EDDI, and also between the SPI and SPEI, showed a negative trend, although it was only statistically significant between the SPI and the SPEI. On the other hand, there was a non-significant trend in the difference in the number of flash drought events identified by the EDDI and SPEI in winter and autumn.

Figure 7 presents the spatial pattern of the correlation and associated significance between flash drought series recorded by the SPI, EDDI, and SPEI over the period 1961–2018 at annual and seasonal scales. In general, the annual flash drought series obtained by the SPI and EDDI showed a low, non-significant correlation in most of the study area. In contrast, there was a significant correlation between the series recorded by the EDDI and the SPEI at an annual scale, especially in areas of southern and northeastern Spain, where higher correlations were found. The annual flash drought series from the SPI and SPEI returned a high and significant correlation in most of the study area, although a stronger spatial correlation was found in northern regions (Pearson's r > 0.8).

At a seasonal scale, the spatial correlation between flash drought series recorded by the SPI, EDDI, and SPEI showed notable differences. In winter, a low, non-significant correlation was found between the series recorded by the SPI and EDDI. This was the same for the series obtained by the EDDI and SPEI. On the contrary, the SPI and SPEI showed a very high and significant correlation in most of the study area in winter, with the exception of some areas of the Mediterranean coastland and the Ebro Depression. In spring, the correlation between flash drought series from the SPI and EDDI was generally low and non-significant, although in some areas of northwestern, Spain it was high and significant. In contrast, there was a high and significant correlation between flash drought series recorded by the EDDI and SPEI, especially in the Mediterranean coastland. The series recorded by the SPI and SPEI also indicated a high and significant correlation in most of the study area in spring. In summer, the correlation between series obtained through the SPI and EDDI was generally low and non-significant. However, those series recorded by the EDDI and SPEI indicated a very high and significant correlation in this season, especially in southern regions and areas of northwest and north of Spain. The flash drought series recorded by the SPI and SPEI generally exhibited a high and significant correlation in central and northern regions in summer, while these were low and non-significant in southern Spain. In autumn, the correlation between the flash drought series recorded by the SPI and EDDI was low and non-significant, with the exception of some areas of central Spain. The series obtained from the EDDI and SPEI displayed a high correlation across large areas in the study, although these were low and non-significant in the northern regions, and also in some areas of southern and central Spain. On the other hand, the flash drought series identified by the SPI and SPEI showed a high and significant correlation in autumn, with the exception of few areas of southeastern Spain.

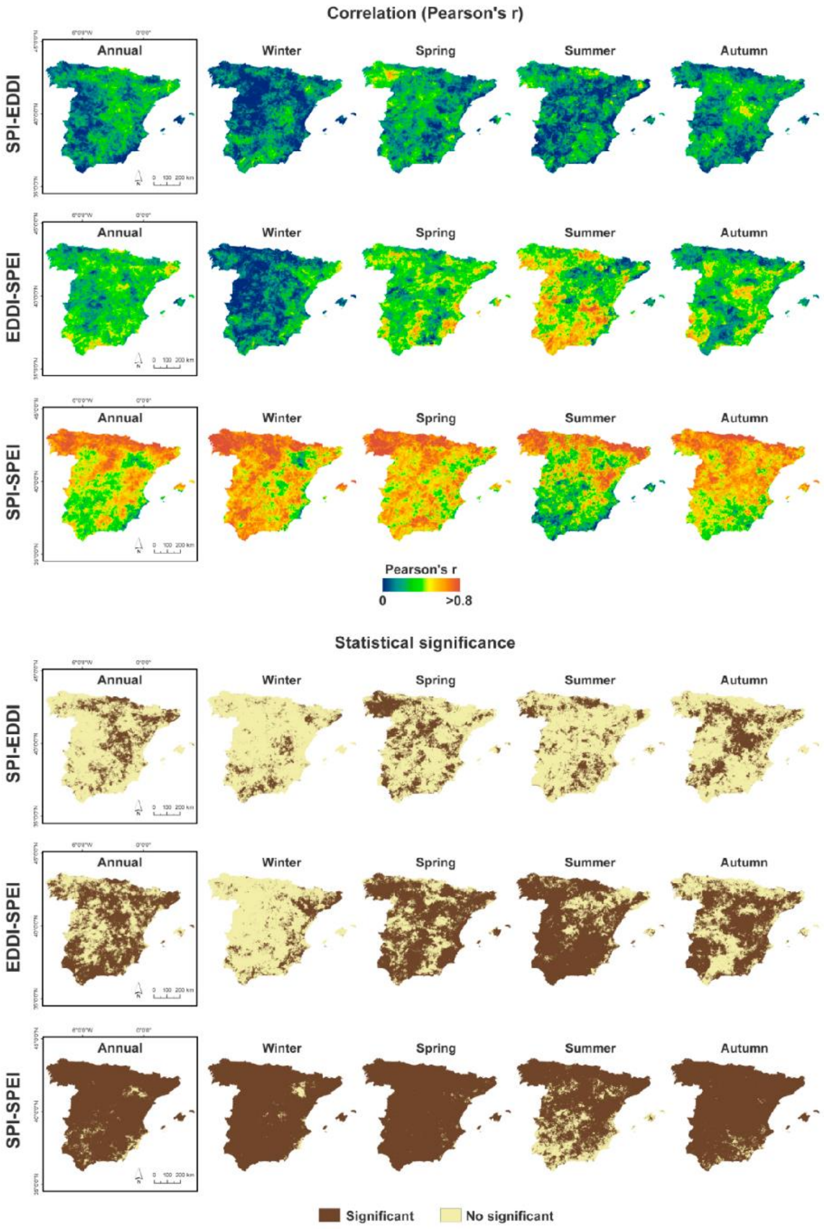

Figure 7. Spatial pattern of the correlation (Pearson's r) and associated significance between flash drought series identified by the SPI, EDDI, and SPEI over the period 1961–2018 at annual and seasonal scale.

3.3. Sensitivity of Flash Droughts to AED

To determine the differential sensitivity of the flash droughts recorded in different periods of the year, we analyzed the sensitivity of the 1-month SPEI to changes in precipitation and the AED. Table 1 shows the sensitivity SPEI values to AED on mainland Spain and the Balearic Islands from 1961 to 2018 at a 1-month time scale. As expected, the sensitivity of SPEI to AED showed noticeable seasonal contrasts. SPEI values display low sensitivity to AED in winter (December, January, and February), and the values were close to zero in December and January. Spring indicated a moderate sensitivity of the SPEI to AED with values increasing from March (14.35%) to May (34.60%). The highest was noted in June, July, and August, reaching maximum values in July of 46.68%. In autumn, there was a gradual decrease from September (23.11%) to November (2.23%).

Table 1. Sensitivity of the SPEI to atmospheric evaporative demand (AED) on mainland Spain and the Balearic Islands over the period 1961–2018 at a short time scale (1-month). The monthly series include the weekly data for the last week of each month in each year.

SPEI 1-month	AED Sensitivity (%)
January	1.37
February	6.54
March	14.35
April	22.13
May	34.60
June	37.98
July	46.68
August	37.06
September	23.11
October	12.50
November	2.23
December	0.50

The monthly spatial distribution of the sensitivity of SPEI to AED from 1961 to 2018 at a 1-month time scale also presents notable contrasts (Figure 8). There is a gradual increase in the sensitivity of the SPEI to AED from winter to summer, when the highest values were observed, and this increase was followed by a subsequent gradual decrease from summer to winter (Supplementary Materials Figure S2). Similarly, there is a large spatial difference in the sensitivity of the SPEI to AED values during the warm season. In winter, when the AED in Spain is low, the SPEI showed the lowest sensitivity to AED, with values below 10% across most of the study area, meaning that flash droughts during these months are mostly determined by precipitation anomalies. In spring, the role of the AED increases, mostly in May, with average sensitivity values of around 30%. Therefore, the precipitation deficits play a principal role in the occurrence of flash droughts, although the slight increase in sensitivity of the SPEI to AED was noted during the late spring in southern Spain. In summer, there is higher sensitivity of the SPEI to AED in large areas of the study domain, with a marked south–north gradient. The maximum sensitivity of the SPEI to the AED was noted in July, with values above 70% in southern Spain. In autumn, the sensitivity of the SPEI to AED is generally low over most of the study area, with average values below 10% except in September (≈18%).

Figure 9 illustrates the relationship between the total number of flash drought events recorded using the SPEI and its sensitivity to AED in each month of the year over the period 1961–2018 at a short time scale (1-month). As indicated, from October to January, the sensitivity of the SPEI to AED is very low, even in those areas where most of the flash droughts were identified, so the role of precipitation in the development of flash droughts in those months seems clearly dominant. From February to April, the sensitivity of the SPEI to AED is slightly greater, and the areas where it was higher also recorded a greater occurrence of flash droughts, which clearly suggests that AED is highly relevant in the development of certain flash drought events during this time. Nonetheless, as the average sensitivity values are generally below 20%, the dominant role of precipitation during spring seems clear, regardless of the number of flash droughts recorded. In contrast, from May to August, sensitivity to AED is notably stronger and wide areas with a high frequency of flash drought events also showed high sensitivity to AED, so the contribution of AED in the development of flash droughts recorded during these months is expected to be very important. However, there are also areas of northern Spain with low sensitivity that recorded a high incidence of flash drought events. This suggests large spatial differences in the drivers of flash droughts and also that the role of precipitation is crucial for the development of these in north Spain during summer.

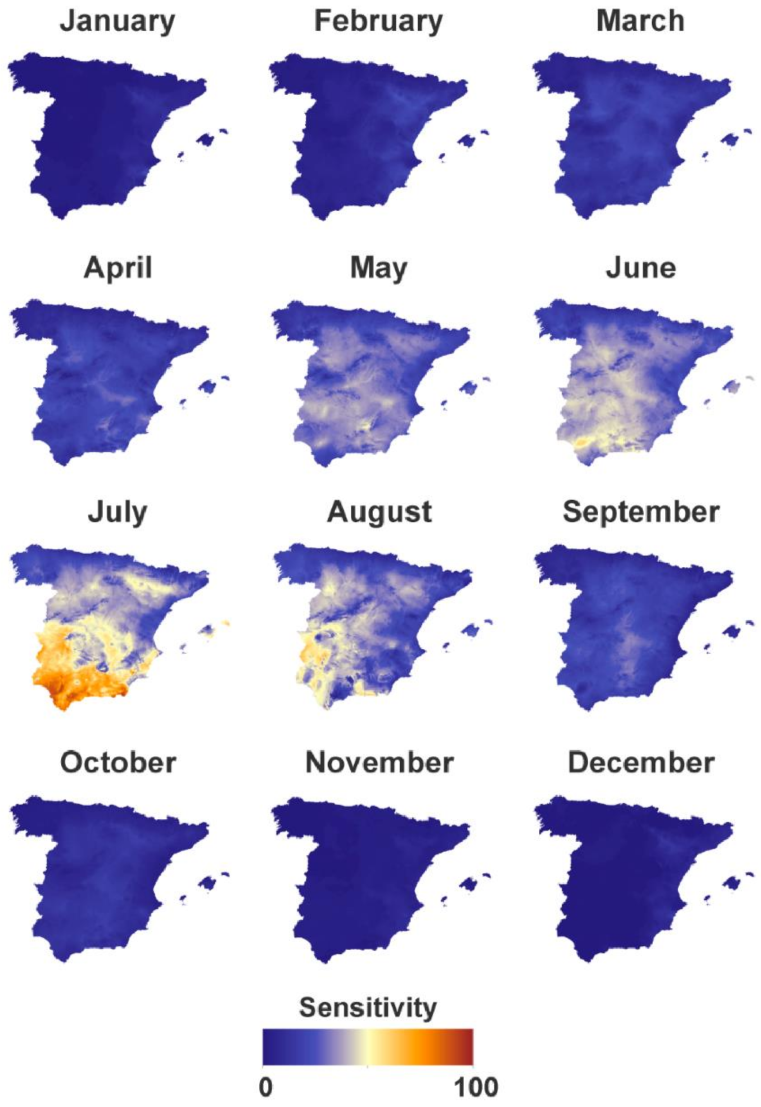

Figure 8. Monthly spatial distribution of the sensitivity (%) of the SPEI to AED on mainland Spain and the Balearic Islands over the period 1961–2018 at a short time scale (1-month). The monthly series include the weekly data for the last week of each month in each year.

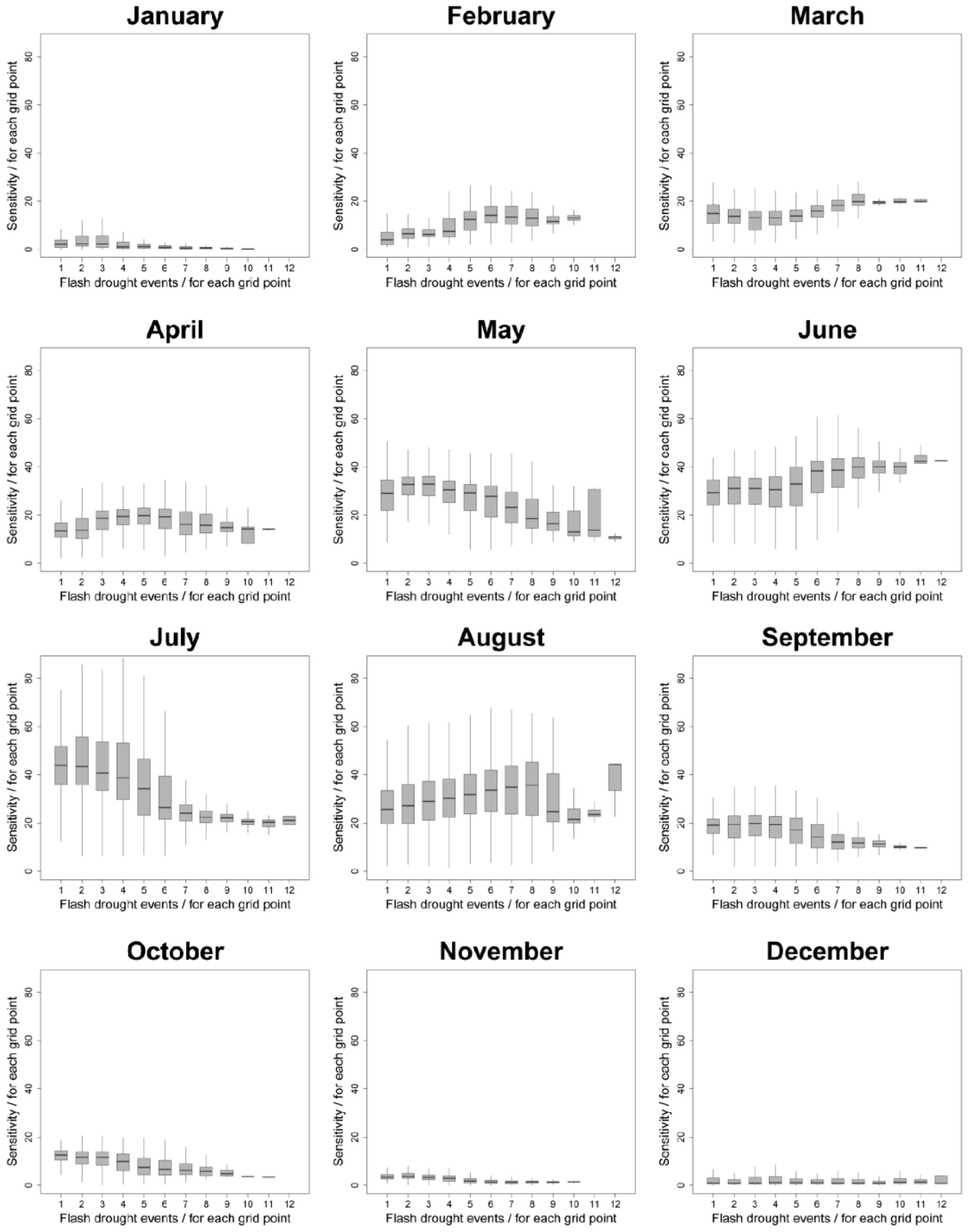

Figure 9. Monthly frequency of flash drought events/for each grid point obtained from the SPEI and its sensitivity (%) to AED on mainland Spain and the Balearic Islands in each month over the period 1961–2018 at a short time scale (1-month). Frequencies of flash drought events with a residual number of cases are not represented.

4. Discussion

In this study, we identified flash droughts based on different drought indices including the SPI, the EDDI, and the SPEI. This enabled the role of precipitation and AED in the development of flash droughts to be established, in addition to how this role determines the spatial and temporal patterns of flash droughts in Spain. The main advantage of these standardized indexes in comparison to other metrics is that they are comparable in time and space, making it possible to apply the same methodology and to obtain comparable results based on indices from different variables. Furthermore, these indices also enable flash drought analyses in the long-term, since they are based on widely available climate information.

Numerous studies proved the usefulness of widely used, standardized drought indices such as the SPI or SPEI in identifying different types of impacts [57–60]. Previous studies also proved the robustness of standardized drought indices, such as the SPI, EDDI, and SPEI in identifying and characterizing flash droughts over different regions of the world [18,19,51,61]. Although it is not easy to determine which metric is more suitable for the analysis of flash droughts, we think that the implementation of different indices for flash drought analysis can be useful for a more comprehensive understanding.

The spatial and temporal behavior of flash droughts in Spain is highly complex and variable [18]. The results obtained in this research suggested that flash droughts in Spain can develop from both precipitation deficits and anomalous increases in AED, although there is a differentiated seasonal and spatial behavior. This is reflected in the notable differences found between the spatial and temporal patterns of flash droughts identified by the SPI, EDDI, and SPEI. Thus, even when the drought indices showed high spatial and temporal correlation in most months of the year, the spatial and temporal frequency of flash drought events was dependent on the index used, since although there is consistency among the three indices, there are large seasonal differences. For example, in winter, in which AED is low and drought conditions are closely related to precipitation deficits, correlation between the EDDI and SPI is low. Therefore, it is not recommended to use the EDDI to assess drought severity and, particularly, to identify flash droughts during winter. In autumn and spring, when the AED is slightly higher but precipitation is also the main driver controlling variations in index values, correlation of the EDDI with the SPI and SPEI was generally high, especially with the SPEI. This suggests an increase in the influence of the AED on drought severity. In summer, there is higher consistency between the EDDI and SPEI, with correlations similar to those found between the SPI and SPEI. This means that changes in AED can be as relevant or even more so than precipitation deficits in the response of indices during the summer, particularly in the driest areas. This indicates that in summer, the use of indices based exclusively on precipitation is not suitable to assess drought severity, and they are particularly unsuitable to identify flash droughts. The SPI showed a high spatial and temporal coherence with the SPEI in almost every month of the year, reflecting the fact that the SPEI responds mainly to variations in precipitation, except in the dry summer period. These findings prove the sensitivity of the SPEI to changes in AED during dry periods, and they are very consistent with the patterns in the response of the SPEI to AED shown by Tomas-Burguera et al. [9] at a global scale.

In general, there are noticeable spatial differences in the occurrence of flash droughts identified for each index. The spatial patterns recorded by the SPI and SPEI were strongly coherent in winter, particularly in northern Spain. This suggests that during wet periods, in which the role of precipitation deficits in drought development is not in doubt [17], precipitation is the main driver of flash droughts. However, the role of the atmospheric evaporative demand (AED) on droughts is more complex and exhibits large spatial and seasonal differences [17,62], making it difficult to determine its role in the development of flash droughts [63]. Several studies showed that flash droughts can be driven by anomalous increases in AED associated with heat waves and land–atmosphere feedbacks that cause or reinforce the rapid depletion of soil moisture [12,14–16]. Thus, the occurrence of flash drought is usually associated with strong anomalies of AED [6,19]. Here, we have shown that AED can play an important role in the warm season. In summer, when precipitation is generally very low in Spain [40,64], there were notable differences in the spatial patterns of flash droughts found by the SPI and SPEI. Compared to the SPI, the SPEI showed a greater spatial consistency with the EDDI, indicating that during the warm season, the AED is a key variable in explaining the occurrence of flash droughts. The physical processes explaining the importance of this variable can be diverse. Some studies showed that in periods of very low soil moisture and strong land–atmosphere coupling, AED would be driven by the limited latent heat fluxes from a dry soil, which could favor some self-intensification of drought conditions [10,62]. However, in Spain, it is more probably due to the dominant role of warm, dry air advections originating in the Sahara, which are very frequent in summer [65].

In spring and autumn, opposite spatial patterns were found for the flash droughts identified by the SPI and EDDI. This could be related to a variable contribution of precipitation and AED in the development of the flash droughts, which seems reasonable considering the wide spatial and temporal variability of precipitation [32–35] and AED [36–38] during these seasons. Thus, it is possible that AED plays an important role in the occurrence of flash droughts in the Mediterranean coastland and northeastern Spain where the EDDI recorded a high incidence in spring and, to a lesser extent, in autumn. However, it would be secondary to precipitation in most of Spain. This is also reflected in the spatial patterns of the number of flash droughts identified by the SPEI, since there is spatial consistency with the SPI in most of the study area in spring and especially in autumn, but the SPEI also reported a high frequency of flash droughts in the Mediterranean coastland in spring, which is a pattern also found in the EDDI. Although in some cases, the different indices showed similar spatial patterns at an annual and seasonal scale, the shared variance was not generally high. This seems to confirm that the flash droughts in Spain can be triggered by different drivers, as well as the role of precipitation and AED being seasonally and spatially variable.

Only the SPI reported a negative and significant trend in the frequency of flash droughts, whereas the EDDI and SPEI recorded a non-significant trend for these events from 1961 to 2018. However, the EDDI and SPEI reported significant increases in the frequency of flash droughts in some areas of southern and southeastern Spain. Since the SPI reported non-significant trends in summer over most of the study area, these increases must necessarily be related to an increase in the contribution of the AED to the development of flash droughts in these areas. This hypothesis seems coherent with various studies that recorded increased AED in Spain during the summer [36,38]. Some areas of the Mediterranean coastland also showed increases in flash droughts in spring, but considering that only the SPI and SPEI reported a statistically significant trend, these increases could relate to variations in precipitation.

In addition to the markedly seasonal character indicating the role of AED in the development of flash droughts, we also found a strong spatial component determining the role of AED in these events in Spain. The AED shows strong spatial differences in Spain, with a clear north–south gradient between the humid regions of the north and the drier regions of southern and central Spain [36,39]. Several studies suggested that the contribution of AED is much higher in dry regions than in humid ones, since its role is only important during periods of low precipitation or limited soil moisture [9,17]. This could explain the contrasts found between the drier regions of central and southern Spain and the humid ones in northern Spain, which, even in summer, exhibited very low sensitivity to AED. Thus, during summer, when the AED in Spain is high and precipitation is generally very low [40], strong AED anomalies play a key role in the development of flash droughts, especially in dry areas such as the Ebro Depression and southern Spain. Although the increased in AED was probably the main driver of changes in flash drought frequency in summer, we must stress that we have demonstrated that precipitation is still the main driver in the temporal variability of droughts in Spain, and it is also the main contributing factor in triggering flash droughts. Precipitation deficits are the major climatic variable triggering drought conditions [66,67], and it seems reasonable to expect that precipitation also has an essential role in the development of flash droughts. We have demonstrated this pattern in winter as well as in spring and autumn. However, it is possible that the AED has a relevant role in the development of certain flash drought events in the late spring.

The results of this research cannot be easily extrapolated. Spain is characterized by high spatial and seasonal variability in precipitation and AED, so it was expected that their role in the development of flash droughts would be strongly variable. However, the role of precipitation and AED anomalies may exhibit significant changes in other regions of the world, and flash droughts could develop under diverse conditions. For example, Hobbins et al. [52] and Pendergrass et al. [19] pointed out that the occurrence of flash droughts is typically related to a change from energy-limited to water-limited conditions. This can be true in some cases, but it cannot be considered as a situation characteristic for most flash drought events worldwide. At a global scale, previous studies found similar patterns in the contribution of AED during periods characterized by low levels of precipitation in sub-humid regions [9]. Specifically, certain studies also indicated that precipitation is the main variable explaining the occurrence of flash droughts in the United States [63]. However, considering the complexity of the role played by AED in drought development, and its spatial and seasonal variability [17], further research into these issues is needed.

5. Conclusions

This study focused on the analysis of the role of precipitation and atmospheric evaporative demand (AED) in the occurrence of flash droughts in Spain. For this purpose, we analyzed the spatial and temporal patterns of flash drought identified through different drought indices based on precipitation (SPI), AED (EDDI), and both (SPEI). We also examined the sensitivity of the SPEI to AED to clarify the possible contribution of precipitation deficits and anomalous increases in AED to the development of flash droughts. The main conclusions from this study are as follows:

- Standardized drought indices such as SPI, EDDI, and SPEI are robust metrics for the identification of flash droughts. However, the use of indices based exclusively on precipitation or AED may have some limitations under certain circumstances.
- The spatial and temporal patterns of flash droughts can be highly variable, depending on the metrics used in analysis.
- Flash droughts in Spain can be triggered by both precipitation deficits and increases in AED, but their contribution to the development of flash droughts is highly variable spatially and seasonally.
- Precipitation is the main variable driving flash droughts in Spain, although AED anomalies can play a crucial role in the development of some flash drought events, especially in arid areas during the warm season.
- The sensitivity of the SPEI to AED during dry periods enables the drought conditions triggered by anomalous decreases of precipitation and/or increases of the AED to be captured, making it possible to identify and characterize flash droughts over very different climatic conditions seasonally and spatially.

Supplementary Materials: The following are available online at https://www.mdpi.com/2073-4433/12/2/165/s1, Figure S1: Temporal evolution of the annual and seasonal differences (events/for each grid point) between the flash drought series recorded by the SPI, EDDI and SPEI on mainland Spain and the Balearic Islands over the period 1961–2018, Figure S2: Monthly frequency of the sensitivity (%) of the SPEI to AED on mainland Spain and the Balearic Islands over the period 1961–2018 at a short time scale (1-month). The monthly series include the weekly data for the last week of each month in each year.

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Chapter 4

The rise of atmospheric evaporative demand is increasing flash droughts in Spain during the warm season

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The Rise of Atmospheric Evaporative Demand Is Increasing Flash Droughts in Spain During the Warm Season

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Key Points:

- The role of the atmospheric evaporative demand on the development of flash droughts exhibits a notable contrast between regions and seasons
- The contribution of the atmospheric evaporative demand on the development of flash droughts has increased notably in Spain over last years
- Atmospheric evaporative demand has become a decisive driver in explaining the occurrence of the latest flash droughts in Spain

Supporting Information:

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

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Abstract Flash droughts are characterized by rapid development and intensification, generating a new risk for drought impacts on natural and socio-economic systems. In the current climate change scenario, the meteorological drivers involved in triggering flash droughts are uncertain. We analyzed the role of meteorological drivers underlying the development of flash droughts in Spain over the last six decades, evidencing that the effect of atmospheric evaporative demand (AED) on flash drought is mainly restricted to water-limited regions and the warm season. However, the contribution of the AED has increased notably in recent years and particularly in summer (∼3.5% per decade), thus becoming a decisive driver in explaining the occurrence of the latest flash droughts in some regions of Spain. Our findings have strong implications for proper understanding of the recent spatiotemporal behavior of flash droughts in Spain and illustrate how this type of event can be related to global warming processes.

Plain Language Summary Flash drought is a complex phenomenon characterized by rapid development and intensification, which increases potential impacts on natural and socio-economic systems. Nowadays, little is known about the role played by the meteorological drivers involved in triggering this type of events. In this study, we analyze the influence of these drivers on the development and intensification of flash droughts in Spain over the last six decades. We show that atmospheric evaporative demand (AED) plays a minor role compared to precipitation deficits. However, the contribution of the AED to flash drought development has increased notably in recent years. Our findings highlight the importance of AED role in explaining the occurrence of the latest flash droughts in Spain and how this type of event can be more and more related to global warming.

1. Introduction

Drought is commonly considered as a slow, long-term phenomenon (Wilhite, 2000; Wilhite et al., 2007). However, a new term known as "flash drought" (Svoboda et al., 2002) has become popular to distinguish droughts characterized by a rapid development and intensification that trigger a drastic change in humidity conditions in the short-term (few weeks), reducing the time available for hazard management and thus increasing the potential impacts of water deficits on crops and ecological systems. Recently, numerous flash drought events with heavy economic and environmental impacts have been reported in different regions, e.g., United States (He et al., 2019; Otkin et al., 2016), China (Yuan et al., 2015), Australia (Nguyen et al., 2019, 2021), southern Africa (Yuan et al., 2018), and Russia (Christian et al., 2020). Therefore, flash drought has become a topic of special interest to the scientific community (Lisonbee et al., 2021), but little has been done to understand the drivers under a changing climate.

Usually, these events are associated to severe precipitation deficits and/or anomalous increases in atmospheric evaporative demand (AED), but little is known about the role that each plays in triggering flash drought conditions. Despite the fact that flash drought variability shows a primary response to precipitation deficits (Hoffmann et al., 2021; Koster et al., 2019; Noguera et al., 2021; Parker et al., 2021), several studies demonstrated that an anomalous increase in AED can be crucial in explaining the rapid development and intensification of some flash drought events, causing rapid depletion of soil moisture and more water stress in plants (Anderson et al., 2016; McEvoy et al., 2016; Mo & Lettenmaier, 2015; Otkin et al., 2013; Pendergrass et al., 2020). Whereas the role of precipitation seems obvious and essential, the role played by AED in triggering or reinforcing drought episodes is much more complex, since AED affects drought severity in different ways, including effects on plant transpiration and soil moisture, alterations in plant hydraulics, photosynthesis and carbon uptake (Breshears et al., 2013;

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Grossiord et al., 2020), and land-atmosphere feedback that may reinforce drought severity (Miralles et al., 2019). Likewise, the physical dynamics of the AED that affect drought are strongly influenced by large-scale climate drivers such as atmospheric circulation, and also for other important thermodynamics drivers associated with the differential warming between oceanic and continental regions (Sherwood & Fu, 2014).

Under global warming conditions, several studies suggest a rise in the frequency and severity of droughts (Dai, 2011, 2012; Dai et al., 2018; Zhao et al., 2017) mainly driven by the increase in AED worldwide (Scheff & Frierson, 2014; Vicente-Serrano et al., 2020; Wang et al., 2012), which results in a major impact on the ecology and agriculture (Allen et al., 2010, 2015; Asseng et al., 2014; Lobell et al., 2011; McDowell, 2011). Related to this process, some studies reported an increase in flash drought frequency in regions such as China (Wang & Yuan, 2018; Wang et al., 2016; Yuan et al., 2019), southern Africa (Yuan et al., 2018), Brazil and the Sahel (Christian et al., 2021) in response to a rise in temperature. In contrast, others studies have suggested mixed trends in flash drought frequency in Spain (Noguera et al., 2020, 2021) or even decrease in the United States (Mo & Lettenmaier, 2015). Given that the contribution of AED to drought exhibits important contrast between regions and seasons worldwide (Tomas-Burguera et al., 2020b), it is expected that its influence on flash drought development and intensification will also display significant spatial and temporal variability.

In Spain, flash drought is a frequent phenomenon, which is characterized by a great spatial and seasonal variability as a result of the climatic complexity of the Iberian Peninsula (Noguera et al., 2020). Likewise, the meteorological drivers involved in the triggering of flash drought in Spain can be quite diverse, showing important variations between seasons and regions with large climatic contrasts (Noguera et al., 2021). In this way, the particular case of Spain can be useful to picture the role of meteorological drivers underlying the development of a wide diversity of flash drought events over different climatic conditions as well as for a better-understood of the implications of the general increase of AED in flash droughts. Also, recent increase in vapor pressure deficit (VPD) worldwide has important implications in agricultural and environmental drought impacts (Eamus et al., 2013; Grossiord et al., 2020; Will et al., 2013), which could also translate to flash droughts. In Spain, some studies reported an increase in the severity of drought events (Vicente-Serrano, Lopez-Moreno, et al., 2014) associated with the rise in AED noted over the last few decades (Tomas-Burguera et al., 2020a). Therefore, in a context in which the role of AED on drought severity is increasing, there is a need to unravel the possible effects on flash droughts. Here, we evaluate the role of AED in the development and intensification of flash droughts in Spain and its recent evolution as a representative example of the possible implications of AED increase in flash droughts frequency in a global context.

2. Data and Methods

2.1. Climate Data

This study used a high spatial resolution (1.21 km^2) gridded climate data set for mainland Spain and the Balearic Islands over the period 1961–2018. This data set comprised weekly data on precipitation, maximum and minimum air temperature, relative humidity, sunshine duration (as a surrogate of solar radiation), and wind speed. The gridded data set was created using all daily observational information from the National Spanish Meteorological Service (AEMET). The climate series were subjected to a thorough quality control and homogenization process (Tomás-Burguera et al., 2016). Details of the data set development and validation have been described in Vicente-Serrano et al. (2017). We used the FAO-56 Penman-Monteith equation (Allen et al., 1998) to calculate the reference evapotranspiration (ETo), which is a spatially and temporally comparable metric for the AED.

2.1.1. Flash Drought Identification

Flash droughts events were identified using the Standardized Precipitation Evapotranspiration Index (SPEI; Vicente-Serrano et al., 2010), which is obtained from the difference between precipitation and AED (i.e., climatic water balance). SPEI can be computed at different time scales over long-term records to obtain SPEI values comparable in time and space (Beguería et al., 2014). The SPEI is widely used to analyze the response of hydrological (Lorenzo-Lacruz et al., 2010; Peña-Gallardo et al., 2019b; Vicente-Serrano & López-Moreno, 2005), agricultural (Peña-Gallardo et al., 2018b, 2019a; Potop et al., 2012), and environmental systems (Peña-Gallardo et al., 2018a; Vicente-Serrano et al., 2013; Vicente-Serrano, Camarero, et al., 2014; Zhang et al., 2017). Likewise, SPEI also proved to be a reliable and robust metric to identify and quantify flash drought (Hunt et al., 2014; Noguera et al., 2020, 2021).

Following the methodology proposed by Noguera et al. (2020), we used the SPEI at a short time scale (1 month) and high-frequency data (weekly) to identify sharp changes in humidity conditions associated with the onset of flash drought events. This method focuses on the rapid development characteristic of flash drought (Otkin, Svoboda, et al., 2018; Svoboda et al., 2002), which results in a sudden and severe decline in SPEI. Thus, flash drought is defined as: (a) a minimum length of 4 weeks in the development phase; (b) a ΔSPEI equal to or <-2 z-units; and (c) a final SPEI value equal to or <-1.28 z-units (corresponding to return periods of 10 years). Further details of the methodology to identify flash drought events, as well as the spatial and seasonal characteristics and trends of flash droughts in mainland Spain and the Balearic Islands over the period 1961–2018, can be consulted in Noguera et al. (2020).

2.1.2. Calculation of the Contribution of AED to the Development of Flash Droughts

The relative contribution of a given variable (i.e., precipitation or AED) to SPEI was estimated by calculating the "SPEI PRE," 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 each week of the year over the period 1961–2018. This method was used in several studies to calculate the contribution of different variables in triggering drought periods (Cook et al., 2014; Scheff & Frierson, 2014; Williams et al., 2015; Zhao & Dai, 2015).

To determine the relative contribution of precipitation and AED to the development of flash droughts, we judged that the difference between zero and SPEI PRE was due to precipitation variability, while the difference between SPEI PRE and SPEI was due to AED contribution. These differences were expressed as a percentage, and for those weekly data in which SPEI PRE was equal to or less than SPEI, the AED contribution was 0%. Since this study focuses on the development of flash droughts, we looked at the weekly data corresponding to the onset of each of flash drought events identified as it captures the cumulative anomaly in P-AED over the last 4 weeks (i.e., during the development phase). Thus, we specifically examined the spatial and temporal patterns of the AED contribution to the development of flash droughts at seasonal scale (winter DJF, spring MAM, summer JJA, autumn SON) over the period 1961–2018.

2.2. Trend Analysis

We examined the magnitude of change in AED contribution to flash drought development at seasonal scale using a linear regression analysis between the series of time (independent variable) and the series of AED contribution (dependent variable). To assess the significance of the trend, 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 & Ramachandra Rao, 1998; Yue & Wang, 2004).

3. Results and Discussion

In last few decades, numerous flash drought events linked to different drivers were reported in Spain (Figure 1). For example, the flash drought of February 1962 is associated with severe precipitation deficits affecting most of Spain. The effect of AED during this episode was very low (Figure 1a), and the substantial precipitation deficit from late January was the cause of the flash drought conditions in large areas of Spain, with the exception of some regions of the north (Figures 1b and 1c). In the spring of 1992, a new flash drought event was reported as a result of strong precipitation deficits recorded in April over wide areas of western Spain. The contribution of AED had a slight effect, reaching average values around 8% (Figures 1a and 1c), so the lack of precipitation was the key driver triggering this flash drought event. We also identified flash droughts in which the role of the AED is very relevant or even dominant (Figure 1a). In 2012, the anomalous increase in AED during May and June together with a lack of precipitation (AEMET, 2012a, 2012b) triggered a severe flash drought characterized by spreading extensively. Initially, a flash drought started in the northeastern regions due to a strong precipitation deficit in late spring, and then spread rapidly across most of Spain driven by the increase in AED (Figures 1b and 1c), which resulted in large contrasts between the observed AED contribution values (Figure 1a). A more illustrative example of how AED can play a dominant role is the flash drought of summer 2015. This event was the result of a rapid and anomalous increase in AED associated with an extreme heat wave affecting most of Spain, causing a flash drought conditions in large northern, eastern, and southern regions (Figures 1b and 1c). Thus, even though some areas of Spain recorded some rainfall in June (AEMET, 2015b), and precipitation remained at normal levels in

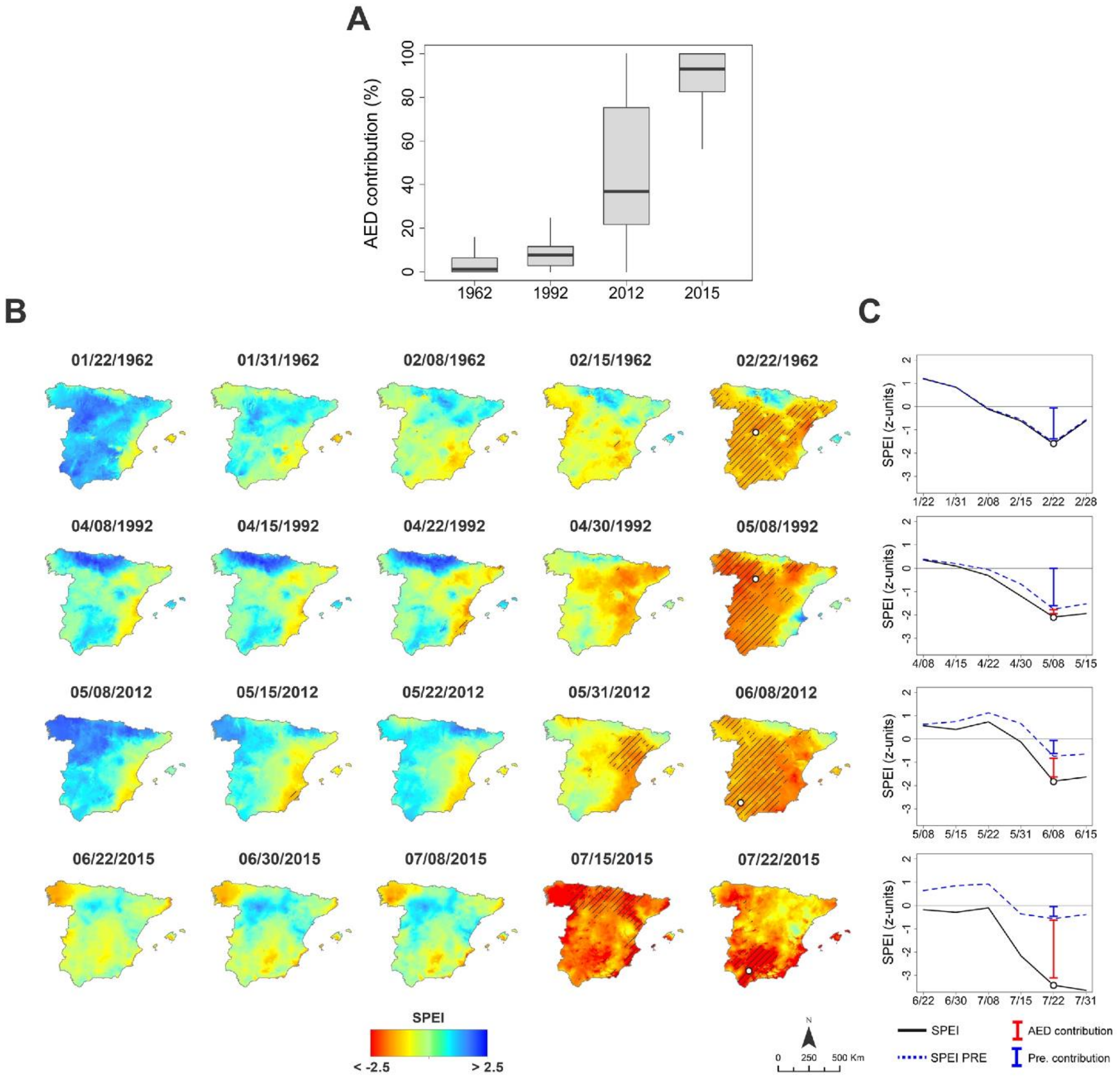

Figure 1. (a) Atmospheric evaporative demand (AED) contribution to flash drought events of 1962, 1992, 2012, and 2015, and (b) spatiotemporal evolution of SPEI at a 1-month time scale during these episodes, overlay areas represent the spatial extent of the flash drought; (c) examples of temporal evolution of Standardized Precipitation Evapotranspiration Index (SPEI) and SPEI PRE values at a random point in which flash drought conditions was identified. The white dot with black halo on the map shows the location of the example points shown on the graph.

July (AEMET, 2015a), flash drought conditions emerged strongly driven by increases in AED, which was around 90% responsible for the onset of the flash drought (Figure 1a). These examples clearly illustrate the great variability found in the contribution of precipitation deficits and AED to the rapid development and intensification of flash drought events in Spain.

However, the average contribution of AED to the development and intensification of flash droughts in Spain is generally small and characterized by strong seasonal variability (Figure 2a). The contribution of AED in the development of flash droughts during winter is slight, normally <5%, so flash droughts in this season are basically caused by severe precipitation deficits for short periods. The contribution of AED increases in spring, but

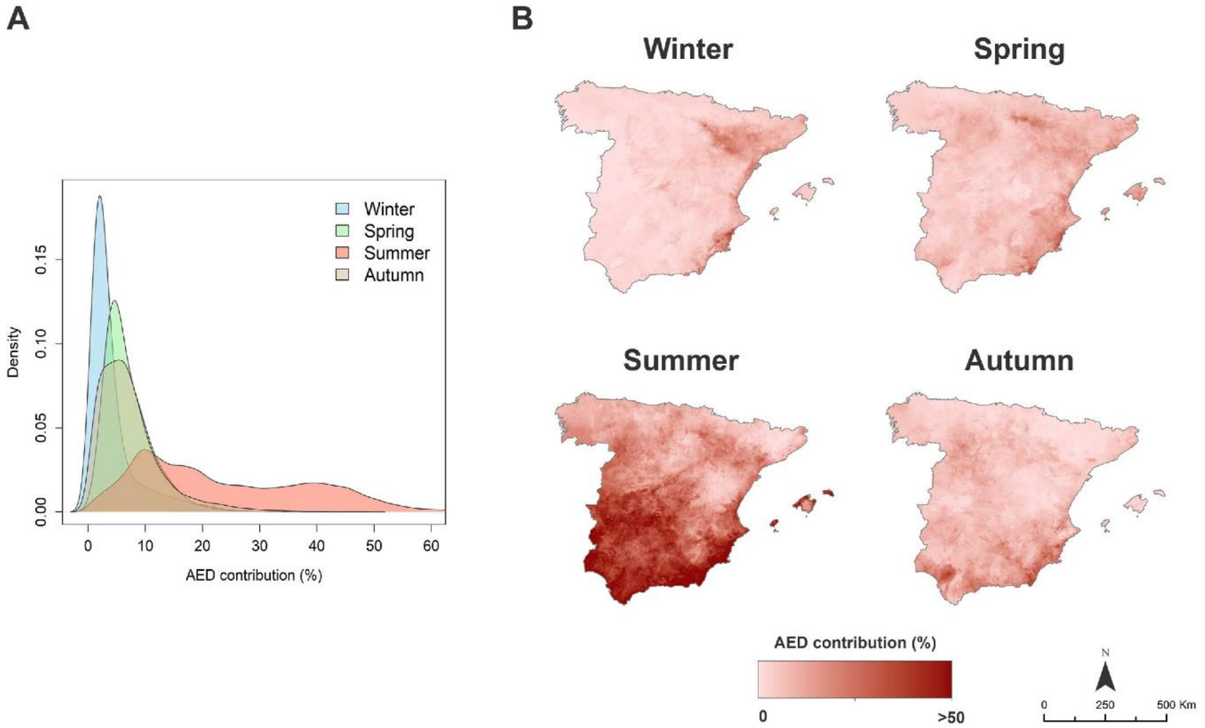

Figure 2. Seasonal (a) density of the average atmospheric evaporative demand (AED) contribution to the development of flash droughts and (b) its spatial distribution in mainland Spain and the Balearic Islands over the period 1961–2018.

precipitation still shows a clear dominant role in the development of flash droughts. In summer, precipitation deficits are still the main driver of flash droughts in the region, although the maximum contribution of AED is reached during this season, with an average value >20%, but in some regions, it exceeds 40%. Lack of rainfall is normal over most of Spain in summer (Martin-Vide & Olcina-Cantos, 2001), so the anomalous increase in AED associated with extreme heat waves may be a determinant in triggering a flash drought. In autumn, with the decline of the AED, precipitation deficits again have a dominant role in the development of flash droughts.

In addition to these seasonal differences, the contribution of AED to flash drought development also exhibits geographic differences (Figure 2b). There is a clear contrast in the average AED contribution reported in the humid northern regions and the drier regions such as the Mediterranean coast, northeast or southern Spain. The average contribution of AED to flash drought development is close to 0% in most of Spain during winter, with the exception of some areas of the Mediterranean coast and northeast Spain. Similarly, in spring, the highest AED contribution is recorded in the Mediterranean coast, northeast Spain and also in the Balearic Islands. AED makes the highest contribution to flash droughts only in summer, with average values of over 30% in large areas of northeast, central, and southern Spain and the Balearic Islands. In autumn, the influence of AED is low, although in some areas of southern Spain it still may contribute heavily to the development of flash droughts.

The spatiotemporal patterns of AED contribution to drought development show a close spatial relationship with seasonal average precipitation (Figure S1 in Supporting Information S1). Thus, the contribution of AED to flash droughts is generally limited to the Mediterranean coast and southern Spain during the warm season, when precipitation is close to zero, while it is very low in humid regions of the north and also in cold periods. The seasonal and spatial patterns in the role of AED in triggering flash droughts are consistent with previous studies suggesting that AED is mostly relevant in periods of low precipitation and in dry areas (Tomas-Burguera et al., 2020b; Vicente-Serrano et al., 2020). Nevertheless, under the current climate change scenario characterized by an increase in AED (Scheff & Frierson, 2014; Wang et al., 2012), it is reasonable to consider that its influence may increase (Vicente-Serrano et al., 2020).

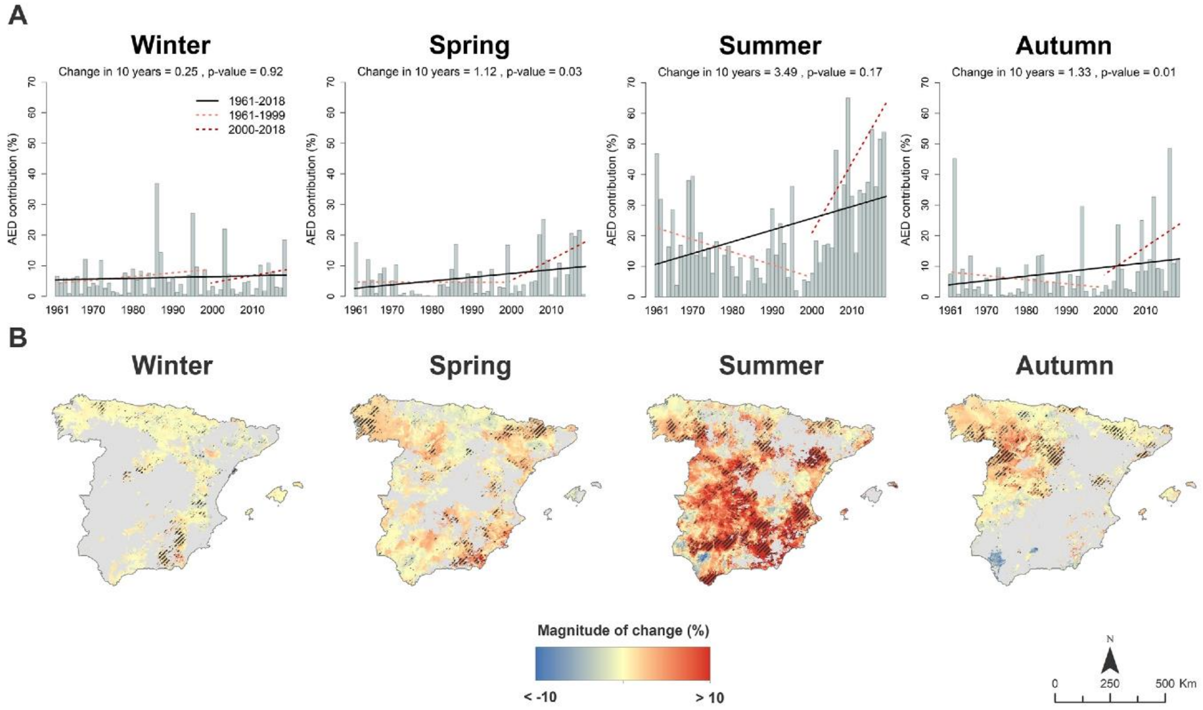

Figure 3. (a) Temporal evolution and (b) spatial distribution of seasonal magnitude of change (per decade) and significance in atmospheric evaporative demand (AED) contribution to flash droughts in mainland Spain and the Balearic Islands over the period 1961–2018. The dotted areas correspond to significant trends, while the gray areas correspond to pixels in which less than 10 events were recorded.

AED has increased in Spain over the last few decades (Tomas-Burguera et al., 2020a; Vicente-Serrano, Lopez-Moreno, et al., 2014) and we found that this evolution has also caused an increase in its contribution to the development and intensification of flash droughts (Figure 3a). All seasons, except winter, show a noticeable increase in the contribution of AED to flash droughts. This increase is especially remarkable in summer (~3.5% per decade), but only spring and autumn report a statistically significant trend. The trends also exhibit large spatial differences (Figure 3b). In winter, there are no relevant changes in the contribution of AED to flash droughts and only some areas of Mediterranean coast showed a statistically significant increase. The contribution of the AED to flash drought development in spring reported significant trends in some areas of Mediterranean coast, northeastern and northwestern Spain, where it has increased by ~4% per decade. The most important changes in AED contribution are noted in summer, with significant increases across Mediterranean coast, central and southern Spain with magnitudes of change per decade exceeding 10%. Meanwhile autumn reported significant increases in AED contribution in some areas of northwestern Spain, reaching magnitudes of change per decade around 4%.

In addition to the overall rise in the average AED contribution, there was an increase in the percent contribution of AED among the total amount of flash drought events (Figure 4). Thus, the percentage of flash droughts in which the AED contribution is high has risen in most cases, while the percentage of flash droughts in which it is irrelevant (i.e., 0%) exhibit a significant decrease in spring, summer, and autumn over the period 1961–2018 (Table S1 in Supporting Information S1). The increase in the percentage of events in which the AED is relevant to the development of flash drought conditions is particularly remarkable in summer, but it is also evident in spring and autumn.

The trends observed in the contribution of AED to flash drought are basically responding to the observed increase in AED (Tomas-Burguera et al., 2020a), but lower precipitation during summer (Domínguez-Castro et al., 2019) could also play a role since, in dry areas, a further decrease in precipitation would reactivate the sensitivity of the SPEI to variations in AED (Tomas-Burguera et al., 2020b). Previous research also evidenced that temperature plays a major role in explaining the recent increases in AED in Spain (Tomas-Burguera et al., 2020b;

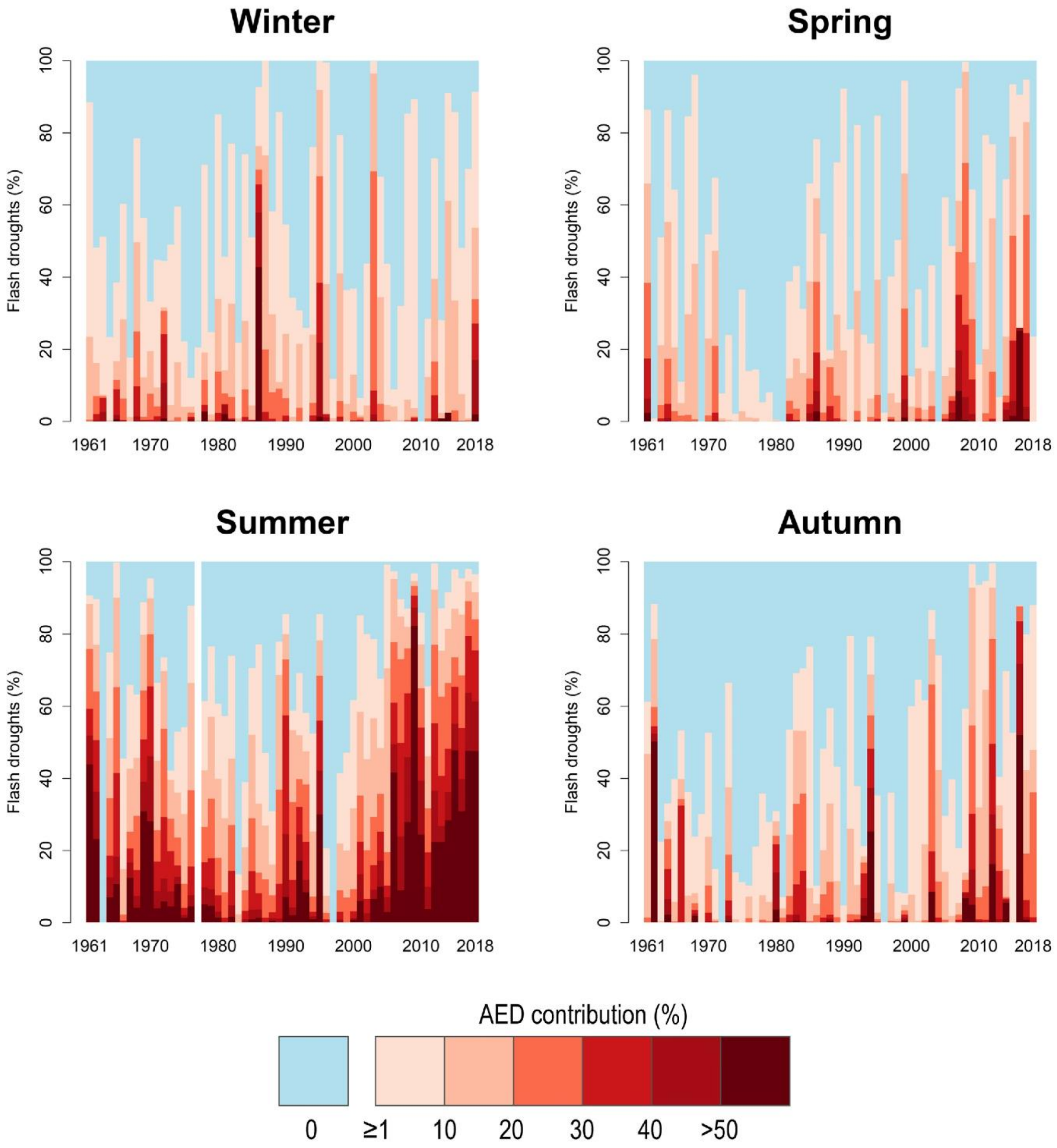

Figure 4. Temporal evolution of the seasonal percentage of flash droughts taking into account different atmospheric evaporative demand (AED) contribution thresholds in mainland Spain and the Balearic Islands over the period 1961–2018.

Vicente-Serrano, Camarero, et al., 2014), so this means that temperature has been the main variable that would also control the higher influence of AED on flash droughts. The increase in AED contribution to flash drought development is especially striking in the last two decades, in which the average in summer and spring almost doubled compared to the previous four decades (spring: from 5.5 to 9.9%; summer: from 16.7 to 31.3%; Figure S2 in Supporting Information S1). These findings are coherent with the expected response of water-limited regions to more severe droughts associated with the increase in AED. Recent studies based on the Palmer Drought Severity Index (PDSI) show that the severity of drought in some water-limited regions of the world, such as the west and southwest of the United States, has responded mainly to the increase in temperature over the last few years (Ault et al., 2016; Williams et al., 2015, 2020), which would emphasize the importance of AED in triggering recent drought events that could also affect the occurrence of flash droughts. For example, Christian et al. (2021) suggested a significant increase in flash droughts in some regions, such as the Iberian Peninsula, Brazil, and the Sahel, associated with global warming. Other studies also reported an increase in flash drought frequency in China (Wang & Yuan, 2018; Wang et al., 2016; Yuan et al., 2019) and southern Africa (Yuan et al., 2018) linked to this process.

The increase in AED would explain the higher frequency and severity of agricultural and ecological droughts during the last few decades (IPCC AR6 WGI, 2021) and this could extend to flash drought events that impacted severely on agriculture (Christian et al., 2020; He et al., 2019; Hunt et al., 2021; Jin et al., 2019; Otkin, Haigh, et al., 2018, 2019) and which are associated with anomalous increases in AED, soil moisture depletion and plant stress (Hunt et al., 2014). Therefore, the role of AED linked to global warming could be seen as the main driver in explaining the suggested recent increase of flash droughts in some regions of the world, as well as their possible rise in future scenarios characterized by higher AED. Several recent studies have suggested an escalation in droughts in future climate change scenarios linked to enhanced AED (Cook et al., 2014; Dai et al., 2018; Vicente-Serrano et al., 2020). As flash droughts are mostly relevant during the warm season, and associated with agricultural and ecological disasters (e.g., tree mortality, crop failure, increased risk of forest fires), it is reasonable to consider that future climate scenarios may be affected by more frequent and severe flash droughts, which would increase these consequences for vegetation activity and growth (Jin et al., 2019; Otkin et al., 2016, 2019; Zhang & Yuan, 2020). Thus, although there are some studies suggesting that drought metrics that include AED might overestimate future drought severity in comparison with metrics based on evapotranspiration (ET; Berg & Sheffield, 2018; Scheff, 2018), in fact the role of AED in the development of flash droughts is mainly restricted to water-limited areas and dry periods (e.g., Figure 2); therefore, under these conditions ET is limited by water availability. Nevertheless, if there is low soil moisture, although an increase in AED would not result in a notable increase in ET, it undoubtedly would enhance vegetation stress (Breshears et al., 2013; Grossiord et al., 2020) and, consequently, the severity of agricultural and environmental droughts (Allen et al., 2010, 2015; Asseng et al., 2014; Lobell et al., 2011; McDowell, 2011). Thus, during periods of no air advection typical of the warm season in Spain (García-Herrera & Barriopedro, 2018; Garrido-Perez et al., 2021), AED increases driven by surface-atmosphere coupling, which results in a progressive decrease in ET over this transition from energy-limited to water-limited conditions (Pendergrass et al., 2020). Moreover, plant physiology may also play a certain role given VPD influence on leaf stomata resistance and plant transpiration (Grossiord et al., 2020). Under conditions of air advection, it is expected that atmospheric dynamic is the main driver of AED changes and its possible role on flash droughts.

In Spain, the influence of AED is essential in explaining recent flash drought trends, especially during the summer, when a significant increase in the number of flash drought events was reported (Noguera et al., 2020, 2021). In any case, we must also stress that precipitation deficits are still the most important driver for flash drought development. Thus, the occurrence of flash droughts from early autumn to early spring responds almost exclusively to variations in precipitation in most of Spain over the period 1961–2018 and there are no noticeable trends in the magnitude and surface area affected by flash droughts associated with enhanced AED in the cold season. However, AED contribution to flash drought development and to the observed trends is highly important in the warm season, especially in water-limited regions where extreme temperature episodes, such as heat waves (Furió & Meneu, 2011; Kenawy et al., 2011) and water stress conditions are frequent. Therefore, a stronger influence by AED has noticeable ecological and agricultural implications, so it could result in increased drought impacts caused by such events, especially in the current observed trends projected for future climate scenarios.

4. Conclusions

This study provides a comprehensive assessment of the relative contribution of the AED and precipitation deficits on the development and intensification of flash drought in Spain over the last six decades, both of which exhibit an influence with important spatial contrasts and seasonal differences. In water-limited regions, the increase in AED is very important in triggering and intensifying flash droughts in the warm season, and contribute around

40% of flash drought development. In humid regions, flash drought responds almost exclusively to precipitation deficits in the short-term, with little influence of AED.

Trends suggest a general rise in the contribution of AED to flash droughts over the period 1961–2018, mainly associated with the increase in AED. The increase in AED contribution is especially notable in warm season over the last two decades. This means that recent trends reported in flash drought occurrence in Spain (Noguera et al., 2020, 2021) cannot be explained without the effect from the higher AED recorded in the warm season. These recent changes are particularly remarkable in dry regions of southern Spain where AED contribution has increased over 10% per decade in summer, but also in other regions, such as the Mediterranean coast during spring and northwestern Spain in autumn, with average increases of around 4% per decade.

The findings of this study have important implications for the early warning, decision-making, preparedness, and mitigation of flash drought in Spain. Likewise, this research can be useful to unravel flash droughts dynamics across a wide range of climatic conditions, but especially in water-limited regions in which the effect of AED increase worldwide could result in major ecological and agricultural impacts associated with flash droughts. In this way, under the projected increase in water stress linked to global warming, it also expected that the relevance of AED in driving the severity of flash droughts will increase in Spain as well as in other water-limited regions worldwide.

Data Availability Statement

The data used in this study can be obtained in the Climatology and Climate Services Laboratory (https://lcsc.csic.es/); both the SPEI data set (https://monitordesequia.csic.es/historico/) and the code for its calculation (https://lcsc.csic.es/software-2/) are openly available. Additional technical information about SPEI data set development and calculation can be found in Vicente-Serrano et al. (2017). Likewise, at the time of publication, the SPEI data set and also the meteorological data required for its calculation can obtain through this URL: https://doi.org/10.5281/zenodo.5849767.

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Chapter 5

Near-real time flash drought monitor for Spain

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Data Article

Near-real time flash drought monitoring system and dataset for Spain

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ABSTRACT

Flash droughts are characterized by rapid development and intensification, which makes early warning and monitoring difficult. Flash drought monitor (FDM) is a near-real time monitoring system for Spain (https://flash-drought.csic.es) based on the Standardized Precipitation Evapotranspiration Index (SPEI). Flash drought identification was based on rapid and anomalous declines in SPEI at a short time scale (1-month). Thus, FDM enables operational tracking of flash drought conditions in Spain at high spatial resolution (1.1 × 1.1 km) and high temporal frequency (weekly). Likewise, to put flash drought monitoring into a temporal context, the FDM also provides weekly flash drought conditions recorded in Spain from 1961 to the present. The FDM is a useful tool for preparedness and mitigation of flash droughts in Spain. Furthermore, the data provided by the FDM could be useful to develop future studies in relation to the flash drought in Spain.

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Specifications Table

Subject	Environmental sciences
Specific subject area	Drought analysis and monitoring
Type of data	Web-tool and dataset
How data were acquired	Daily meteorological data (precipitation, maximum and minimum air temperature, relative humidity, sunshine duration and wind speed) is recorded from the network of weather stations of the National Spanish Meteorological Service (AEMET). The data is subjected to quality control, aggregated weekly and interpolated to obtain gridded datasets for each meteorological variable, which are used to calculate the Standardized Precipitation Evapotranspiration Index (SPEI). Flash drought conditions are identified based on quick and abrupt declines in SPEI at a 1-month time scale.
Data format	Filtered and analyzed. netCDF (network Common Data Form) and CSV (comma-separated values)
Description of data collection	Flash drought conditions are collected for each pixel (1.1 × 1.1 km) at weekly frequency across Spain. Flash drought condition is defined as a decline ≥2 in SPEI 1-month values over 4-week period that results in a final SPEI value equal or less than −1.28 (moderate drought; corresponding with a 10-year return period). Flash conditions identified for each pixel are encoding as follows: value = 0 (no flash drought) value = 1 (flash drought onset), value = 2 (1st week from onset), value = 3 (2nd week from onset), value = 4 (3rd week from onset).
Data source location	Institution: Climatology and Climate Services Laboratory (LCSC). City: Zaragoza (Aragón) Country: Spain
Data accessibility	Users can download and visualize the data on flash drought conditions in Spain at the Climatology and Climate Services Laboratory (LCSC) website: https://flash-drought.csic.es Likewise, the FDM input and output data is available in an open access repository; Repository name: Zenodo, Title of the dataset: Flash drought monitor (FDM) datasets, URL: https://zenodo.org/record/7434135, DOI: 10.5281/zenodo.7434135.
Related research article	I. Noguera, F. Domínguez-Castro, S.M. Vicente-Serrano, Characteristics and trends of flash droughts in Spain, 1961–2018, Ann. N. Y. Acad. Sci. 1472 (2020) 155–172, doi:10.1111/nyas.14365. S.M. Vicente-Serrano, F. Domínguez-Castro, F. Reig, S. Beguería, M. Tomas-Burguera, B. Latorre, D. Peña-Angulo, I. Noguera, I. Rabanaque, Y. Luna, A. Morata, A. el Kenawy, A near real-time drought monitoring system for Spain using automatic weather station network, Atmos. Res. 271 (2022), doi:10.1016/J.ATMOSRES.2022.106095.

Value of the Data

- Flash drought monitor (FDM) provides detailed information on flash drought conditions for the whole of Spain at near-real time by means a user-friendly web-tool.
- Flash drought is a complex phenomenon, difficult to identify and monitor over the time and space. The presented monitoring system allows the automatic identification and tracking of flash drought conditions at high spatial resolution (1.1 × 1.1 km) and temporal frequency (weekly). Thus, FDM is an operative tool to early warning and decision-making by land and water managers.
- The information presented in this monitoring system was obtained by means of a robust method to identify flash drought conditions [1], which is based on Standardized Precipitation Evapotranspiration Index (SPEI) at a 1-month time scale.

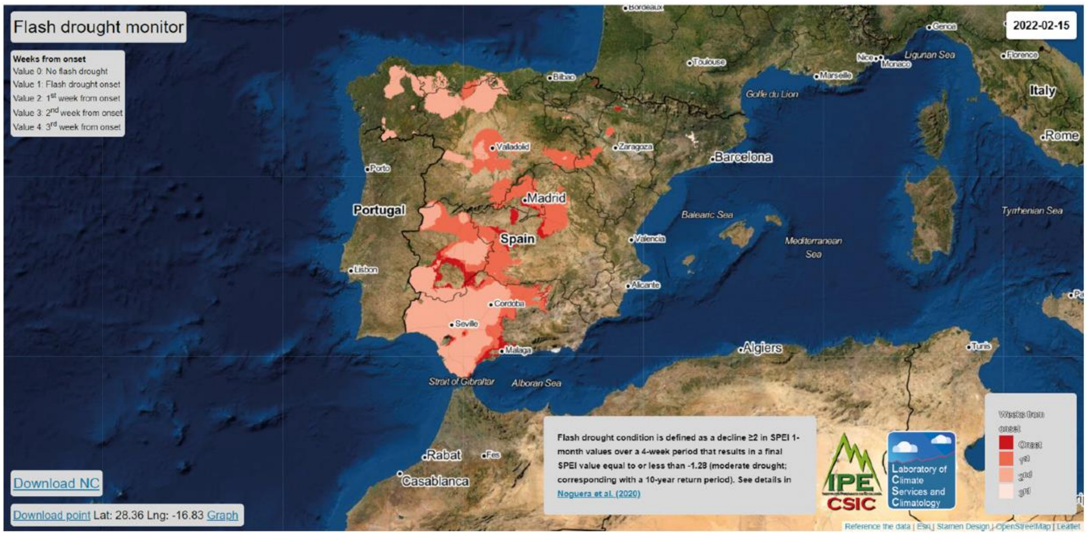
- Flash drought is a frequent phenomenon in Spain, representing around 40% of all droughts recorded at short-term. Furthermore, this type of events can occur in any season, resulting in major and diverse impacts on agricultural, environmental and socioeconomic systems. Therefore, the FDM represents a relevant and useful tool and data source for preparedness and mitigation of flash droughts in Spain.
- The data available in the FDM could be used by the scientific community to develop futures studios focused on flash drought in Spain.

1. Objective

The main objective of the Flash drought monitor (FDM) is to provide near real-time information about flash drought conditions in Spain by means a user-friendly web-tool, making it easily accessible and comprehensible by users. This information is crucial for preparedness and mitigation of flash droughts in Spain, representing a useful tool to early warning and decision-making by agricultural and water managers. In order to provide a temporal context of flash drought occurrence in Spain, the FDM also includes weekly data about flash droughts conditions recorded from 1961 to the present. In addition, all data presented in FDM are available for download by users and may be useful for future research on flash droughts in Spain.

2. Data Description

The Flash drought monitor (FDM) is available at https://flash-drought.csic.es. This monitoring system provides high spatial (1.1 × 1.1 km) and temporal (weekly) resolution data on flash drought conditions in Spain. The FDM allows near-real time monitoring of the spatial extent of flash droughts and their evolution over time, using a simple color code to indicate the number of weeks elapsing from the onset of a flash drought (i.e., from onset week for pixels where a flash drought has just been recorded to 3rd week for pixels where it was recorded 3 weeks previously). The definition adopted to identify flash droughts is always displayed at the bottom of the screen, while hovering the mouse over the top left shows details of the legend. Fig. 1 shows an example of the general display of the FDM during one of the last flash drought episodes recorded in Spain.



Flash drought monitor

Weeks from onset
Value 0: No flash drought
Value 1: Flash drought onset
Value 2: 1st week from onset
Value 3: 2nd week from onset
Value 4: 3rd week from onset

Flash drought condition is defined as a decline ≥ 2 in SPEI 1-month values over a 4-week period that results in a final SPEI value equal to or less than -1.28 (moderate drought; corresponding with a 10-year return period). See details in Noguera et al. (2020)

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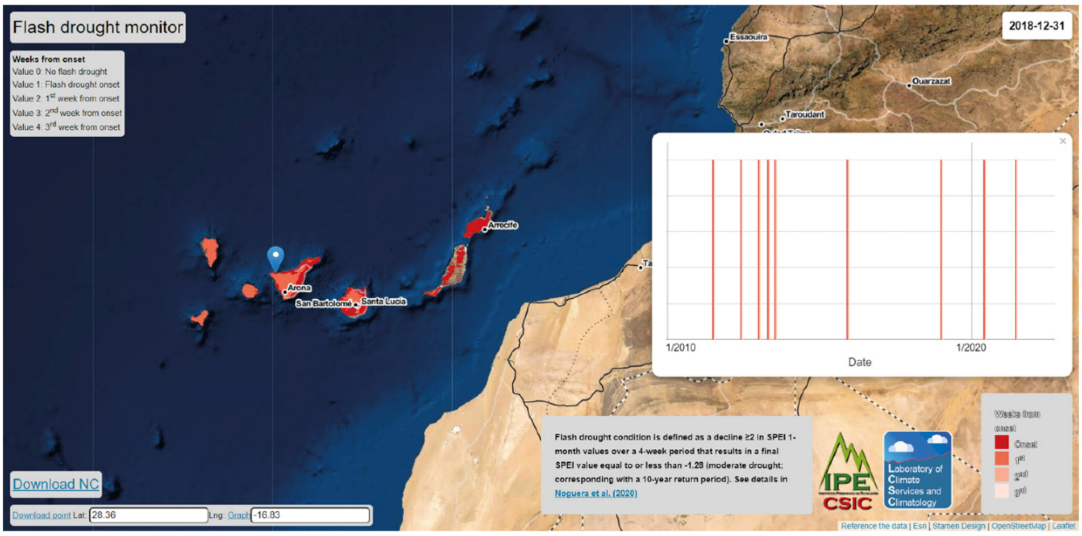
Fig. 1. Flash drought conditions recorded over mainland Spain and Balearic Island at 02/15/2022 by the FDM.


Flash drought monitor

Weeks from onset
Value 0: No flash drought
Value 1: Flash drought onset
Value 2: 1st week from onset
Value 3: 2nd week from onset
Value 4: 3rd week from onset

Flash drought condition is defined as a decline ≥2 in SPEI 1-month values over a 4-week period that results in a final SPEI value equal to or less than -1.28 (moderate drought; corresponding with a 10-year return period). See details in Noguera et al. (2020)

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Fig. 2. Flash drought conditions recorded over the Canary Islands at 12/31/2018, as well as the temporal evolution of flash drought conditions in a specific pixel over the period 2010–2022.

The home map shows the information on flash drought conditions in the last week available, but weekly maps of flash drought conditions from 1961 to the present can also be displayed, allowing users to visualize the evolution of any of the flash droughts affecting Spain over the last six decades. In addition, the flash drought conditions recorded in each pixel over the weekly time series can be also visualized by selecting a point on the map by means of an interactive graph, with the option to zoom in on a specific period (Fig. 2).

All data presented in the FDM is available for download in netCDF (network Common Data Form) and CSV (comma-separated values) format using the box at the bottom left. At regional scale, a netCDF file is provided with all flash drought events recorded in Spain from 1961 to the present. This netCDF file contains weekly series sorted by year for the whole of Spain (i.e., a grid of 1570 rows and 1257 columns, containing 418,597 grid points with data), with the following encoding: value = 0 (no flash drought), value = 1 (flash drought onset), value = 2 (1st week from onset), value = 3 (2nd week from onset), value = 4 (3rd week from onset). At pixel scale, CSV files are provided, with record of flash droughts identified from 1961 to the present in each pixel of the gridded dataset. These files can be downloaded by selecting any pixel in the study area to obtain a CSV file that contains weekly data sorted by year with the same encoding as described above.

3. Experimental Design, Materials and Methods

3.1. The Relevance of Flash Droughts in Spain

Spain is one of the regions most affected by drought in Europe, with heavy impacts on crops [2], forestry [3] and water resources [4]. Likewise, drought events commonly termed as "flash droughts" [5] are also frequent in Spain, representing almost 40% of all droughts identified [1]. Flash drought is distinguished from conventional slower-onset droughts by its rapid development and intensification linked to strong precipitation deficits and/or anomalous increases in atmospheric evaporative demand (AED) (e.g., associated with heat waves), triggering an abrupt decline in soil moisture and stress on vegetation, which can cause major agricultural and environmental impacts [6]. In Spain, flash droughts show wide spatiotemporal variability and remarkable seasonal differences [1]. Thus, flash drought in Spain may occur in any season associated with different meteorological drivers [7,8], causing diverse impacts. For these reasons, there is a need for flash drought monitoring and early warning in Spain.

3.2. Drought Index Calculation

These days, the Standardized Precipitation Evapotranspiration Index (SPEI) is the most widely used metric of drought severity worldwide [9]. The SPEI has been employed in numerous studies to analyze drought impacts on agriculture [10,11], hydrology [12,13] and environmental [14,15] systems in different regions of the world. The SPEI is calculated by the difference between precipitation and AED (i.e., climatic balance), which is accumulated at different time scales and standardized in order to be spatially and temporally comparable.

Daily data on precipitation, maximum and minimum air temperature, relative humidity, sunshine duration and wind speed from the complete network of weather stations in the National Spanish Meteorological Service (AEMET), which includes automatic stations (AWS), are used to generate SPEI real-time data for the whole of Spain. AED is computed based on maximum and minimum air temperature, relative humidity, sunshine duration and wind speed by means of the FAO-56 Penman–Monteith equation [16]. SPEI series are calculated at a 1-month time scale and high spatial (1.1 × 1.1 km) and temporal (weekly) resolution using the Log-logistic distributions as recommended by Vicente-Serrano and Beguería [17]. Additional information about generation and validation of meteorological datasets are available in Vicente-Serrano et al. [18].

To use SPEI for monitoring purposes, the AWS data undergo exhaustive quality control [19], aggregated weekly and then spatially interpolated using Universal Kriging as soon as new meteorological data are available to generate new SPEI values for the whole of Spain (see all details in Vicente-Serrano et al. [20]).

3.3. Flash Drought Monitoring

Flash drought events were identified following the method proposed by Noguera et al. [1], which is focused on the rapid development and intensification characteristic of this type of events [6]. In order to avoid the influence of past climatic conditions and only consider climatic anomalies developed at short-term, this approach is based on rapid changes in SPEI values at short time scales (i.e., 1-month) over 4-week periods. Thus, a flash drought event is defined as:

(i) A minimum length of four weeks in the development phase.
(ii) A ΔSPEI (in 4 weeks) equal to or less than -2 z-units.
(iii) A final SPEI value equal to or less than -1.28 z-units (i.e., a 10-year return period).

This definition was applied to the SPEI 1-month weekly series of each pixel to obtain a flash drought record over the lasts six decades in Spain. Similarly, we adopted this definition to identify flash drought events at near-real time as new SPEI data are available and to generate a flash drought monitoring system. Fig. 3 summarizes the process followed for the FDM to monitor flash drought conditions in Spain at near-real time.

To illustrate the performance and usefulness of the FDM, we show two representative examples of recent flash drought events in Spain (Fig. 4). The 2021 flash drought affected large areas of the country in March and early April associated with notable precipitation deficits, which resulted in the driest March of this century in Spain [21]. Despite normal temperatures, the marked lack of precipitation during the entire month triggered flash drought conditions in some areas of the northwest in late March that quickly spread to some areas of southern and large areas of northeastern Spain in early April. The 2022 flash drought hit most of Spain over May and June as a result of the combination of precipitation deficits and a high AED, reaching markedly anomalous temperatures in both months [22,23]. The flash drought started in the northeast and the Balearic Islands in late May and then affected all of eastern Spain in early June. These examples highlight the ability of the FDM to identify events with different characteristics, which

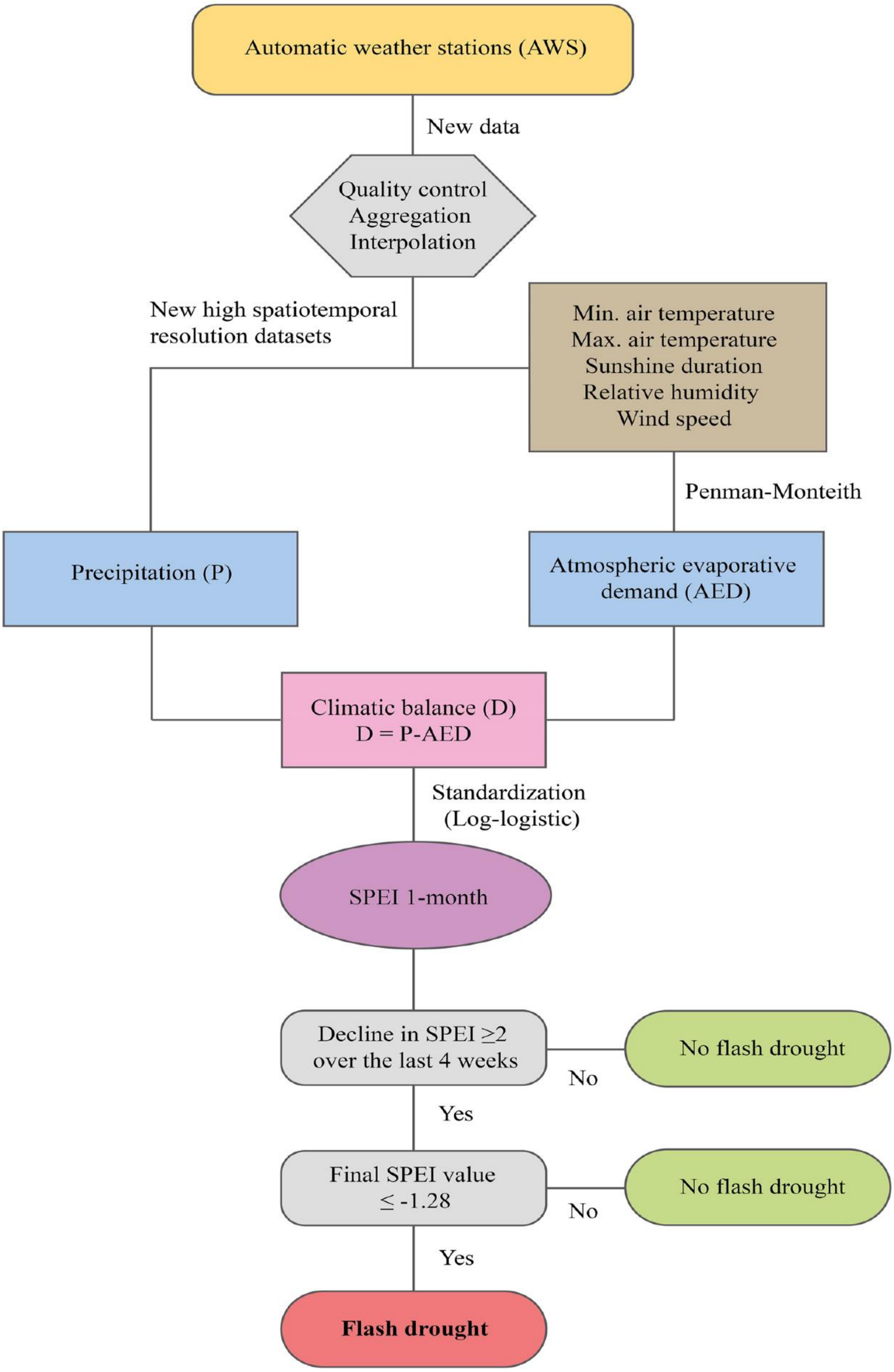
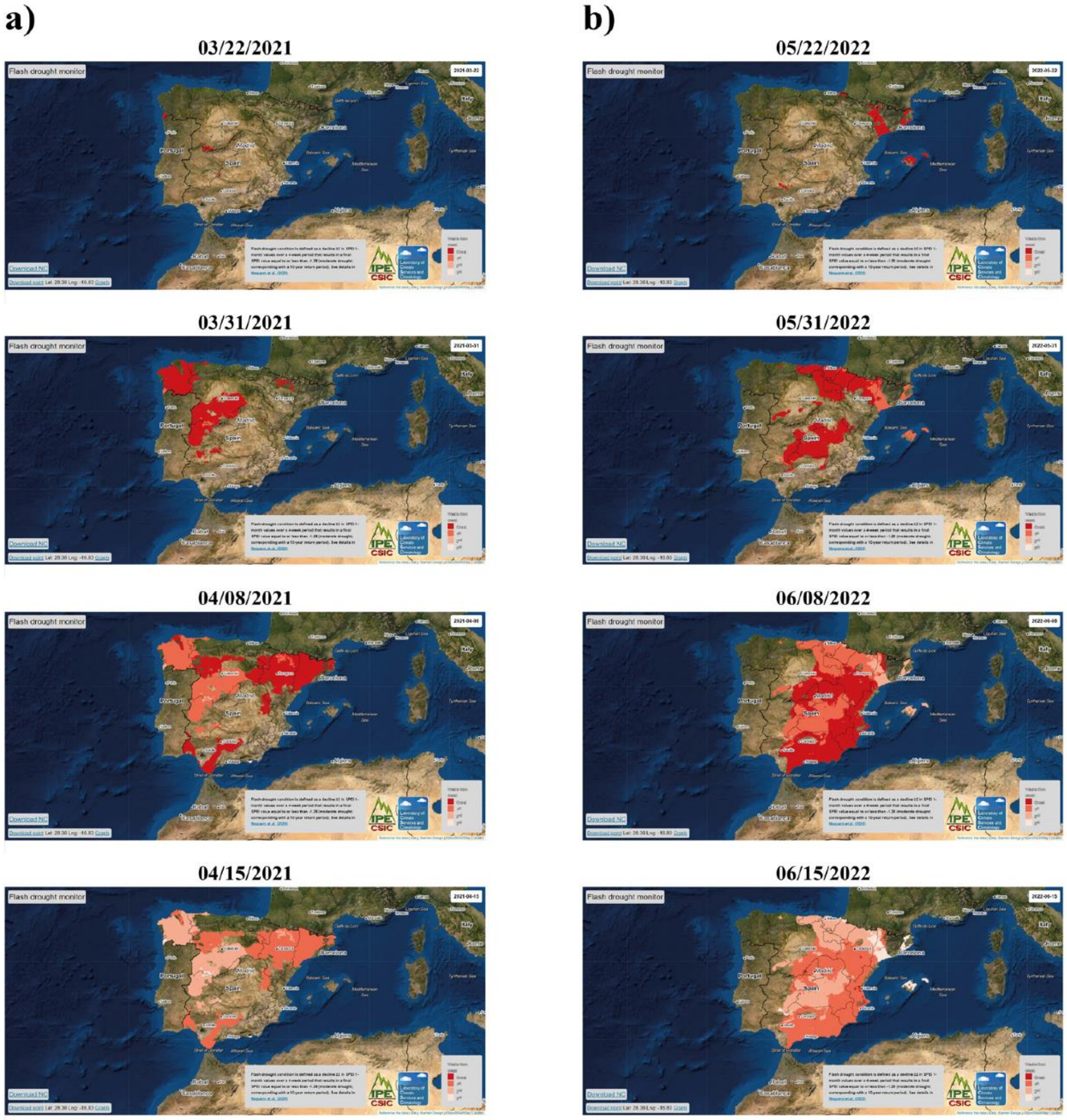


Fig. 3. Summary of the process followed for the monitoring of flash drought conditions.



03/22/2021 05/22/2022

03/31/2021 05/31/2022

04/08/2021 06/08/2022

04/15/2021 06/15/2022

Fig. 4. The (**a**) March-April 2021 and (**b**) May-June 2022 flash drought events recorded by the FDM.

is crucial in Spain as flash droughts can occur at any period of the year related with different drivers.

Ethics Statement

This work did not involve human subjects, animal experiments and data collected from social media platforms.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Flash drought monitor (FDM) (Original data) (https://flash-drought.csic.es).

CRediT Author Statement

I. Noguera: Conceptualization, Methodology, Formal analysis, Visualization, Validation, Writing – original draft, Writing – review & editing; **F. Domínguez-Castro:** Conceptualization, Methodology, Supervision, Writing – original draft, Writing – review & editing; **S.M. Vicente-Serrano:** Conceptualization, Methodology, Supervision, Writing – original draft, Writing – review & editing; **F. Reig:** Formal analysis, Visualization, Validation, Writing – original draft, Writing – review & editing.

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Chapter 6

Discussion and general synthesis

1. Methods and metrics for flash drought identification

The unusual rapid onset of flash drought, as well as lack of a widely accepted definition or objective criteria to identify and distinguish it from a conventional drought, makes its assessment difficult (Otkin et al., 2022). In this research, we have proposed an objective method for the identification of drought events characterized by a rapid development and intensification. Our method focuses on the detection of rapid and abrupt changes in drought indices values at short time scales (i.e., 1-month) that results in moderate drought conditions (i.e., 10-year return period) to define flash drought and distinguish it from conventional drought. Short time scales allow capturing meteorological anomalies that trigger flash drought at short-term (Hunt et al., 2014). Given that the unusual rapid onset is the main characteristic that distinguish flash drought from conventional slow-developing droughts (Otkin et al., 2018; Svoboda et al., 2002), our approach focused on the velocity of development of events, providing a more coherent definition of flash drought than methods based on their duration (Y. Liu et al., 2020). Furthermore, standardized and multiscalar drought indices allows the application of this methodology in regions with different climatic conditions, providing results comparable over the time and space. Likewise, the use of indices based on widely available meteorological information (e.g., SPI, EDDI, SPEI), makes it possible to easily replicate this method for identification and characterization of flash droughts in most world regions and in the long-term.

Our approach could be applied based on different standardized and multiscalar drought indices. In this research, we stress how the use of different indices (i.e., SPI based on precipitation, EDDI based on AED or SPEI based on both) can results in very different spatio-temporal patterns of flash droughts or even, in some cases, opposite trends in their frequencies (e.g., negative trends in flash drought frequency reported by SPI over most of Spain, versus the generally positive trends recorded by EDDI and SPEI). In complex climatic regions as Spain, it is expected that the occurrence of events varies over time and space depending on the metric applied, since the events may develop under different conditions and driven by different factors. Despite flash drought occurrence mostly responds to precipitation variability (Hoffmann et al., 2021; Koster et al., 2019; Parker et al., 2021; Y. Wang & Yuan, 2022b), the metrics based exclusively on precipitation (i.e., SPI) present some limitations, as precipitation deficit is not usually the unique meteorological driver involved in flash drought triggering (Otkin et al., 2013). These limitations are particularly evident in water-limited regions and in dry periods, when average precipitation may be close to zero. Under these conditions other drivers such as AED are important to explain drought occurrence (Tomas-Burguera et al., 2020). Likewise, the metrics based only on AED (i.e., the EDDI) are also affected by some limitations, since under sufficient water availability, an increased AED is not expected to trigger or aggravate drought conditions (Vicente-Serrano, McVicar, et al., 2020). For this reason, the use of metrics based only on AED may not provide a well assessment of flash droughts in energy-limited regions and during wet periods, as suggest the low correlation found between EDDI and SPI in humid regions of the north of Spain in late autumn and winter.

Here, we stress that it is necessary to use metrics that include the role of precipitation and AED (e.g., SPEI) for a complete and compressible assessment of flash drought. For example, Hunt et al. (2014) analyzed the response of the SPI and SPEI compared to soil moisture data in a rainfed maize site and in an irrigated maize site during a flash drought episode that affected Nebraska (United States) in 2003 growing season, and although they evidenced that both SPI and SPEI enabled to identify the rapid onset of drought conditions during the episode, the SPEI captured the drought much better as consequence of the inclusion of AED influence. SPEI variability is mostly controlled by precipitation, but it is sensitivity to AED during dry periods (Tomas-Burguera et al., 2020). This is clearly illustrated by the high consistency found between SPEI and SPI in humid regions of northern Spain, especially during wet periods, and its high correlation with EDDI in summer months over dry regions of the south. Thus, SPEI would enable a better assessment of flash drought under diverse conditions in both energy-limited and water-limited regions compared to metrics such as SPI and EDDI.

Furthermore, SPEI has been extensively employed for the assessment of drought effects on agricultural (Labudová et al., 2017; X. Liu et al., 2018; Peña-Gallardo, Vicente-Serrano, Domínguez-Castro, et al., 2018) and environmental (Gouveia et al., 2017; Vicente-Serrano et al., 2013; A. Zhao et al., 2018) systems over different regions of the world, showing a better performance than others drought indices widely used (Vicente-Serrano, Beguería, et al., 2012). Therefore, given that flash drought is mainly related to environmental and agricultural impacts (Otkin et al., 2018), SPEI may provide a more comprehensive picture of flash drought effects than other drought metrics.

2. Meteorological drivers of flash drought

Flash drought occurrence is usually associated with marked meteorological anomalies, which cause soil moisture decline and vegetation stress in few weeks. Although flash drought can be driven by diverse factors, including human-induced, its origin is fundamentally climatic. Focusing on meteorological drivers, we found that precipitation is the main factor controlling flash drought variability in Spain, in accordance with others regional (Parker et al., 2021; Y. Wang & Yuan, 2022b) and global (Hoffmann et al., 2021; Koster et al., 2019) studies. However, other factors that control AED (e.g., temperature, wind speed, relative humidity and solar radiation) may play a relevant role triggering flash drought conditions (Otkin et al., 2018). In recent years, numerous studies reported flash drought events (e.g., during heat wave episodes) strongly driven by AED and land-atmospheric feedbacks (Basara et al., 2019; Christian et al., 2020; He et al., 2019; Mo & Lettenmaier, 2015; Nguyen et al., 2019; Pendergrass et al., 2020). In Spain, where the climatic contrasts between regions are remarkable (Molina, 1981), we found important differences in the contribution of precipitation deficits and AED to flash drought development spatially and seasonally, but also between events that occur in the same regions or season. Thus, we recorded events directly related to strong precipitation deficits, others mainly driven by an exacerbated increase in AED, and also events resulting from a combination of precipitation deficits and enhanced AED.

In general terms, the role played by precipitation deficits and AED in flash drought development and intensification is strongly determined by the climatic characteristics and seasonality. On the one hand, in humid regions characterized by energy-limited conditions, flash droughts development typically respond to precipitation variability, since regardless of whether AED is high, strong precipitation deficits are required to trigger drought conditions because usually there is enough water availability. Thus, under normal conditions, an increase in the AED would not result on vegetation stress in these regions (Vicente-Serrano, McVicar, et al., 2020). On the other hand, in dry regions characterized by energy-limited conditions, a deficit of precipitation could be insufficient to trigger flash drought, especially during dry periods, in which precipitation is very low and AED effect on drought is more relevant. During these dry periods, an anomalous increase in AED would result in a depletion of water in the soil as well as land-atmospheric feedbacks (Hobbins et al., 2016; Pendergrass et al., 2020), aggravating notably drought effects on agricultural and environmental systems. In Spain, these regional and seasonal patterns in the role played by AED on flash drought development were clearly identified, showing a high spatial coherence with those found for slow-developing droughts at global scale (Tomas-Burguera et al., 2020).

Although the role of AED is mostly restricted to water-limited regions and dry periods, we found a notable and generalized increase in the contribution of AED to flash drought in Spain. This increase is close related with the general rise of AED observed in Spain over the last few decades (Tomas-Burguera et al., 2021) associated with the currently global warming process. Several studies evidenced that flash drought severity is increasing in different world regions as a result of global warming process (Christian et al., 2021; L. Wang et al., 2016; L. Wang & Yuan, 2018; Yuan et al., 2018, 2019). This suggests that the role of AED in flash drought may became more and more relevant under future climate change scenarios, especially in water-limited regions of the world, where the agricultural and environmental implications of AED are more relevant.

3. Flash drought in Spain

Flash drought represents a major hydrometeorological hazard for natural and human systems, especially in regions usually affected by water stress such as Spain. This research provides for the first time a detailed and comprehensive characterization of flash drought phenomenon in Spain. Several studies have analyzed drought patterns in Spain at different time scales (Coll et al., 2017; Domínguez-Castro et al., 2019; Vicente-Serrano, 2006a, 2006b, 2013), but none of them focused on droughts characterized by rapid onset.

The contribution has not been only related to a better understanding of this phenomenon in Spain, since an objective method for the identification of rapid declines in humidity conditions associated with flash drought onset has been developed. Using the approach developed, annual and seasonal spatio-temporal patterns and trends of flash drought were analyzed in mainland Spain and Balearic Island over the period 1961-2018. Likewise, to put on context the spatial and temporal variability of flash drought, its patterns were compared with those found for all drought events (i.e., considering both flash droughts and conventional slow-developing droughts) recorded in Spain for the same reference period. To unravel the possible factors that explain the spatial and temporal variability of flash drought, we focused on the role played by the main meteorological drivers that control the development of flash drought (i.e., precipitation deficits and AED) and its recent evolution under the current global warming scenario.

Flash drought is a very complex phenomenon in Spain, which is characterized by a high spatial and seasonal variability. This complexity is not only limited to flash drought, as it is a well-known feature of drought in Spain (Domínguez-Castro et al., 2019). Drought is a frequent phenomenon over the whole of Spain, affecting areas with very different climatic characteristics (Olcina-Cantos, 2001; Pita, 1989). The strong variability of drought in Spain is mostly related to the diverse atmospheric circulation patterns and mechanisms that affect this region (García-Herrera et al., 2007; Manzano et al., 2019; Russo et al., 2015; Trigo et al., 2013). In fact, it is common that a drought affects one specific region, while other regions record normal or wet conditions (Vicente-Serrano, 2006b). Given the high spatial variability, and also that this depending on the time scale, some studies found several homogeneous areas according to drought variability at different time scales (Vicente-Serrano, 2006a), evidencing the strong spatial and temporal variability of drought in Spain. Therefore, it is reasonable that the complex spatio-temporal behavior of drought is also translated to flash drought.

Here we have found that in the last decades, flash droughts were more frequency in northern and northwestern Spain compared with the central and southern regions. Likewise, north regions recorded the higher percentage of drought events that developed as flash drought. The spatial distribution of flash drought is coherent with previous studies that reported a higher frequency of drought events in the humid regions of the north in comparison to dry regions of the southern Spain (Domínguez-Castro et al., 2019). Nevertheless, both frequency and spatial distribution of flash droughts varies notably between seasons. In general, flash droughts affected more frequently north regions in winter and autumn months; while in spring and summer, when flash drought is most recurrent, a high frequency of flash droughts was noted over northern and southern regions. Despite the results showed that a substantial percentage of the whole drought events developed as flash drought in the areas with the highest number of events, and especially in summer, there are some regional differences suggesting that the factors underlaying flash drought occurrence can vary from those that control conventional droughts. The high variability found in the frequency and spatial distribution of flash droughts suggests that its occurrence is strongly determined by seasonal component, which is directly related to the role played by precipitation deficits and AED in flash drought development in each region and in each season.

In the humid areas of the north of Spain, the short periods characterized by below-average rainfall are frequent in all seasons and they may cause a rapid decrease in humidity conditions, triggering drought conditions. For example, Domínguez-Castro et al. (2019) reported a large number of drought events of short duration and magnitude in north of Spain associated with dry periods that may be replaced by wet conditions with a high frequency. In these humid regions, characterized by energy-limited conditions, precipitation variability plays a major role in the development of flash drought conditions in all seasons, while the AED has little relevance, even in summer, given the sufficient water availability. By contrast, in dry regions of the central and southern Spain where water-limited conditions are frequent due to rainfall scarcity, the mechanisms that control AED can play an important role triggering drought conditions (Vicente-Serrano, McVicar, et al., 2020). It is necessary to stress that precipitation is also the main driver controlling flash drought variability in these regions in winter, spring and autumn Nevertheless, the anomalous increases in AED play a crucial role in flash drought development during summer months. In summer, precipitation is close to zero in wide areas of the south of Spain (Martin-Vide & Olcina-Cantos, 2001; Serrano et al., 1999), so the anomalous increases in AED associated with the frequent episodes of extreme temperature caused by Saharan advections (Sousa et al., 2019) or land-atmospheric feedbacks (Miralles et al., 2019) may be strongly to trigger flash drought. These patterns are reflected in the spatial distribution of flash drought over Spain, explaining the seasonal differences found between north and south regions.

The marked regional differences in the role of precipitation deficits and AED on flash drought development are given by the climatic complexity of Spain as a result of the location of Iberian Peninsula between Atlantic Ocean and Mediterranean Sea (Martin-Vide & Olcina-Cantos, 2001). Drought occurrence in Spain is determined wide variety of synoptic situations and large-scale circulation patterns that controls precipitation and AED (Esteban-Parra et al., 1998; Fernández-Montes et al., 2013; García-Herrera et al., 2005; Martín Vide & Fernández Belmonte, 2001; Trigo et al., 2004). Preliminary results obtained in the context of this research show that flash droughts develop under high positive anomalies in 500 hPa geopotential heights and sea level pressure (Figure Supplementary 1) associated with high-pressure systems and anticyclonic situations that usually results in strong precipitations deficits over Spain (Molina, 1981; Sahsamanoglou, 1990). Likewise, we noted an important influence of large-scale circulation patterns as NAO, WeMO and MO (Figure Supplementary 2) on flash drought development, especially in winter. NAO is the most important large-scale circulation patterns that control flash drought development, in agreement with previous studies that showed a strong relationship between NAO positive phases and drought occurrence in Spain (Manzano et al., 2019). In addition, other specific mechanisms and atmospheric configurations that may drive extreme temperatures and heat waves episodes (García-Herrera et al., 2007; Serrano-Notivoli et al., 2022; Sousa et al., 2019) may have an important role on flash development in late spring and summer. Thus, and considering the diverse atmospheric dynamics controlling precipitation and AED in Spain, it is reasonable to expect important difference in the spatial distribution of flash drought and in the drivers involved in its seasonal occurrence.

In addition to the differences in spatial patterns of flash drought in Spain, we found a remarkable variability in the temporal frequency and trends of flash droughts. The total number of flash droughts recorded in the whole of Spain has not changed significantly over the last six decades, but some regions of the south and southeast of Spain reported a significant increase. The positive trends observed in these regions are mainly related with the general increase of flash droughts found in summer, as well as to increase of the number of events recorded over the Mediterranean coast in spring. By contrast, negative and generally non-significant trends in flash drought frequency were noted in large areas over central and northern Spain. In general, the changes observed in the frequency of flash drought are consistent with those found for all drought episodes, although the increases observed considering all drought were more remarkable. Both considering all droughts and only flash drought events, the most important changes were recorded over south of Spain in summer months, which is consistent with previous studies that reported a significant decrease in SPEI over southern Spain (Coll et al., 2017; Domínguez-Castro et al., 2019).

The positive trends observed in flash drought frequency seem to be directly related to the general increase in AED identified over Spain (Tomas-Burguera et al., 2021; Vicente-Serrano, Lopez-Moreno, et al., 2014). This rise of AED linked to global warming resulted in a notable increase in the contribution of AED to flash drought development over Spain during the last years. Although the general increase in the contribution of AED does not appear to have an important effect on flash drought trends in winter, autumn and spring, this factor explains the significant increase found in flash drought frequency in summer. The highest increases in AED contribution to flash drought development were recorded over south and southeastern Spain in summer months, showing spatial and seasonal coherence with the reported increases in the number of flash droughts. Despite flash drought responds mainly to the variability of precipitation, the growing relevance of the role of AED associated with the rise of temperatures has important implications, affecting flash drought frequency and severity in Spain.

4. Early warning of flash drought

Nowadays, drought prediction is very limited at medium- and long-term (i.e., seasonal or longer time scales), especially in mid-latitudes, where climate predictability is low (Hao et al., 2017, 2018). Considering that flash droughts develop at short-term (subseasonal), some authors suggest that there is potential for forecasting and early warning (Pendergrass et al., 2020). Nevertheless, the prediction skill of flash drought is still limited and varies considerably among regions (Deangelis et al., 2020; Mo & Plettenmaier, 2020) as subseasonal forecasting systems have difficulties predicting precipitation variability (Otkin et al., 2022). Thus, and given the existing limitations in drought prediction in most of the world regions (Pozzi et al., 2013), early warning systems are usually focus on near-real time monitoring of drought conditions (Dracup, 1991) based on different information sources (earth-surface models, satellite information, meteorological data etc.).

Recently, some studies explored the capability of near real-time monitoring of flash drought using satellite data (Sehgal et al., 2021) or land-surface models (Chen et al., 2020). However, the outputs (e.g., ET, soil moisture etc.) derived from satellite and model information are usually affected by important uncertainties (Ford & Quiring, 2019; Xia et al., 2015), which limits the ability to monitor drought conditions compared to observational data. In the context of this research, we have developed the Flash Drought

Monitor (FDM), a monitoring system based on SPEI that allows the operational tracking of flash droughts in Spain at near-real time using observational meteorological data from automatic weather stations. The use of hydrometeorological data, usually transformed into drought indices, is a common approach (McRoberts & Nielsen-Gammon, 2012; R. D. Shah & Mishra, 2015; Zink et al., 2016) as enable monitoring drought conditions in a robust and easily understandable way for end users (Svoboda et al., 2002). Specifically, SPEI has proven to be a useful metric for drought monitoring (Beguería et al., 2014; Vicente-Serrano et al., 2022; H. Zhao et al., 2017) due to its capacity to capture the response of different systems to drought (Vicente-Serrano, Beguería, et al., 2012). Although the assessment of flash drought based exclusively on SPEI (i.e., precipitation and AED data) may show some limitation, since a robust monitoring of flash drought would require the inclusion of multiple variables and information sources (both meteorological data and information on the conditions of the affected systems), this monitoring system represents an accurate tool to determine areas potentially affected by flash drought conditions in Spain.

The development of early warning systems is one of the main needs and challenges ahead for preparedness and mitigation of flash drought (Otkin et al., 2022). Existing monitoring system may not be suitable for flash drought identification as they were designed to capture slow-developing droughts, so it is necessary to create specific tools focused on the velocity of the development of drought events. Given that SPEI is based on meteorological data widely available, the developed FDM could be reproduced in other regions that dispose of a network of weather stations with a record of at least 30 years. The implementation of this approach would be useful for the early waning of flash drought in regions with different climatic characteristic, providing crucial information for decision-making by land and water managers.

Chapter 7

Conclusion

1. General conclusions

This PhD dissertation analyzed for the first time the flash drought phenomenon in Spain. The development of a methodological approach based on drought indices allowed identification and characterization of flash droughts in mainland Spain and Balearic Island over the period 1961-2018. We analyzed the spatio-temporal variability and trends of flash droughts, as well as the main meteorological drivers involved in flash drought development by means different metrics. The experience and knowledge gained in relation to this phenomenon allowed the development of a monitoring system (i.e., the Flash Drought Monitor) to tracking flash drought conditions over Spain at near-real time.

1. The methodological approach developed in this research enabled to identify flash drought using drought indices based on widely available meteorological data, providing a robust method to analyzed flash drought variability at long-term. Our method focuses on quickly and abrupt changes in drought indices values at short time scales to captured the unusual rapid onset characteristic of flash drought.

2. Flash drought is a complex phenomenon characterized by a high spatial and temporal variability in Spain. In the last six decades, the northern and northwestern regions reported a higher frequency of flash drought events compared to central and southern Spain. Flash droughts were more frequent in summer and spring, affecting both northern regions and large areas of southern Spain, while in winter and autumn the occurrence of flash droughts was mainly limited to northern and northwestern regions.

3. Flash drought is common phenomenon in Spain, with almost 40% of all droughts developing as flash droughts. Although there is a relationship between the occurrence of flash droughts and all drought events (i.e., considering both flash droughts and slow-developing droughts), the important differences found in terms of frequency and distribution suggest that flash droughts respond to different dynamics than conventional droughts.

4. The number of flash droughts and percentage relative to all droughts shows no relevant changes for the whole of Spain, although the trends observed show important differences between regions. Negative and non-significant trends were mainly reported over central and northern regions, while positive trends were generally recorded in south and Mediterranean coast, with significant and notable increases in large areas of

southeastern. The number of flash drought recorded in summer has increased significantly in Spain, especially in southern and southeastern regions.

5. Flash drought in Spain can be triggered by both precipitation deficit and increase in AED, but their role varies notably spatially and temporally. Precipitation variability is the main driver of flash drought development in Spain, while AED is only relevant in water-limited regions and during warm and dry periods. Flash drought occurrence responds almost exclusively to precipitation variability in the humid (energy-limited) regions of the north, while in the dry regions (water-limited) of central and southern Spain AED plays a crucial role in flash drought development during summer.

6. The spatio-temporal patterns and trends of flash drought are highly variable depending on the metric used for events identification. The implementation of methodological approaches that include metrics based exclusively on precipitation (e.g., SPI) or AED (e.g., EDDI) to identify and characterize flash drought present some limitations. Thus, the use of metrics as SPEI based on climatic balance (i.e., precipitation minus AED) are more suitable for flash drought analysis, as it allows to assess flash drought under a wide range of climatic conditions.

7. The rise of AED is the main factor explaining the positive trends in flash drought frequency observed in southern and southeastern Spain. In general, the contribution of AED to flash drought development increased in all seasons over Spain, but especially in water-limited regions during summer.

8. The development of drought monitoring systems (e.g., Flash Drought Monitor), which allow the operational tracking of flash drought conditions at near-real time, is a useful tool for the preparedness and mitigation of flash drought, providing crucial information for decision-making by land and water managers.

2. Conclusiones generales

Esta tesis doctoral analiza por primera vez el fenómeno de la sequía repentina en España. El desarrollo de un enfoque metodológico basado en índices de sequía permitió identificar y caracterizar las sequías repentinas en España peninsular y Baleares durante el periodo 1961-2018. Se analizó la variabilidad espacio-temporal y las tendencias de las sequías flash, así como los principales impulsores implicados en el desarrollo de la sequía repentina mediante diferentes métricas. La experiencia y conocimientos adquiridos en relación con este fenómeno permitieron el desarrollo de un sistema de monitorización (i.e., el Monitor de sequía repentina) para el seguimiento de las condiciones de sequía repentina en España en tiempo casi real.

1. El enfoque metodológico desarrollado en esta investigación permitió identificar la sequía repentina utilizando índices de sequía basados en datos meteorológicos ampliamente disponibles, proporcionando un método robusto para analizar la variabilidad de la sequía repentina a largo plazo. Nuestro método se centra en los cambios rápidos y abruptos en los valores de los índices de sequía en escalas de tiempo cortas para capturar el característico inicio rápido de la sequía repentina.

2. La sequía repentina es un fenómeno complejo caracterizado por una alta variabilidad espacial y temporal en España. En las últimas seis décadas, las regiones del norte y noroeste registraron una mayor frecuencia de episodios de sequía repentina en comparación con el centro y sur de España. Las sequías repentinas fueron más frecuentes en verano y primavera, afectando tanto a las regiones del norte como a amplias zonas del sur de España, mientras que en invierno y otoño la ocurrencia de sequías repentinas se limitó principalmente a las regiones del norte y noroeste.

3. La sequía repentina es un fenómeno común en España, con casi el 40% de toda la sequía desarrollándose como sequía repentina. Aunque existe una relación entre la ocurrencia de la sequía repentina y todos los eventos de sequía (i.e., considerando tanto las sequias repentinas como las sequías convencionales), las importantes diferencias encontradas en términos de frecuencia y distribución sugieren que las sequías flash responden a dinámicas diferentes que las sequías convencionales.

4. El número de sequías repentinas y el porcentaje respecto al todas las sequías no muestra cambios relevantes para el conjunto de España, aunque las tendencias observadas muestran importantes diferencias entre regiones. En las regiones centrales y septentrionales se registraron principalmente tendencias negativas y no significativas, mientras que en el sur y la costa mediterránea se registraron generalmente tendencias positivas, con aumentos significativos y notables en amplias zonas del sureste. El número de sequías repentinas registradas en verano ha aumentado significativamente en España, especialmente en las regiones del sur y sureste.

5. La sequía repentina en España puede ser desencadenada tanto por déficits de precipitación como por el aumento del AED, pero su papel varía notablemente a nivel espacial y temporal. La variabilidad de la precipitación es el principal factor desencadenante de la sequía repentina en España, mientras que la AED sólo es relevante en regiones con limitaciones de agua y durante periodos cálidos y secos. La ocurrencia de la sequía repentina responde casi exclusivamente a la variabilidad de la precipitación en las regiones húmedas (limitadas en energía) del norte, mientras que en las regiones secas (limitadas en agua) del centro y sur de España la AED juega un papel crucial en el desarrollo de la sequía repentina durante el verano.

6. Los patrones y tendencias espaciotemporales de la sequía repentina son muy variables en función de la métrica utilizada para la identificación de los eventos. La aplicación de enfoques metodológicos que incluyen métricas basadas exclusivamente en la precipitación (por ejemplo, el SPEI) o la AED (por ejemplo, el EDDI) para identificar y caracterizar la sequía repentina presenta algunas limitaciones. Por lo tanto, el uso de métricas como el SPEI basadas en el balance climático (es decir, precipitación menos AED) son más adecuadas para el análisis de la sequía repentina, ya que permite evaluar la sequía repentina en un amplio rango de condiciones climáticas.

7. El aumento del AED es el principal factor que explica las tendencias positivas en la frecuencia de la sequía repentina observadas en el sur y sureste de España. En general, la contribución del AED al desarrollo de la sequía repentina aumentó en España en todas las estaciones, pero especialmente en las regiones con limitaciones de agua y durante el verano.

8. El desarrollo de sistemas de vigilancia de la sequía (e.g., el Monitor de sequía repentina), el cual permiten el seguimiento operativo de las condiciones de sequía repentina en tiempo casi real, es una herramienta útil para la preparación y mitigación de la sequía repentina, proporcionando información crucial para la toma de decisiones por parte de los gestores de la tierra y el agua.

3. Future work

This PhD dissertation provide a first general picture of flash drought in Spain, contributing to a better understanding of this phenomenon. Likewise, we provide an objective method that allow define flash drought and distinguish it from conventional slow-developing drought. However, there are still many gaps involving flash drought research at regional and global scale. Below we briefly outline some of the main issues that could and should be addressed.

A key point that needs to be addressed is the propagation of drought conditions (develop as flash drought) through the different affected systems. Although some studies explored the rapid propagation from meteorological to agricultural drought associated with flash drought occurrence (Basara et al., 2019), there is an absence of studies that evaluate its propagation over other natural systems (e.g., environmental, hydrological etc). Some previous studies evidenced the important implication of drought at short time scales (≤ 3-months) on vegetation activity (Vicente-Serrano et al., 2013), tree mortality (Allen et al., 2015; Choat et al., 2018) or streamflows (Peña-Gallardo et al., 2019). However, the use of very short time scales (≤ 1-month) typically employs to identify the rapid onset of flash drought, makes it difficult to quantify the subsequent effects of drought on natural and human systems that responds to longer time scales. Probably, the combination of different time scales to identify (shorth time scales, e.g., ~1-month) and quantify (longer time scales, e.g., ~3-months) could provide a better assessment of the propagation of flash drought over different systems, determining how many of these droughts with an unusual rapid onset become in droughts at long-term. This is an important issue that should be addressed by future studies for a better quantification of flash drought.

The analysis of the atmospheric dynamics involved in the triggering of flash droughts is another point that has received very little attention from the scientific community. Currently, there is an important lack in studies related to the analysis of synoptic situations and general circulation patterns that control flash drought occurrence at global and regional scale. Several studies evidenced the strong influence of large-scale circulation patterns in drought occurrence over different regions of the world (Penalba & Rivera, 2016; Vicente-Serrano et al., 2011), but little is now about its influence on flash drought occurrence. This is an important issue that should be analyzed by future studies at both regional and global scale for a better understanding of the mechanism that explain flash drought development over different climatic conditions.

Probably, the most relevant issue is to unravel the possible effects of climate change on the frequency and severity of flash drought. More and more studies demonstrated the important implications of global warming on flash drought (J. Shah et al., 2022; L. Wang et al., 2016; Yuan et al., 2018, 2019). Considering that the rise in AED may exacerbate flash drought impacts, there is a need to evaluate its effects on flash drought variability and severity at global and regional scale. Likewise, it is necessary to assess flash drought phenomenon in future climate change scenarios. Although some recent studies showed the possible increase of flash drought risk under projected climate scenarios (V. Mishra et al., 2021; Sreeparvathy & Srinivas, 2022), further research to evaluate this issue in depth.

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Annex 1

Assessment of parametric approaches to calculate the Evaporative Demand Drought Index

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RESEARCH ARTICLE

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Assessment of parametric approaches to calculate the Evaporative Demand Drought Index

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Abstract

The Evaporative Demand Drought Index (EDDI), based on atmospheric evaporative demand, was proposed by Hobbins et al. (2016) to analyse and monitor drought. The EDDI uses a nonparametric approach in which empirically derived probabilities are converted to standardized values. This study evaluates the suitability of eight probability distributions to compute the EDDI at 1-, 3- and 12-month time scales, in order to provide more robust calculations. The results showed that the Log-logistic distribution is the best option for generating standardized values over very different climate conditions. Likewise, we contrasted this new parametric methodology to compute EDDI with the original nonparametric formulation. Our findings demonstrate the advantages of adopting a robust parametric approach based on the Log-logistic distribution for drought analysis, as opposed to the original nonparametric approach. The method proposed in this study enables effective implementation of EDDI in the characterization and monitoring of droughts.

KEYWORDS

atmospheric evaporative demand, EDDI, Log-logistic distribution, parametric approach, reference evapotranspiration

1 | INTRODUCTION

Drought is one of the main climate hazards affecting society and the environment, with severe impacts on agriculture, natural ecosystems and water supplies (Wilhite, 1993; Wilhite and Pulwarty, 2017). It is not easy to identify and quantify droughts in terms of intensity, magnitude, duration and spatial extent (Wilhite and Glantz, 1985; Vicente-Serrano, 2016). For this reason, a great deal of effort has been invested in developing objective methods to quantify drought severity, as well as the impacts on various natural and socioeconomic sectors. Climatic drought indices are one of the most broadly used approaches in identifying and quantifying this type of event (Heim, 2002; Keyantash and Dracup, 2002; Mukherjee *et al.*, 2018). Currently, there is a wide variety of drought indices (Mishra and Singh, 2010) based on climatic information, and typically used in drought analysis and monitoring (Mckee *et al.*, 1993a; McKee *et al.*, 1993b; Vicente-Serrano *et al.*, 2010).

Traditionally, drought indices are calculated from precipitation data. However, this perspective is insufficient in that it does not include all the variables causing drought severity, among which the atmospheric evapora-

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tive demand (AED) is also highly significant (Hobbins *et al.*, 2017; Vicente-Serrano *et al.*, 2020). Several studies have suggested that AED is crucial in the development and intensification of certain drought events (Ciais *et al.*, 2005; Hunt *et al.*, 2014; Otkin *et al.*, 2016; Zhang and He, 2016; García-Herrera *et al.*, 2019). Thus, recent drought indices include AED in calculations, among others the Standardized Precipitation Evapotranspiration Index (SPEI; Vicente-Serrano *et al.*, 2010; Beguería *et al.*, 2014) or the Standardized Evapotranspiration Deficit Index (SEDI; Kim and Rhee, 2016; Vicente-Serrano *et al.*, 2018).

Hobbins *et al.* (2016) and McEvoy *et al.* (2016) formulated the Evaporative Demand Drought Index (EDDI), based exclusively on AED data. Adopting the AED as a unique metric of drought severity could give rise to problems in certain circumstances given its complex influence on drought severity (Vicente-Serrano *et al.*, 2020), although it could be very useful during periods of very low soil moisture and strong land-atmosphere feedbacks (Hobbins *et al.*, 2017; Miralles *et al.*, 2019). Thus, the EDDI could identify anomalous increases in the AED that can trigger drought conditions (Pendergrass *et al.*, 2020). Given the complexity of droughts, as many drought indices as possible should be included, since they can complement each other and provide a more accurate picture of drought severity, so the EDDI is a valuable tool that must be tested and used and, if possible, improved.

Unlike other widely used drought indices such as the Standardized Precipitation Index (SPI; Mckee *et al.*, 1993a, 1993b) and the SPEI, the EDDI is based on a nonparametric approach using empirically derived probabilities to obtain a standardized index that can be compared in space and time. This methodological approach is very flexible as it can be used without adopting a specific probability distribution for the reference variable (e.g., precipitation, AED, soil moisture, etc.). Given that nonparametric approaches do not assume that there is a suitable probability distribution representative of the data, there is no need to estimate parameters and evaluate goodness-of-fit, which is a computational advantage (Farahmand and AghaKouchak, 2015). However, as parametric approaches are not bound by the highest and lowest observed values, they have the advantage over nonparametric approaches. This is critical for drought monitoring, as if the new value corresponds to the lowest and highest ones, the index cannot be adequately modelled above or below these maximum and minimum values. Thus, parametric methods are more suitable than nonparametric approaches to calculate drought indices based on a defined reference period so that a new value can be easily placed within the range of the theoretical probability distribution (Beguería *et al.*, 2014; Stagge *et al.*, 2015; Vicente-Serrano and Beguería, 2016; Svensson *et al.*, 2017). In addition, the range of index values in nonparametric methods is a function of the length of the reference climatology, which limits their use when long-term data are not available.

In general, parametric approaches are better at modelling distribution tails corresponding to the most extreme values (Vicente-Serrano and Beguería, 2016), and at determining the anomalous character of a single value, because they are not heavily constrained by the available observations, as in the case of nonparametric approaches. This is a very relevant issue in accurate drought characterization, as these extreme values are crucial for determining the severity and intensity of drought episodes.

If the EDDI is intended to be included in precise drought quantification and monitoring, it is necessary to find the most accurate approach (i.e., probability distribution) to calculate it parametrically. Studies have been made to determine the most accurate probability distributions for calculating the SPI, SPEI and SEDI (Mckee *et al.*, 1993a; 1993b; Stagge *et al.*, 2015; Vicente-Serrano and Beguería, 2016; Vicente-Serrano *et al.*, 2018). There is general agreement that the Gamma distribution performs better in calculating the SPI, and the Log-logistic distribution provides the best results for the SPEI and the SEDI. In this study, we tested several probability distributions and proposed a method to calculate the EDDI by means of a parametric approach. Likewise, we compared this new EDDI formulation based on a parametric approach with the original nonparametric formulation proposed by Hobbins *et al.* (2016). For this purpose, we used a recently developed high spatial resolution gridded dataset of the AED in Spain (Tomás-Burguera *et al.*, 2019), since Spain is characterized by large spatial and seasonal differences in the AED (Vicente-Serrano *et al.*, 2014; Tomas-Burguera *et al.*, 2017; Tomas-Burguera *et al.*, 2021), and enabling the capacity of different probability distributions to be assessed over a wide range of climate conditions.

2 | DATA AND METHODS

2.1 | Atmospheric evaporative demand dataset

This study used a high spatial resolution (1.21 km^2) gridded climate dataset with coverage for mainland Spain and the Balearic Islands at monthly temporal resolution over the period 1961–2018. The dataset is based on the entire daily observational information from the National Spanish Meteorological Service (AEMET), which was subjected to a thorough quality control and homogenization process (Tomás-Burguera *et al.*, 2016). Details of the process followed in developing the dataset are available in Tomas-Burguera *et al.* (2019). The reference evapotranspiration (ET_O), a robust metric of the AED (Vicente-Serrano *et al.*, 2020), was calculated from the maximum and minimum temperature, relative humidity, wind speed, and sunshine duration, using the FAO-56 Penman–Monteith equation (Allen *et al.*, 1998).

The AED is driven by a radiative component, reflecting the available energy to vaporize water, and an aerodynamic component that reflects the capacity of the air to store water (Hobbins *et al.*, 2016). The role of AED in the development and intensification of droughts can be very complex and it is closely related to climatic characteristics, exhibiting large contrasts between humid regions characterized by energy-limited conditions and dry regions characterized by water-limited conditions (Vicente-Serrano *et al.*, 2020). Thus, under the former, increases in AED are not expected to result in a drought,

TABLE 1 Cumulative distribution functions *F*(*x*) of the eight probability distributions tested

Probability distribution	F(x)
General extreme value	$F(x)=1-\left[1-\frac{\kappa}{\alpha}(x-\varepsilon)\right]^{1/\kappa}$
Log-logistic	$F(x)=\left[1+\left(\frac{\alpha}{x-\gamma}\right)^{\beta}\right]^{-1}$
Lognormal	$F(x)=\Phi\frac{\ln(x-a)-\mu}{\sigma}$
Pearson III	$F(x)=\frac{1}{\alpha\Gamma(\beta)}\int_{\gamma}^{x}\left(\frac{x-\gamma}{\alpha}\right)^{\beta-1}e^{-\left(\frac{x-\gamma}{\alpha}\right)}$
Generalized Pareto	$F(x)=1-\left[1-\frac{\kappa}{\alpha}(x-\varepsilon)\right]^{1/\kappa}$
Weibull	$F(x)=1-e^{-\left(\frac{x-m}{a}\right)^{b}}$
Normal	$F(x)=\Phi\left(\frac{x-\mu}{\sigma}\right)$
Exponential	$F(x)=1-e^{-\left(\frac{x-\varepsilon}{\alpha}\right)}$

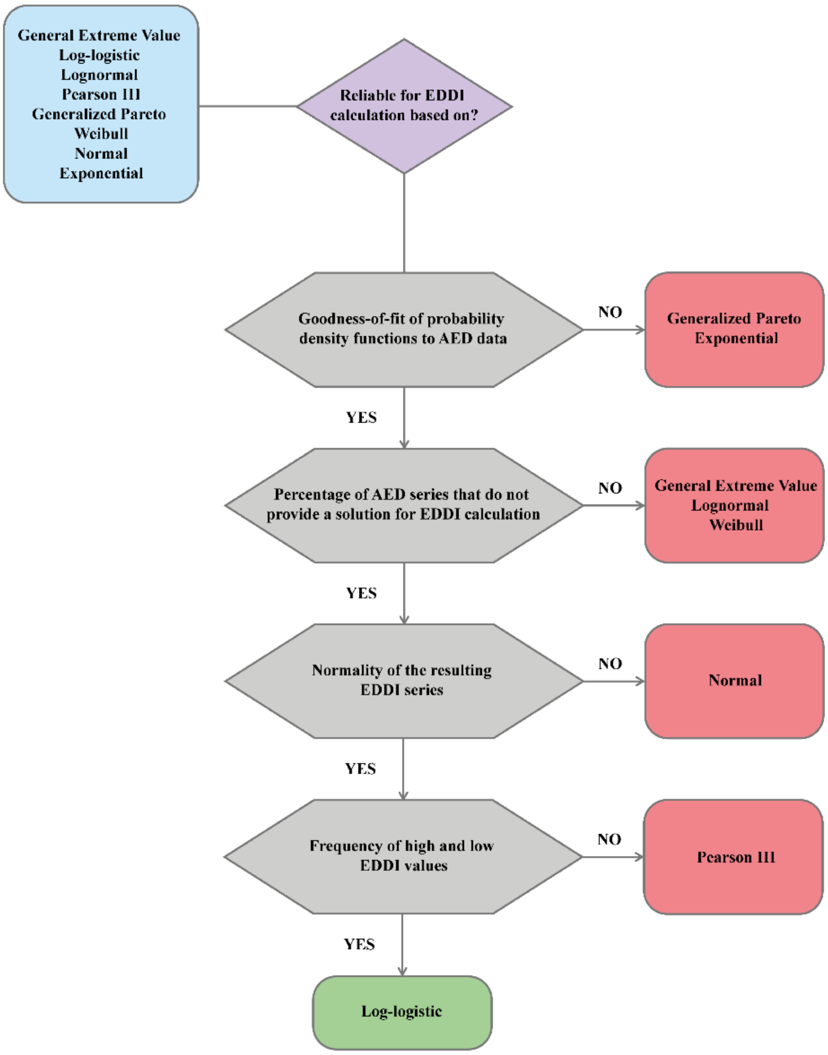

FIGURE 1 Flowchart followed to select the optimal probability distribution to calculate the EDDI [Colour figure can be viewed at wileyonlinelibrary.com]

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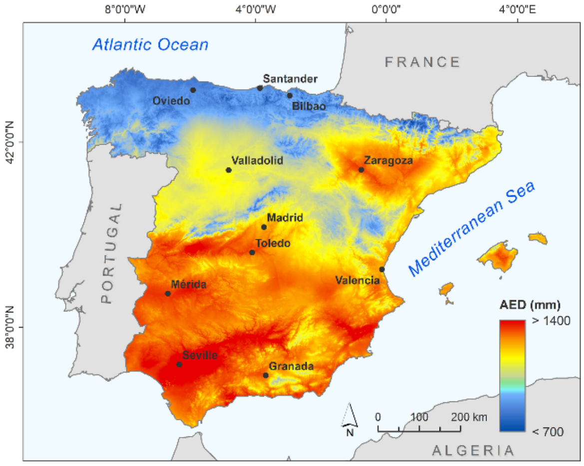

FIGURE 2 Average annual AED (mm) on mainland Spain and the Balearic Islands over the period 1961–2018, and the locations used to compare the parametric and nonparametric formulation of EDDI [Colour figure can be viewed at wileyonlinelibrary.com]

while its influence on the latter, and also under strong land–atmosphere coupling, would trigger or intensify drought conditions (Hobbins *et al.*, 2017; Miralles *et al.*, 2019).

2.2 | Evaluation of different probability distributions for EDDI computation

We tested eight probability distributions to calculate the EDDI, including the three-parameter General Extreme Value, Log-logistic, Lognormal, Pearson III, Generalized Pareto and Weibull distributions, and the two-parameter Normal and Exponential distributions. The probability distributions have been widely tested for different hydroclimatic applications (Hosking, 1990; Rao and Hamed, 2000) and are the most commonly used for scientific and applied purposes (Bobee and Ashkar, 1991; Guttman, 1999; Vicente-Serrano *et al.*, 2010, 2012, 2018; Stagge *et al.*, 2015; Barker *et al.*, 2016). Although some studies suggest using other distributions to calculate standardized drought indices (e.g., the Tweedie distribution; Svensson *et al.*, 2017), our preference was for those more widely used by the scientific community. The cumulative distribution functions of the eight probability distributions tested for EDDI computation are described in the Table 1. More details about the probability distributions are described in depth in Hosking *et al.* (1985), Hosking (1986, 1990), Singh *et al.* (1993), and Rao and Hamed (2000). The parameters of each probability distribution were calculated using unbiased probability weighted moments (UB-PWMs; Hosking, 1990). Each monthly AED series aggregated at different time scales (i.e., 1, 3 and 12 months) over the period 1961–2018 were fitted to each of the eight probability distributions. If the probability distribution proved suitable for fitting monthly AED series, the cumulative probabilities of AED values were calculated and transformed into a normal distribution with a standard deviation equal to 0 and 1 [N(0,1)] to obtain standardized units (i.e., values of EDDI) using the classic approach of Abramowitz and Stegun (1965). The EDDI was calculated for 1-, 3- and 12-month time scales, reversing the index sign (i.e., higher AED results in lower EDDI values).

The flowchart followed to select the optimal probability distribution to calculate the EDDI is presented in Figure 1. We used four approaches to test the suitability of the different distributions:

1. Visual checking of the goodness-of-fit of probability density functions to monthly AED series: for a first evaluation of the suitability of the probability distributions, we examined the fit of the probability density functions of each distribution to the monthly AED series aggregated at 1, 3 and 12 months in locations and seasons with significant climatic contrasts.
2. Determining the percentage of monthly AED series that cannot be fitted by the selected distribution and do not provide a solution for the EDDI: to check the goodness-of-fit of the probability distributions, we fitted the probability density functions of each of the eight distributions to monthly AED series aggregated at 1, 3 and 12 months. Given that the parameters from a specific probability distribution cannot be fitted to the AED data, a solution cannot be found for the EDDI. Also, there are some cases in which the origin parameter of the distribution can be higher than the lowest observed AED value, again providing no solution for the EDDI. In order to evaluate the robustness of the eight probability distributions, we calculated the percentage of monthly series for each probability distribution with no solution for the EDDI.
3. Examining the normality of the resulting EDDI series: to determine the normality of the resulting EDDI series from the probability distributions, we used the Shapiro–Wilks test. A rejection rate of $p < .05$, corresponding to a 95% confidence level, was selected to accept that the EDDI series follows a normal distribution.
4. Analysing the frequency of high and low EDDI values: since distributions model the low and high values, they are very important in assessing the quality of the fit (Vicente-Serrano and Beguería, 2016; Vicente-Serrano *et al.*, 2018). Therefore, we also compared the frequency of low and high EDDI values

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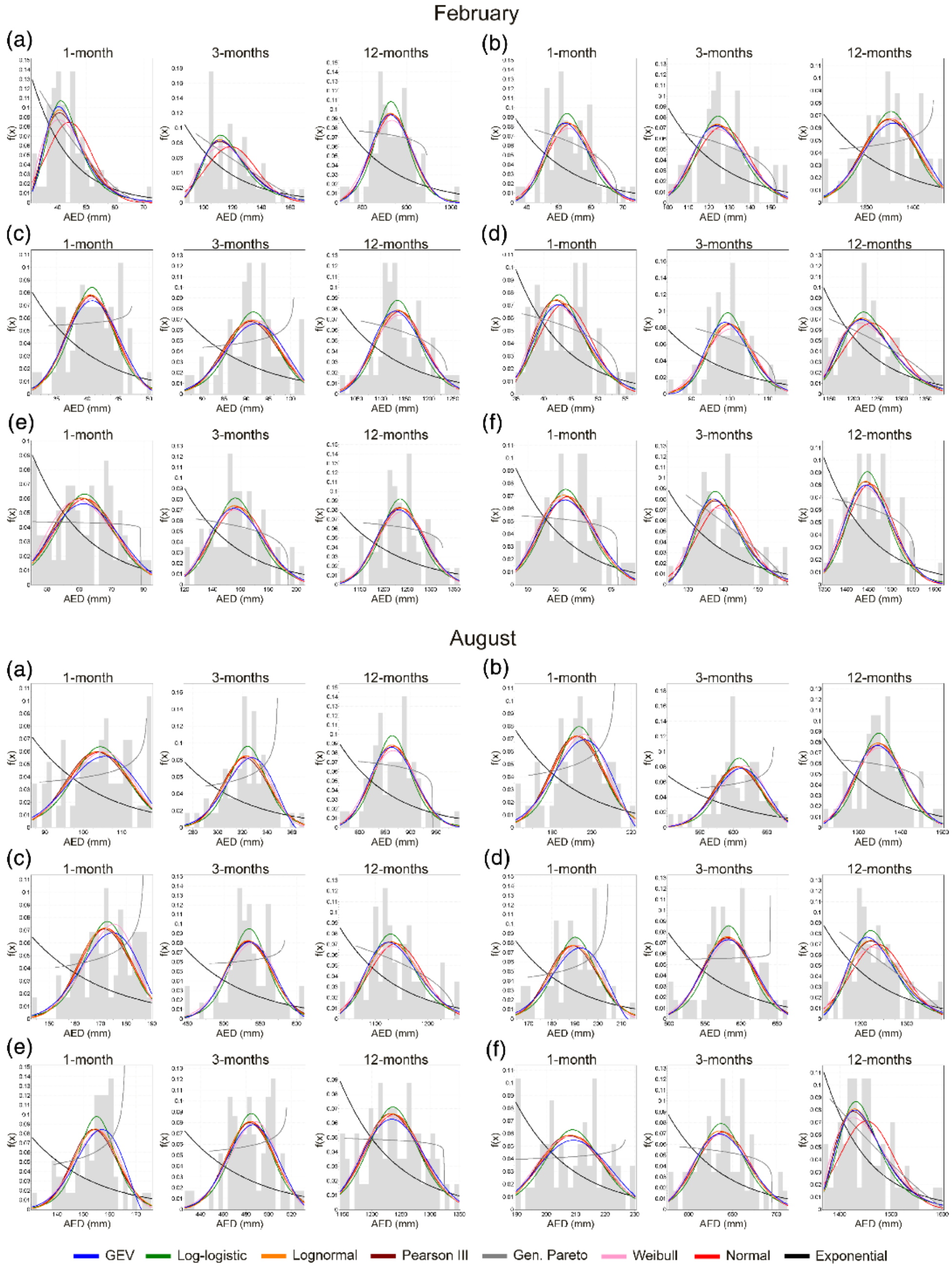

FIGURE 3 February and August AED series from (a) Santander, (b) Zaragoza, (c) Valladolid, (d) Madrid, (e) Valencia and (f) Seville aggregated at 1, 3 and 12 months' time scales, with the eight theoretical distributions that fit the data [Colour figure can be viewed at wileyonlinelibrary.com]

(on 1-, 3- and 12-month time scales) and the associated return period obtained by the most suitable probability distributions. More specifically, we compared the relative frequency of negative extreme EDDI values (threshold of −2.58, corresponding to a return period of 1 in 200 years).

2.3 | Comparison between parametric and nonparametric EDDI formulation

We contrasted the new parametric approach suggested in this study with the original nonparametric formulation proposed by Hobbins *et al.* (2016) for EDDI computation.

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TABLE 2 Percentage of the total monthly series of AED with no fitting solution tested through the eight probability distributions at 1-, 3- and 12-month time scales on mainland Spain and the Balearic Islands

	GEV	Log-logistic	Lognormal	Pearson III	Pareto	Weibull	Normal	Exponential
1 Month								
January	20.40	0	84.69	1.91	99.82	4.57	0	100
February	4.77	0	83.49	0	100	0.87	0	100
March	2.25	0	53.98	0	99.95	7.22	0	100
April	2.89	0	55.41	0	100	5.98	0	100
May	0	0	15.21	0	100	2.35	0	100
June	4.24	0	27.57	0.01	100	9.15	0	100
July	0.82	0	11.56	0	99.99	26.78	0	100
August	0.04	0	9.32	0.09	100	24.9	0	100
September	2.54	0	12.49	0.01	99.86	11.43	0	100
October	2.47	0	62.23	0.14	99.90	2	0	100
November	44.24	0	95.40	11.35	100	18.18	0	100
December	27.21	0	74.43	6.25	100	26.72	0	100
3 Months								
February	14.77	0	64.94	0.47	99.99	5.44	0	100
May	11.69	0	79.50	0	99.90	0.02	0	100
August	9.96	0	40.70	0	100	5.58	0	100
November	9.64	0	40.33	0	99.96	5.09	0	100
12 Months								
December	10.46	0	80.31	0.06	100	2.92	0	100

For this purpose, we compared the EDDI series obtained by both approaches at 1-, 3- and 12-month time scales over the period 1961–2018 in several locations of Spain that represent a wide variety of annual AED values (Figure 2). In order to illustrate some of the advantages of the parametric approach, especially those related to drought characterization and monitoring, we also calculated and compared the EDDI series obtained by both approaches based on a reference period (i.e., 1961–1989) at 1-, 3- and 12-month time scales over the period 1961–2018 as well as during two extreme drought events. The sign of the nonparametric EDDI was also reversed (i.e., higher AED results in lower EDDI values).

3 | RESULTS

3.1 | Evaluation of different probability distributions for EDDI computation

The eight candidate probability distributions for EDDI calculation were evaluated and successively filtered following the four criteria proposed (see Figure 1):

1. Figure 3 presents several examples from the February and August AED series from different locations over Spain aggregated at 1-, 3- and 12-month time scales with the eight theoretical distributions that fit the data. In general, all probability distributions exhibit great flexibility and goodness-of-fit, with the exception of Exponential and Generalized Pareto distributions that, in most cases, do not fit the AED data and are therefore unsuitable for EDDI calculation. As depicted, both the peak and the lower and upper tails of the probability density function of General Extreme Value, Log-logistic, Lognormal, Pearson III, Weibull and Normal distributions are generally well adapted to AED histograms, regardless of the time-scale and climatic conditions. Therefore, and given that these six probability distributions exhibit a similar fit at this stage, it is difficult to determine which distribution is most suitable for EDDI computation.
2. Table 2 shows the percentage of monthly AED series computed at the time scales of 1-, 3- and 12-months with no solution from each of the eight probability distributions tested. As expected, the Generalized Pareto and Exponential distributions exhibited a

TABLE 3 Percentage of the total EDDI series calculated through the remaining three probability distributions (i.e., the Log-logistic, Pearson III and Normal) at 1-, 3- and 12-month time scales on mainland Spain and the Balearic Islands for which the null hypothesis of normality was rejected by the SW test at a confidence level $p < .05$

	Log-logistic	Pearson III	Normal
1 Month			
January	96.09	95.23	85.33
February	93.84	99.43	93.35
March	85.98	99.32	94.01
April	99.99	99.90	99.22
May	98.60	100	98.92
June	99.42	99.90	99.89
July	99.87	97.40	87.73
August	99.36	98.30	95.94
September	99.49	99.62	82.81
October	95.69	99.24	97.16
November	99.67	82.85	63.01
December	99.26	81.94	63.73
3 Months			
February	98.96	97.98	90.94
May	94.85	99.79	99.39
August	99.68	95.48	83.33
November	99.95	99.89	94.92
12 Months			
December	99.76	99.33	87.92

percentage of series with no solution for the EDDI close to 100% in all months and time scales, so they were rejected for EDDI calculation. The Weibull, Log-normal and General Extreme Value (GEV) distributions also showed high percentages of monthly series with no solution at 1-, 3- and 12-month time scales, so they were also discarded as unreliable alternatives for calculating the EDDI. Thus, further evaluations were based on only the three distributions that exhibited a low percentage of monthly AED series with no fitting solution (i.e., the Log-logistic, Pearson III and Normal distributions) to EDDI computation at 1-, 3- and 12-month time scales.

3. Table 3 depicts the percentage of monthly EDDI series obtained at 1-, 3- and 12-month time scales from the three remaining probability distributions (Log-logistic, Pearson III and Normal) that follow a normal distribution according to the Shapiro–Wilks normality test (95% confidence level). The Log-logistic and Pearson III distributions were the highest overall, with values that commonly exceeded 95% at 1-, 3- and 12-month time scales. The normal distribution exhibited the highest percentage of series in which the normality of the series is rejected, especially in November and December at short time scales.

   Figure 4 shows the spatial distribution of monthly EDDI series calculated through Log-logistic, Pearson III and Normal for which the null hypothesis of normality was rejected over mainland Spain and the Balearic Islands. The EDDI calculated by the Log-logistic returned series that follow a normal standard distribution for almost all months and time scales over the whole of Spain. Similarly, the EDDI series obtained by Pearson III distribution followed a normal distribution in most of the study area at 1-, 3- and 12-month time scales. In addition, Log-logistic and Pearson III did not reveal any spatial biases. On the contrary, the normal distribution showed wide areas in which the null hypothesis of normality was rejected, especially in November and January at the 1-month time scale, but also in central regions in July and September. Likewise, there are wide areas of the northwest in August at 3-month and southwest at 12-month time scales in which the series do not follow a normal distribution. Therefore, only Log-logistic and Pearson III distributions were used for further assessment.
4. Figure 5 shows the percentage of the total monthly EDDI series which returned values of less than −2.58 (corresponding to a return period of 1 in 200 years) for Log-logistic and Pearson III distributions at 1-, 3- and 12-month time scales. Given the available length of the AED series (1961–2018), it was expected that these extreme values would be infrequent. Nevertheless, the Pearson III distribution provided a large percentage of series with extreme values, which unrealistically overestimates the frequency of these extreme drought events in comparison with a more coherent frequency provided by the Log-logistic distribution. The spatial distribution of these extreme values showed wide variability at 1-, 3- and 12-month time scales (Figure 6). In general, the Log-logistic distribution displayed a low frequency of extreme negative values in all months and across the whole study area, regardless of the time scale. On the contrary, the Pearson III distribution provided a high number of extreme negative values in several months at 1-, 3- and 12-month time scales. For example, in December and July EDDI series at the 1-month time scale showed cases below −2.58 across most of the study area. Likewise, large parts of the study area exhibited EDDI series with cases below −2.58 in February and November at the 3-month time scale, and also at the 12-month time scale in western regions. This demonstrates that the Pearson III distribution generally

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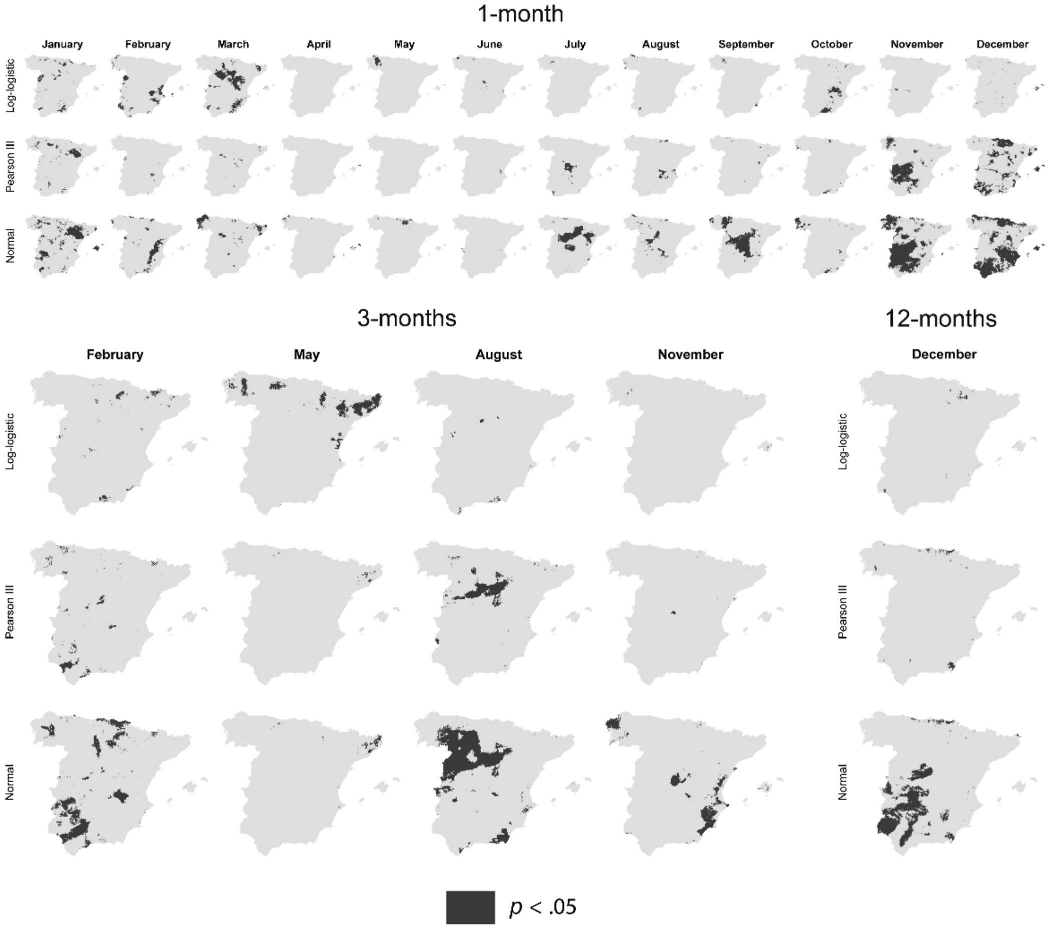

FIGURE 4 Spatial distribution of monthly EDDI series calculated through the Log-logistic, Pearson III and Normal at 1-, 3- and 12-month time scales for which the null hypothesis of normality was rejected by the SW test at a confidence level $p < .05$ on mainland Spain and the Balearic Islands over the period 1961–2018

provides an unrealistic frequency of extreme EDDI values.

Figure 7 illustrates the relationship between EDDI values at 1-, 3- and 12-month time scales and the associated return periods obtained by the Log-logistic and Pearson III distributions. The EDDI values obtained by both distributions at different time scales showed a high degree of consistency over a wide range ($\pm 1.80\sigma$) in which the Log-logistic and Pearson III distribution provided similar values. However, there are notable differences in the lower and upper tails of distributions, corresponding to the extreme EDDI values. As depicted, the Pearson III distribution exhibited more extreme negative and positive EDDI values than the Log-logistic across all time scales, but especially at short time scales. Consequently, the associated return periods obtained through the Pearson III distribution are higher than for the Log-logistic, regardless of time scale. It was noted that Pearson III resulted in some cases in return period of 1 in 500 years for EDDI values, which reported periods shorter than 1 in 100 years with the Log-logistic distribution. Therefore, the Pearson III distribution was rejected in favour of the Log-logistic distribution, which provides much more coherent extreme values and associated return periods for EDDI computation.

3.2 | Comparison between parametric and nonparametric EDDI formulation

The parametric approach providing the best performance for EDDI computation (i.e., the Log-logistic distribution) was contrasted with the original nonparametric approach (i.e., that of Hobbins *et al.* (2016)) at a variety of time scales and climatic conditions. For several locations in

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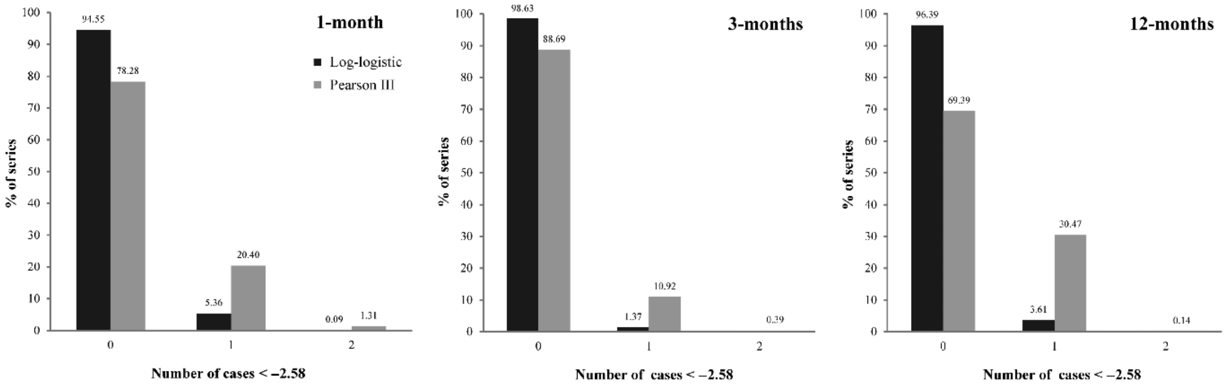

FIGURE 5 Percentage of the total monthly EDDI series with cases below −2.58 (return period of 1 in 200 years) at 1- (all months), 3- (February, May, August and November) and 12-month (December) time scales on mainland Spain and the Balearic Islands

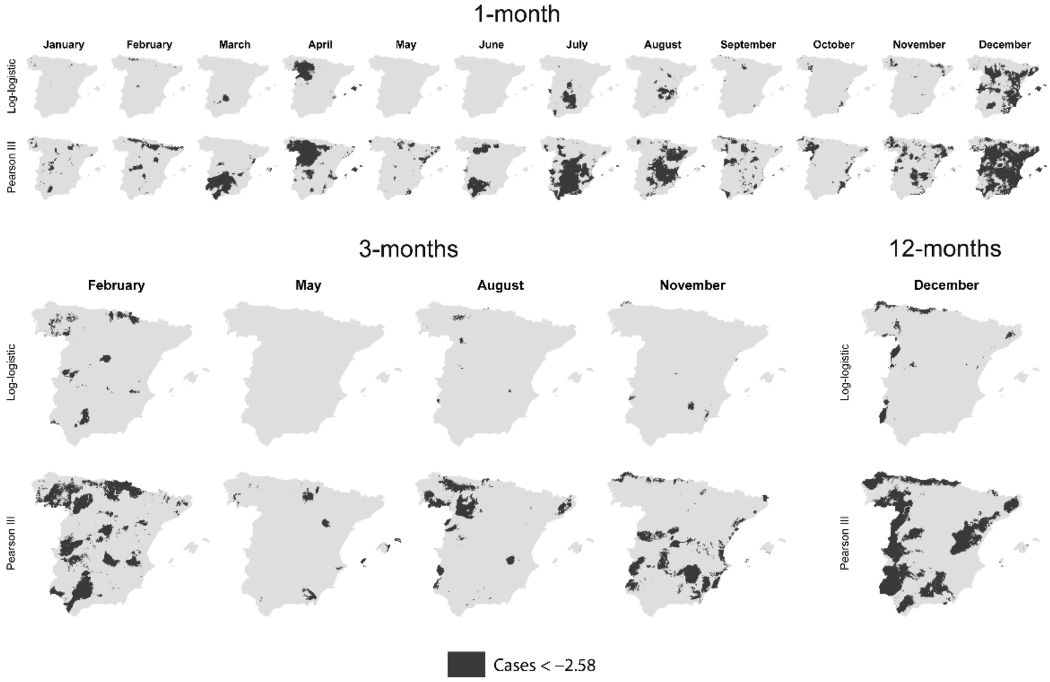

FIGURE 6 Spatial distribution of monthly EDDI series with cases below −2.58 (return period of 1 in 200 years) at 1-, 3- and 12-month time scales on mainland Spain and the Balearic Islands over the period 1961–2018

Spain, the EDDI was estimated using both approaches at 1-, 3-, and 12-month time scales and using two different reference periods: a 29-year period from 1961 to 1989 and the full 58-year period of record from 1961 to 2018. In general, both approaches exhibited a robust performance to model EDDI values when the index was calculated retrospectively for long-term periods regardless of time scale and climatic conditions (Figure 8). Only in few cases (i.e., very extreme dry/wet episodes) did the nonparametric approach show limitations in modelling extreme EDDI values when the entire period (1961–2018) was used to calculate the index. However, when the shorter reference period (1961–1989) is used to compute the EDDI, a common practice in operational drought monitoring, the nonparametric approach cannot model the extreme values at different time scales if the new values exceed the maximum or minimum value of the reference climatology (Figure 9). As depicted, the limitations of a nonparametric approach to modelling extreme EDDI values are frequent and easily recognized during dry/wet

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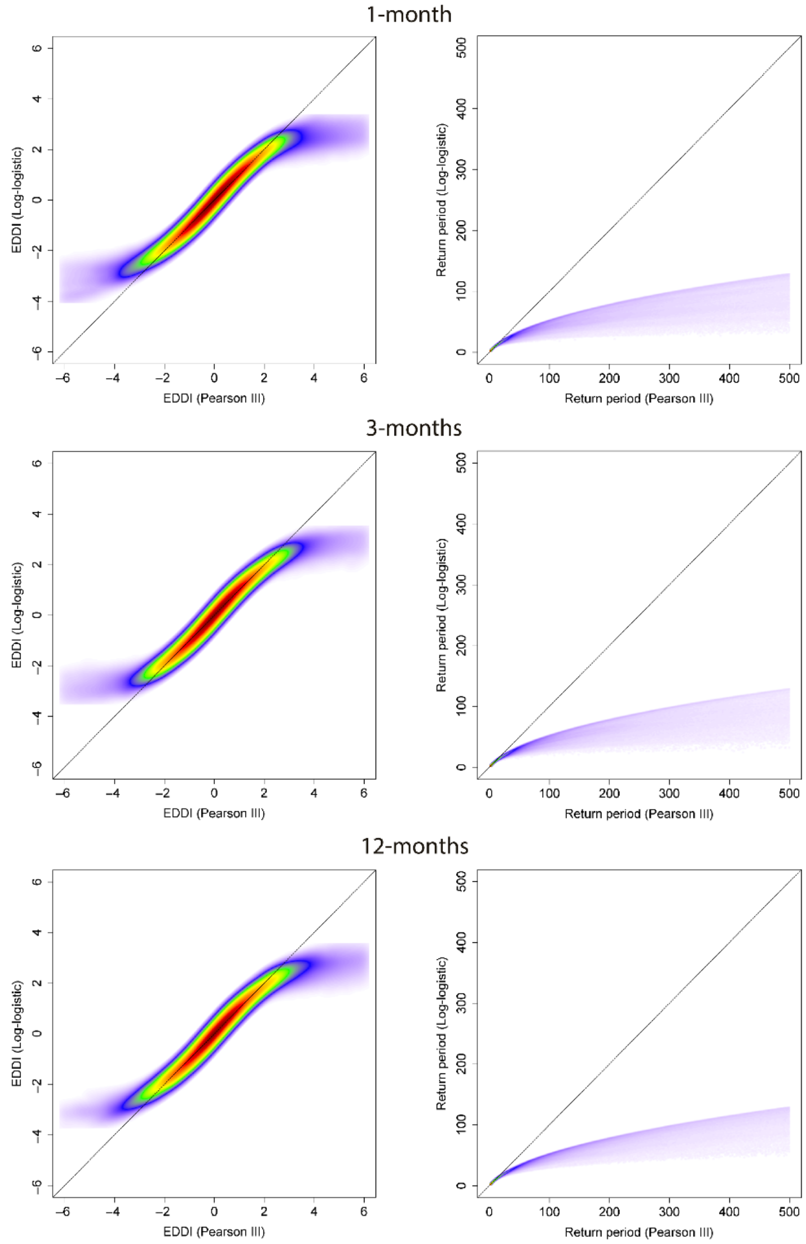
FIGURE 7 Relationship between EDDI values and the associated return periods calculated with Log-logistic and Pearson III distribution at 1-, 3- and 12-month time scales. The colours represent the point density, with the highest density shown in red [Colour figure can be viewed at wileyonlinelibrary.com]



periods at different time scales and climatic conditions, but especially at long time scales as evidenced in Madrid (Figure 9d) or Seville (Figure 9f). This issue of nonparametric approaches to modelling EDDI values at long time scales is very common during drought episodes in central and southern Spain (Figure 10), since these areas generally show a positive trend in AED and the periods characterized by strong increases in AED were recurrent over the last two decades. In contrast, the parametric approach based on Log-logistic distribution shows well-modelled extreme EDDI values, even if the new values are outside of the reference climatology, regardless of time scale and climatic conditions (Figure 9). Likewise, this approach reported a robust performance with series that show a trend or high frequency of extreme drought episodes (Figure 10).

To illustrate the relevance of this issue in detail, we compared the EDDI series obtained through parametric and nonparametric approaches based on the 29-year reference period (i.e., 1961–1989) at 12-month time scales in several locations during two extreme drought episodes in 1990 and 2017 (Figure 11). During these periods characterized by severe drought conditions affecting large areas of northern (Figure 11a), central, and southern

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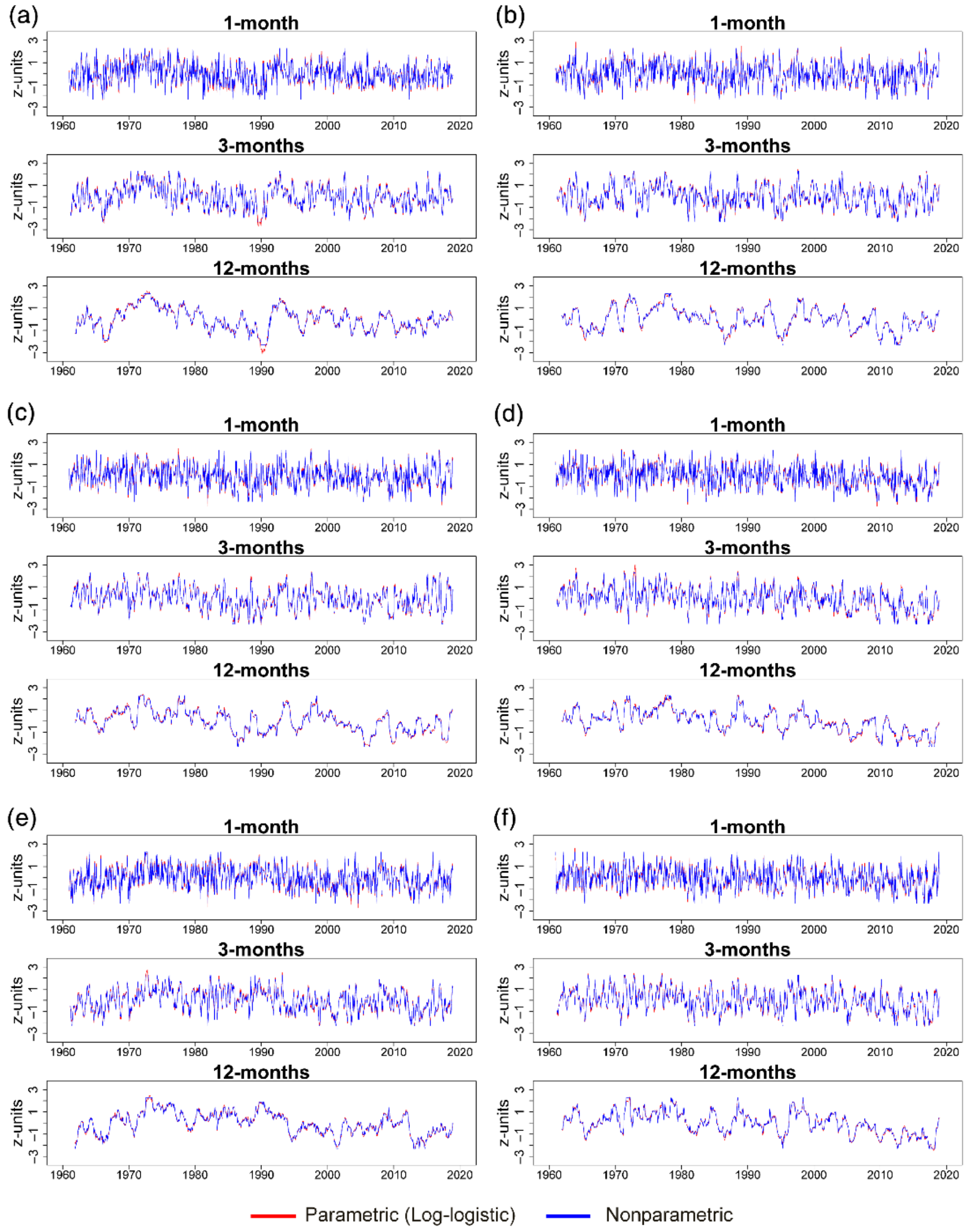

FIGURE 8 EDDI series from (a) Santander, (b) Zaragoza, (c) Valladolid, (d) Madrid, (e) Valencia and (f) Seville at 1-, 3- and 12-month time scales computed through a parametric and a nonparametric approach based on the entire period available (1961–2018) [Colour figure can be viewed at wileyonlinelibrary.com]

Spain (Figure 11b) and lasting for approximately 1 year, the nonparametric approach cannot adequately model EDDI values because these anomalous AED values are outside the climatology used as a reference to compute the index. On the other hand, the parametric approach based on Log-logistic provides very relevant information on the severity and intensity of the drought events, making it possible to accurately identify how the drought conditions developed over time and space. Thus, for example, it can be seen how the drought of 1990 reached its maximum intensity in summer (Figure 11a) or how the drought of the 2017 progressed in intensity from the central (i.e., Madrid) to the southern regions of Spain (i.e., Mérida and Seville) over the period (Figure 11b).

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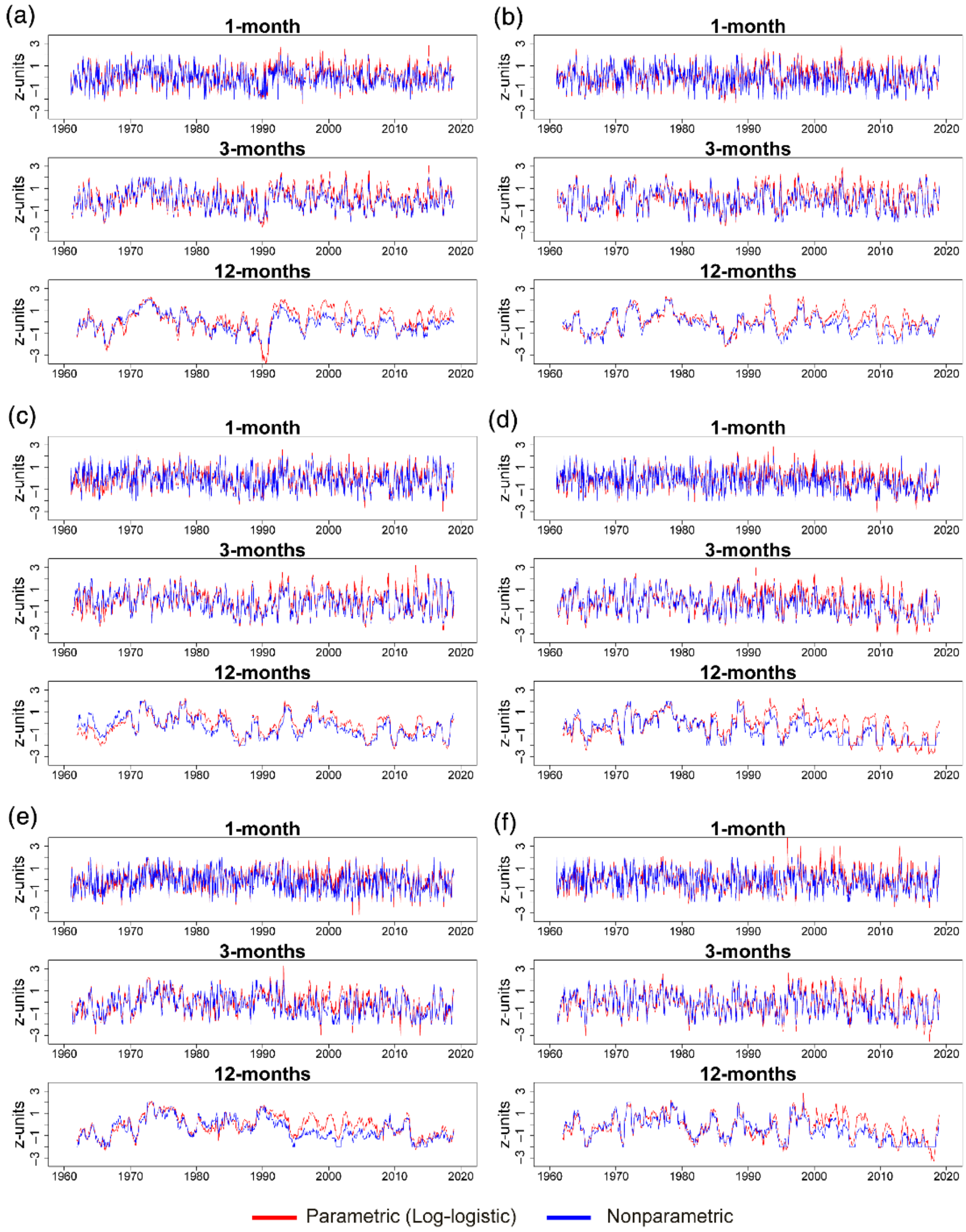

FIGURE 9 EDDI series from (a) Santander, (b) Zaragoza, (c) Valladolid, (d) Madrid, (e) Valencia and (f) Seville at 1-, 3- and 12-month time scales computed through a parametric and a nonparametric approach based on a reference period (1961–1989) [Colour figure can be viewed at wileyonlinelibrary.com]

4 | CONCLUSIONS

This study assessed the suitability of eight parametric distributions of probability to calculate the Evaporative Demand Drought Index (EDDI). This was tested in mainland Spain and the Balearic Islands over the period 1961–2018. The majority of the tested probability distributions had no fitting solution to calculate the EDDI and were rejected. From the eight probability distributions tested, only the Log-logistic, Pearson III, and Normal provided solutions for EDDI calculation over most of the study area at 1-, 3- and 12-month time scales. However, the normal distribution was also discarded because it exhibited a high percentage of EDDI series that did not follow a normal distribution relative to the Pearson III and Log-logistic distributions. Finally, the Pearson III

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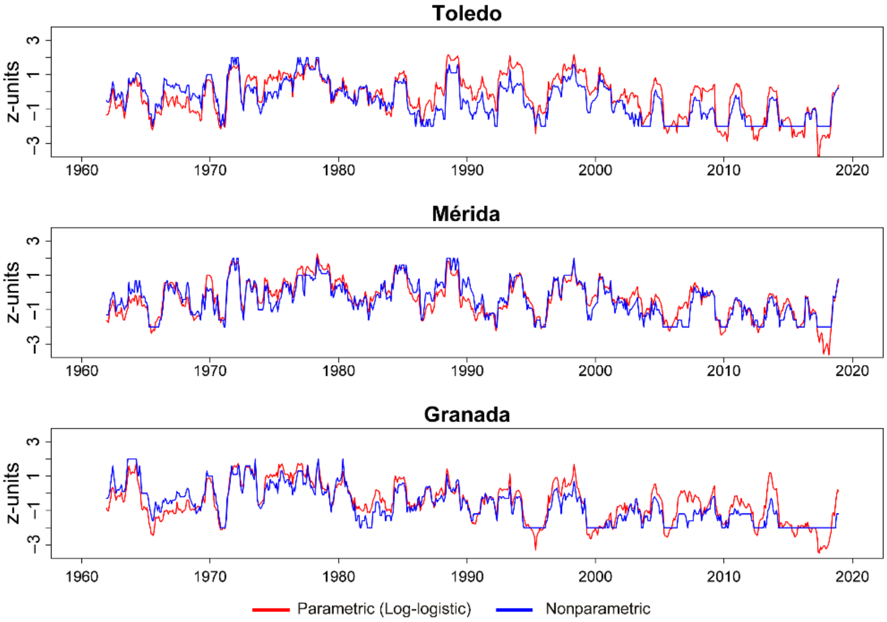

FIGURE 10 EDDI series from Toledo, Mérida and Granada at 12-month time scale over the period 1961–2018, computed through a parametric and a nonparametric approach based on a reference period (1961–1989) [Colour figure can be viewed at wileyonlinelibrary.com]

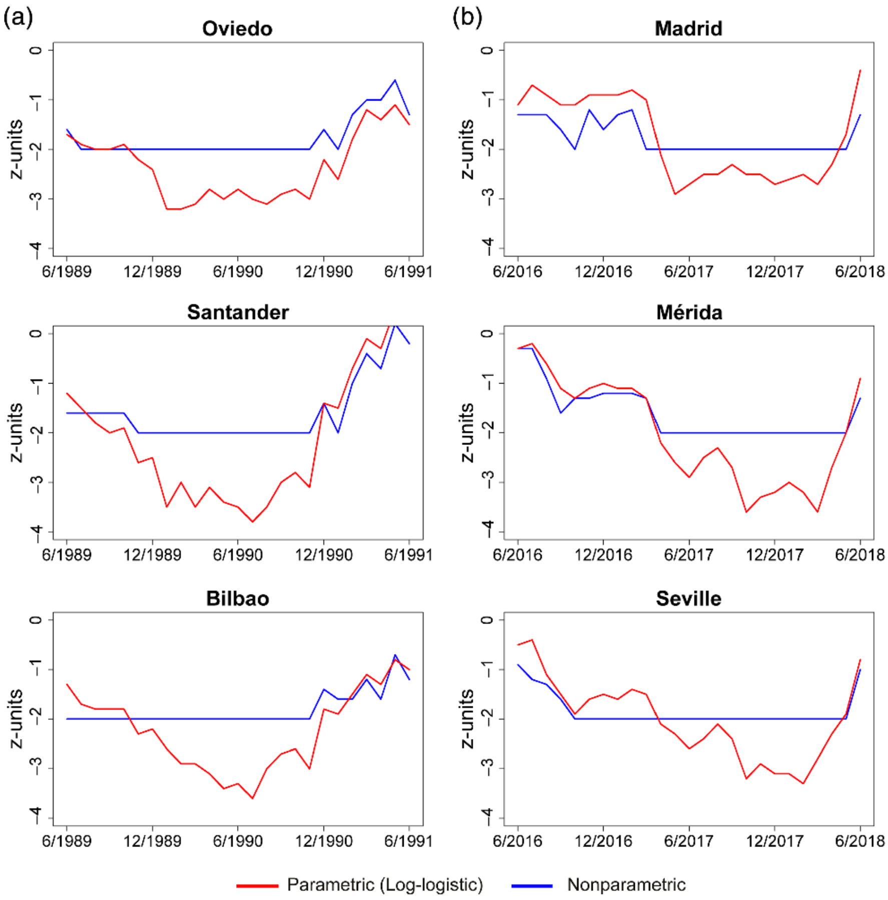

FIGURE 11 EDDI series during drought events of (a) 1990 (Oviedo, Santander and Bilbao) and (b) 2017 (Madrid, Mérida and Seville) at 12-month time scale, computed through a parametric and a nonparametric approach based on a reference period (1961–1989) [Colour figure can be viewed at wileyonlinelibrary.com]

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distribution was also discarded because it yielded a higher frequency of positive and negative extreme values and longer return periods than Log-logistic distribution, regardless of the time scale analysed. Therefore, we conclude that the Log-logistic is the most suitable and robust probability distribution for EDDI computation using a parametric approach.

The parametric approach based on Log-logistic distribution proposed in this study also performed better when compared to the original nonparametric approach, which is heavily constrained by the length of the series since the distribution is bound by the highest and lowest observational values, which limits the modelling of new values more extreme than that observed in the reference climatology. Thus, the original nonparametric approach showed very similar values to the parametric approach based on Log-logistic distribution when the index is computed retrospectively and long-term periods are available, but it exhibited notable limitations in modelling new EDDI values when the index calculations are based on a previous reference period. This demonstrates the issues of adopting a nonparametric approach to modelling the extreme values of EDDI, especially if long-term series are not available. In contrast, the parametric approach based on Log-logistic distribution modelled extreme EDDI values very well, even when using a reference period, as it can model the new values outside the reference climatology, providing an important advantage for drought analysis and monitoring.

Therefore, based on the results obtained in this study, we recommend the use of Log-logistic distribution to calculate the Evaporative Demand Drought Index (EDDI). This distribution proved to be the best fit to AED series for EDDI calculation and provided robust results, regardless of the time scale and climate region. Likewise, Log-logistic distribution also returned a better performance compared to the original nonparametric formulation for EDDI computation, since this parametric approach is less limited by the length of the climatology. The Log-logistic distribution has already been recommended for calculating other drought indices such as SPEI (Vicente-Serrano *et al.*, 2010; Vicente-Serrano and Beguería, 2016) and SEDI (Vicente-Serrano *et al.*, 2018) worldwide. Our study focused exclusively on Spain, but given the wide range of climatic conditions characteristic of the country and the absence of spatial bias in fitting AED series, we consider that the results seen here may be representative for other regions; we therefore also recommend the Log-logistic distribution for calculating the EDDI in other areas of the world. In summary, this study provided a robust parametric approach for EDDI computation, indicating that this standardized drought index can be optimally implemented in drought analysis and monitoring. The code used to calculate EDDI based on the Log-logistic distribution in the R programming language is available on (https://github.com/ivannoguera/EDDI-Log-logistic).

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AUTHOR CONTRIBUTIONS

Iván Noguera: Conceptualization; data curation; formal analysis; funding acquisition; investigation; methodology; resources; software; validation; visualization; writing-original draft; writing-review & editing. **Sergio M. Vicente-Serrano:** Conceptualization; data curation; funding acquisition; investigation; methodology; project administration; resources; supervision; validation; visualization; writing-original draft; writing-review & editing. **Fernando Dominguez-Castro:** Conceptualization; data curation; funding acquisition; investigation; methodology; project administration; resources; supervision; validation; visualization; writing-original draft; writing-review & editing. **Fergus Reig:** Data curation; resources; software; writing-original draft; writing-review & editing.

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Annex 2

Supporting information

1. Supporting information for Chapter 2

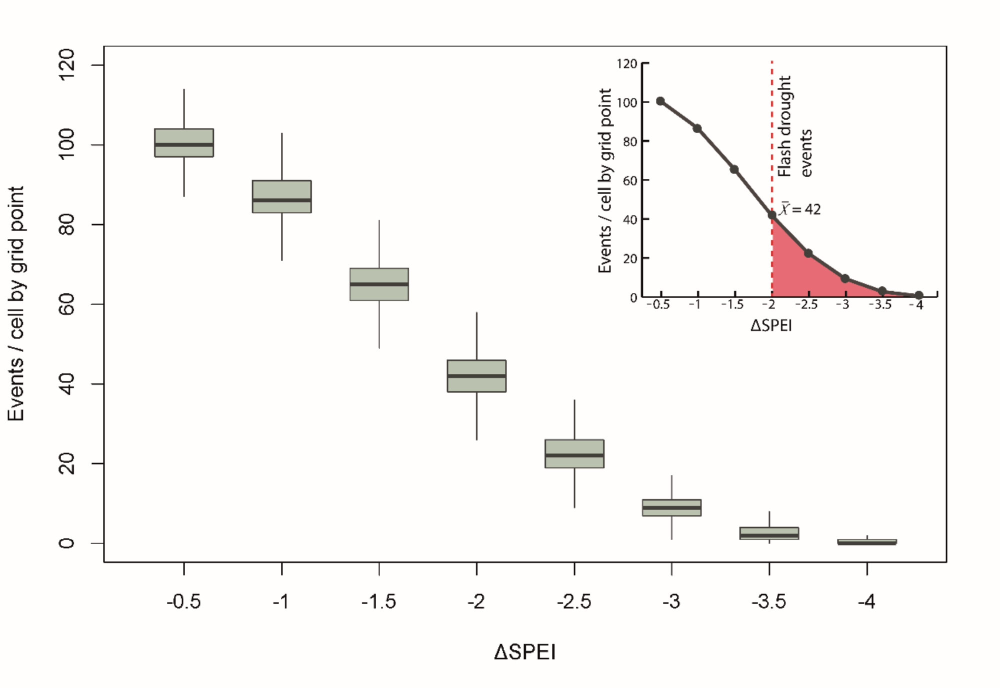

Figure S1. Flash drought events/cell by grid point recorded based on various ΔSPEI thresholds.

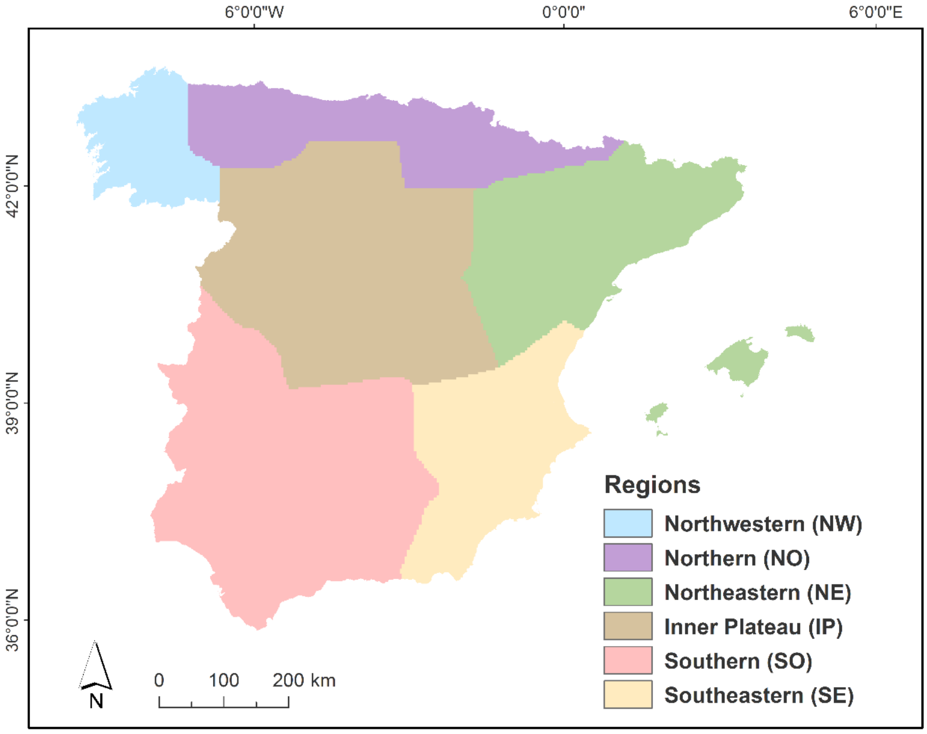

Figure S2. Regional classification of mainland Spain and the Balearic Islands based on the temporal evolution of droughts at a 1-month time scale (based on Vicente-Serrano, 2006a).

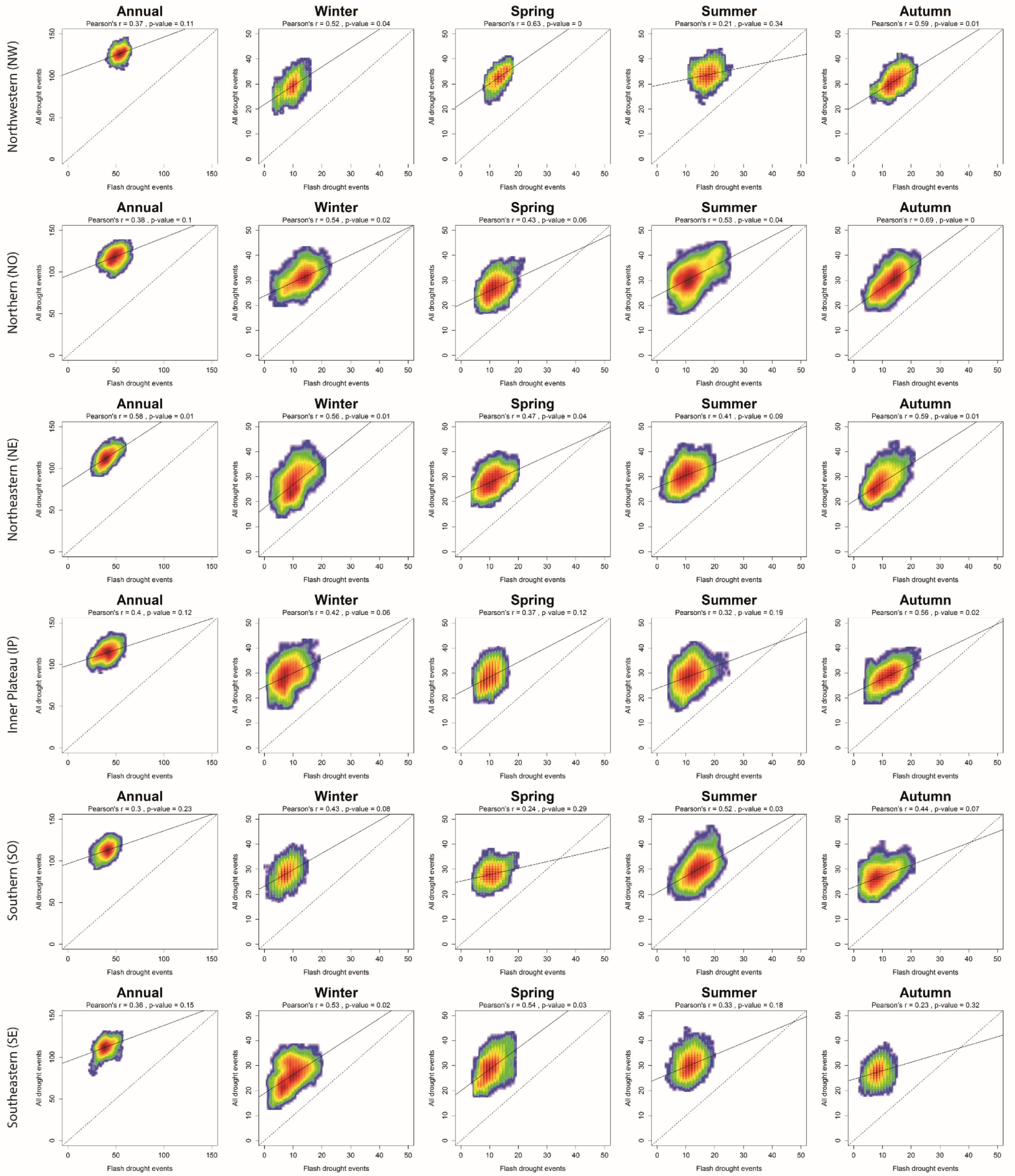

Figure S3. Scatterplots showing the annual and seasonal relationship between the absolute frequency of flash droughts and all drought events in the various homogeneous drought regions during the period 1961–2018.

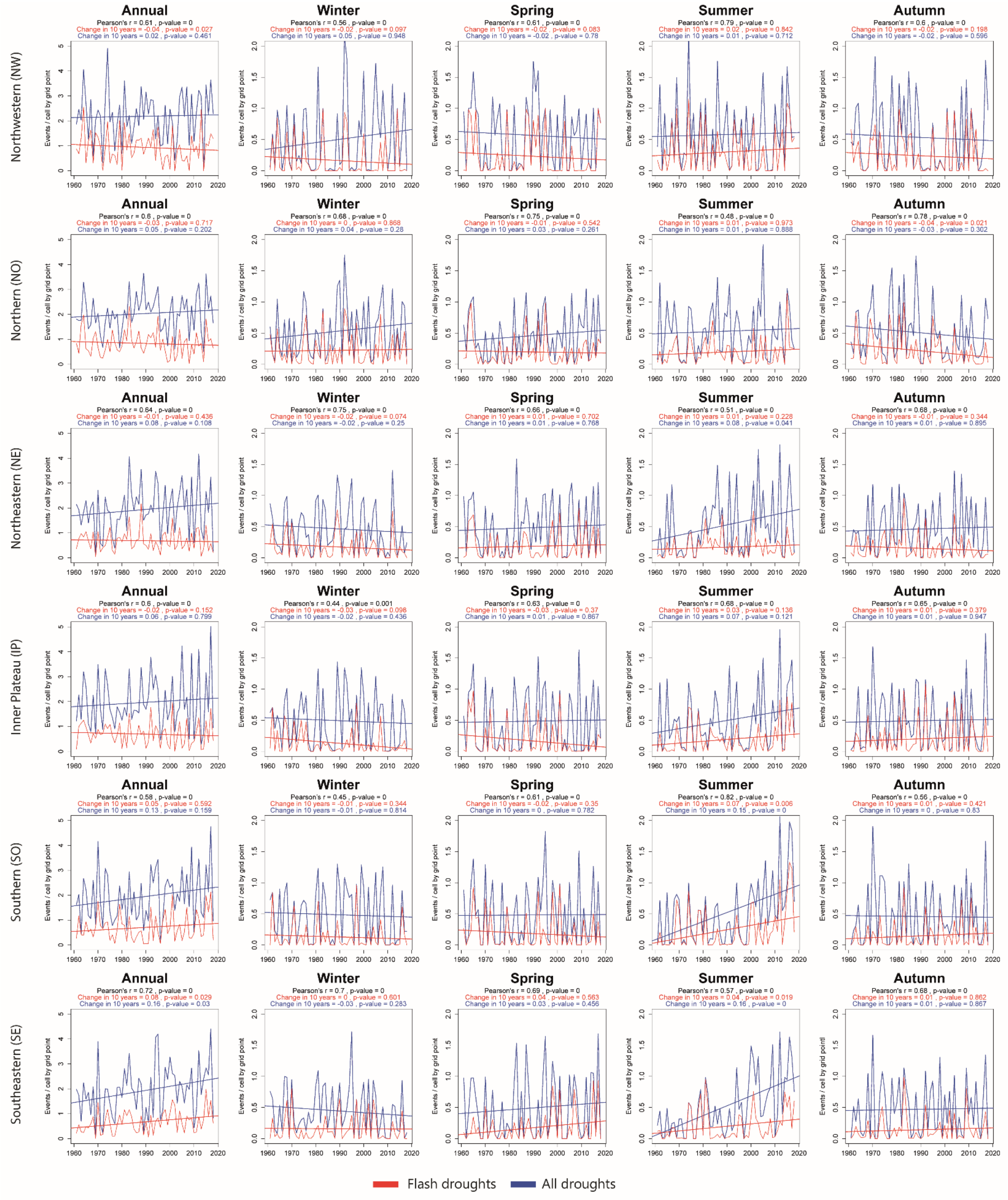

Figure S4. Temporal evolution of the average annual and seasonal frequency of flash droughts and all drought events in the various drought regions.

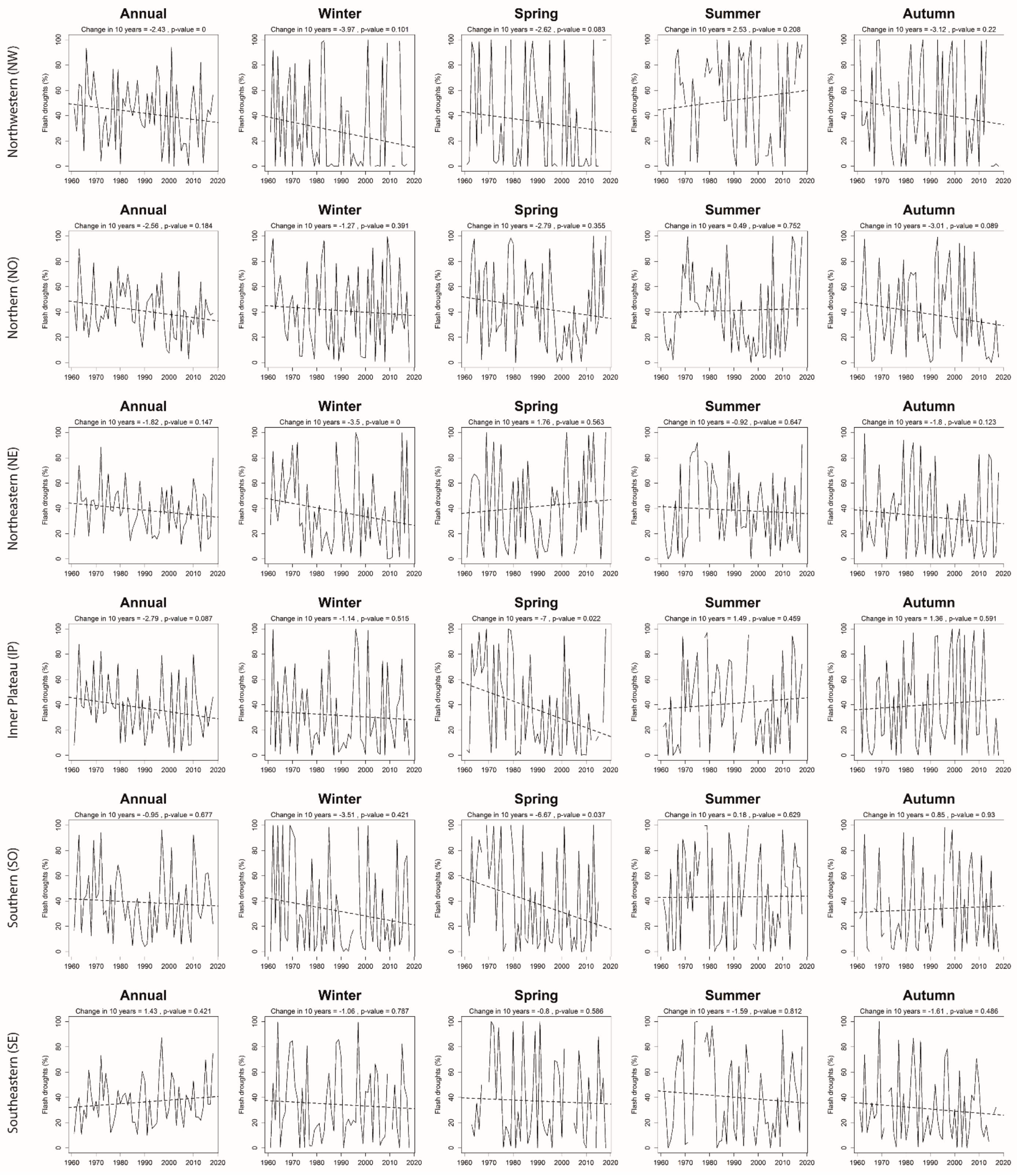

Figure S5. Temporal evolution of the annual and seasonal percentage of flash droughts relative to all droughts in the various homogeneous drought regions during the period 1961–2018, where the years having no records correspond to those in which no drought events were recorded.

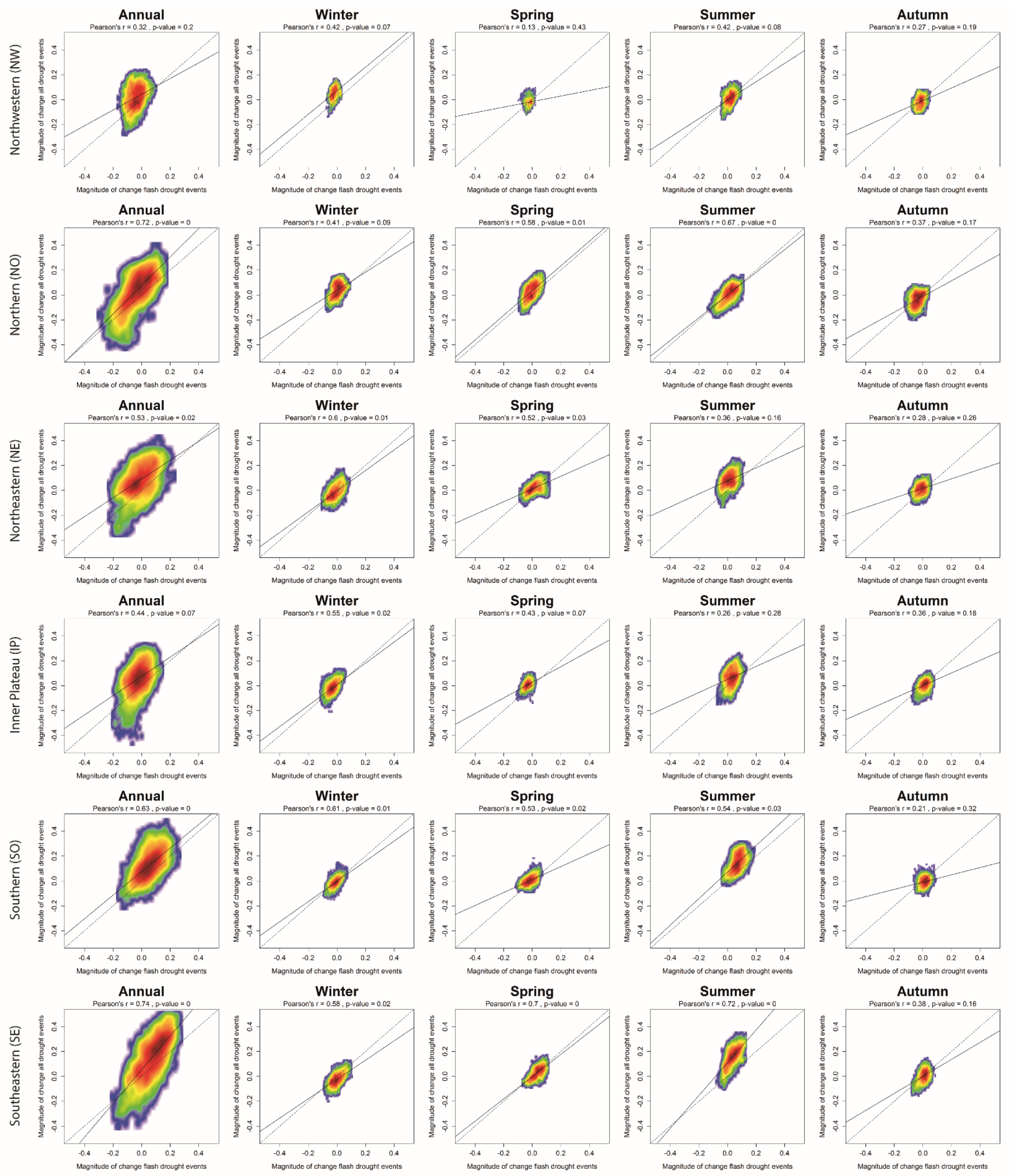

Figure S6. Scatterplots showing the annual and seasonal relationship between the magnitude of change per decade in flash droughts and all drought events in the various homogeneous drought regions during the period 1961–2018.

2. Supporting information for Chapter 3

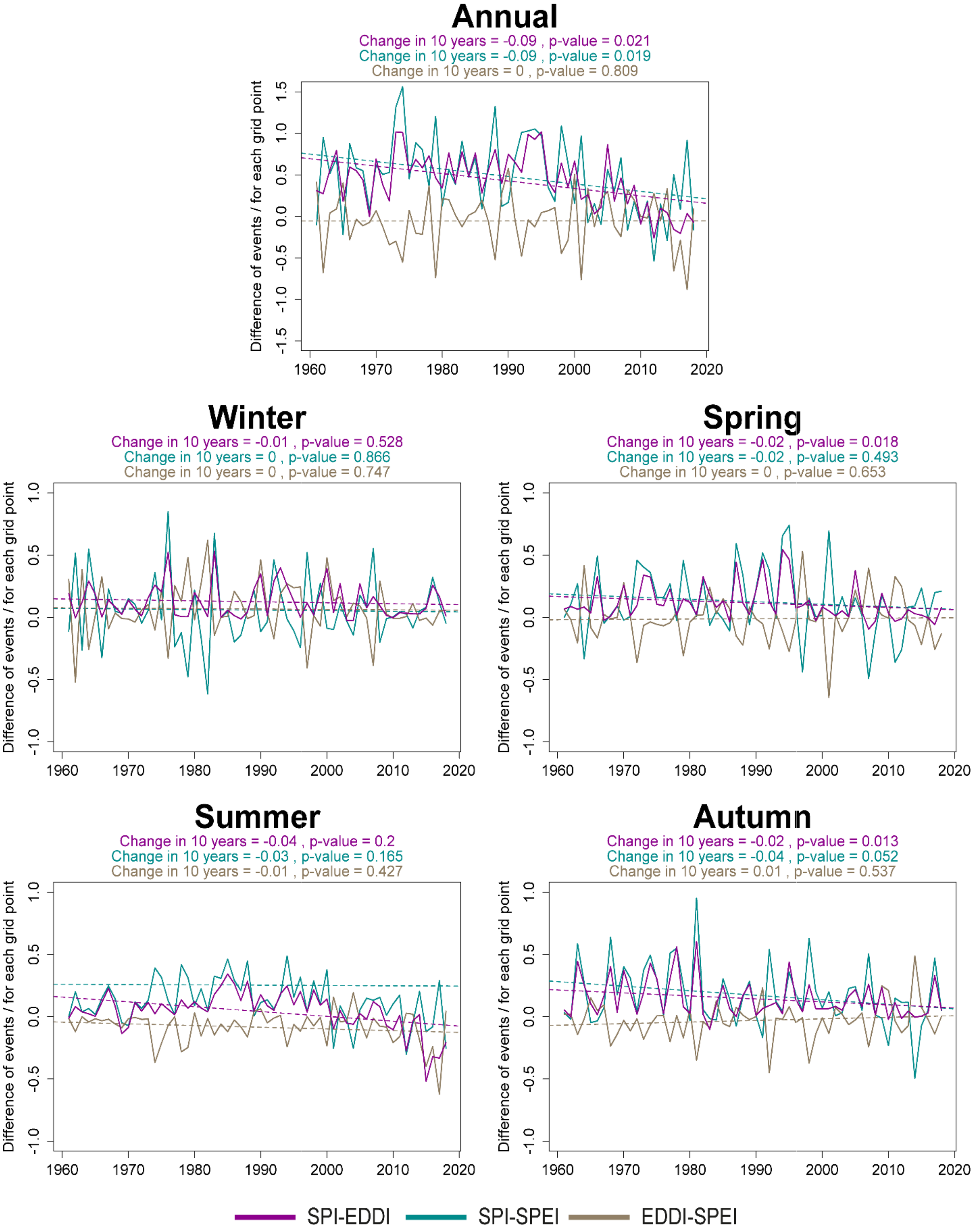

Figure S1. Temporal evolution of the annual and seasonal differences (events/for each grid point) between the flash drought series recorded by the SPI, EDDI and SPEI on mainland Spain and the Balearic Islands over the period 1961–2018.

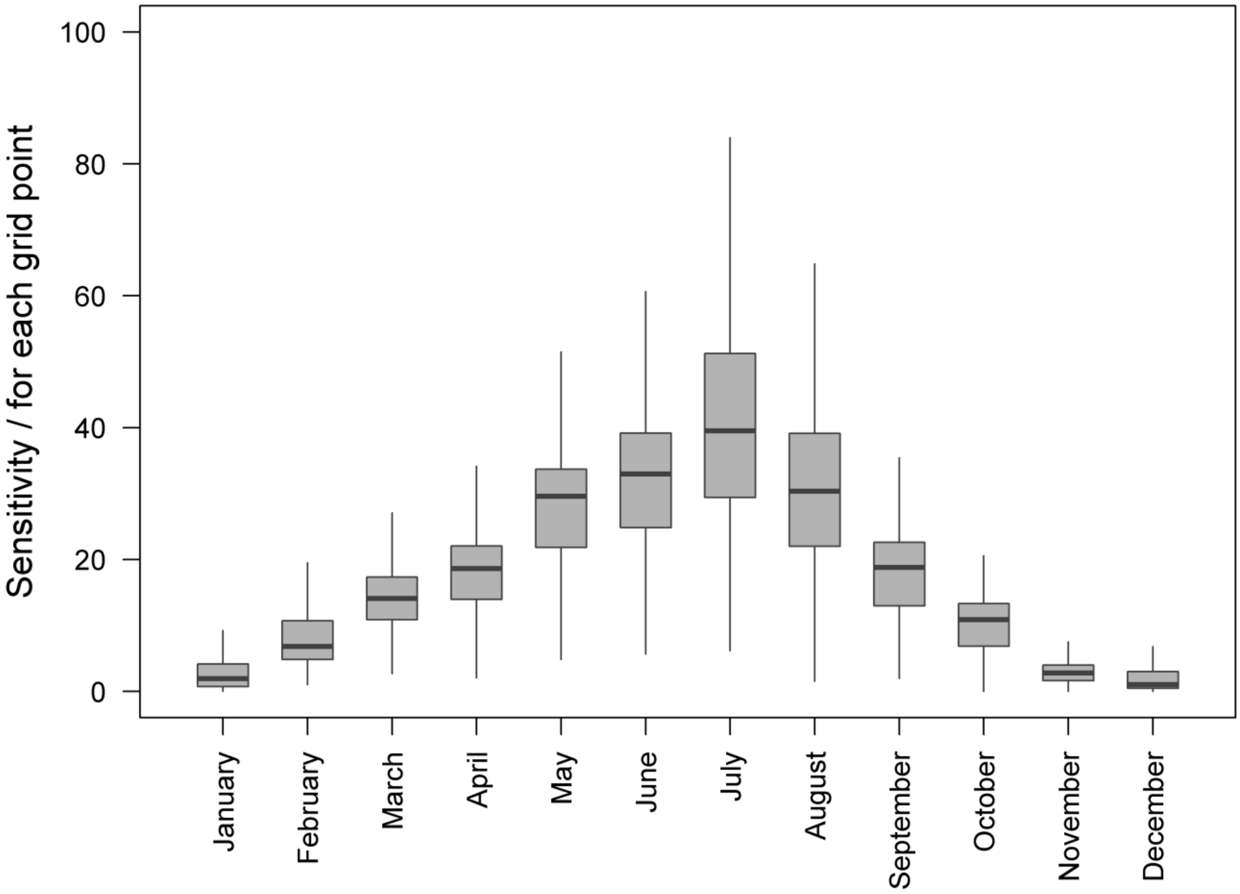

Figure S2. Monthly frequency of the sensitivity (%) of the SPEI to AED on mainland Spain and the Balearic Islands over the period 1961-2018 at a short time scale (1-month). The monthly series include the weekly data for the last week of each month in each year.

3. Supporting information for Chapter 4

AED contribution (%)	Winter		Spring		Summer		Autumn	
	Change	**p-value**	**Change**	**p-value**	**Change**	**p-value**	**Change**	**p-value**
0	-2.22	0.38	-4.21	0.04	-4.41	0	-7.10	0
≥1	2.22	0.38	4.21	0.04	4.41	0	7.10	0
>10	1.59	0.81	2.90	0.25	5.14	0.09	4.22	0.13
>20	0.20	0.54	3.01	0.19	5.40	0.18	3.11	0.16
>30	-0.02	0.46	1.76	0.16	5.25	0.27	1.33	0.24
>40	0.10	0.79	0.86	0.15	4.52	0.28	1.05	0.07
>50	-0.04	0.72	0.51	0.25	3.66	0.33	0.52	0.07

Table S1. Magnitude of change (per decade) and significance of the percentage of flash droughts taking into account different AED contributions to the occurrence of flash droughts in mainland Spain and the Balearic Islands over the period 1961-2018.

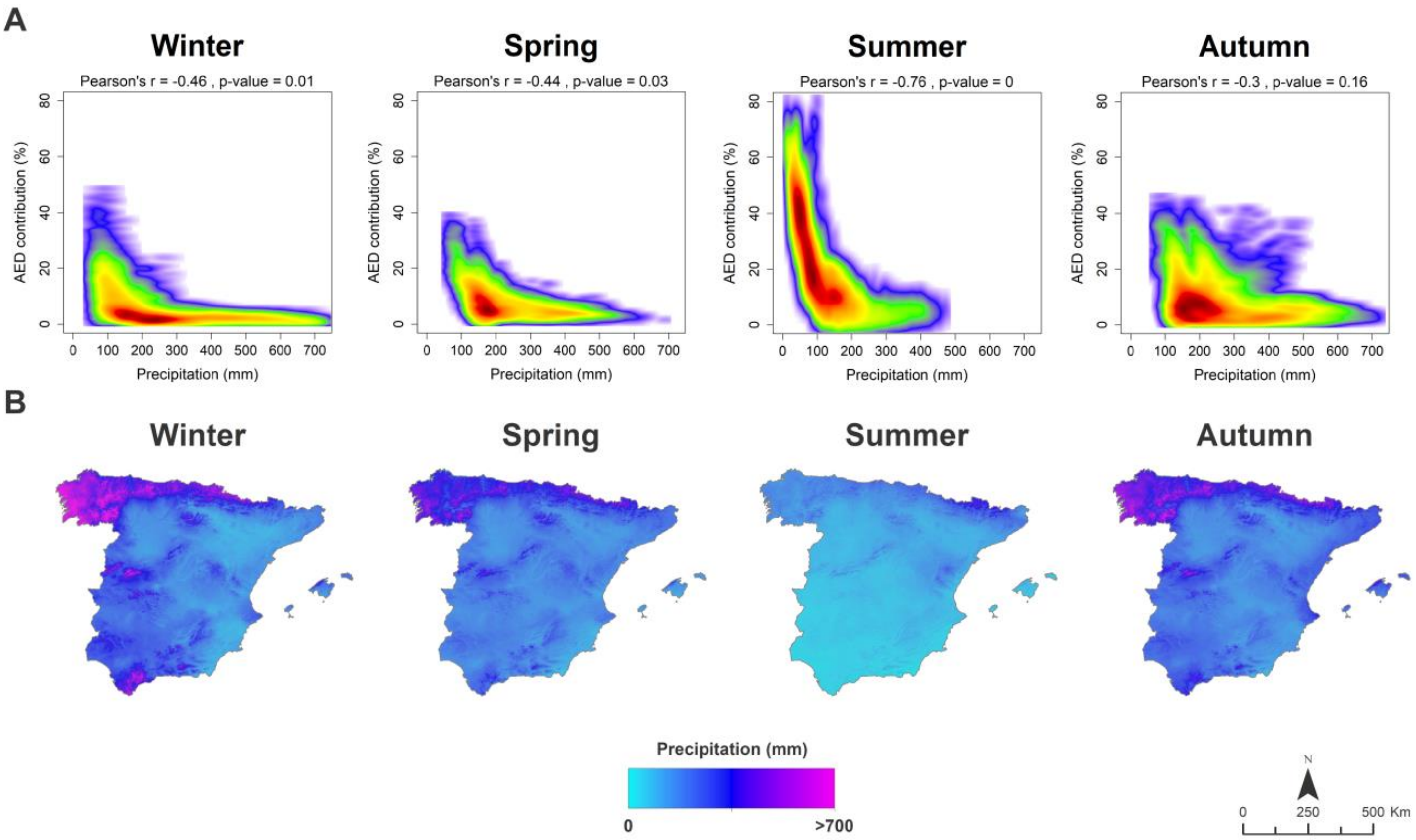

Figure S1. (A) Relationship between seasonal average precipitation and AED contribution. The colors represent the density of points, with red denoting the highest density. The significance of Pearson's r coefficients was estimated using Monte Carlo approach based on 1000 random samples of 30 points. (B) Spatial distribution of seasonal mean precipitation in mainland Spain and the Balearic Islands for the period 1961-2018.

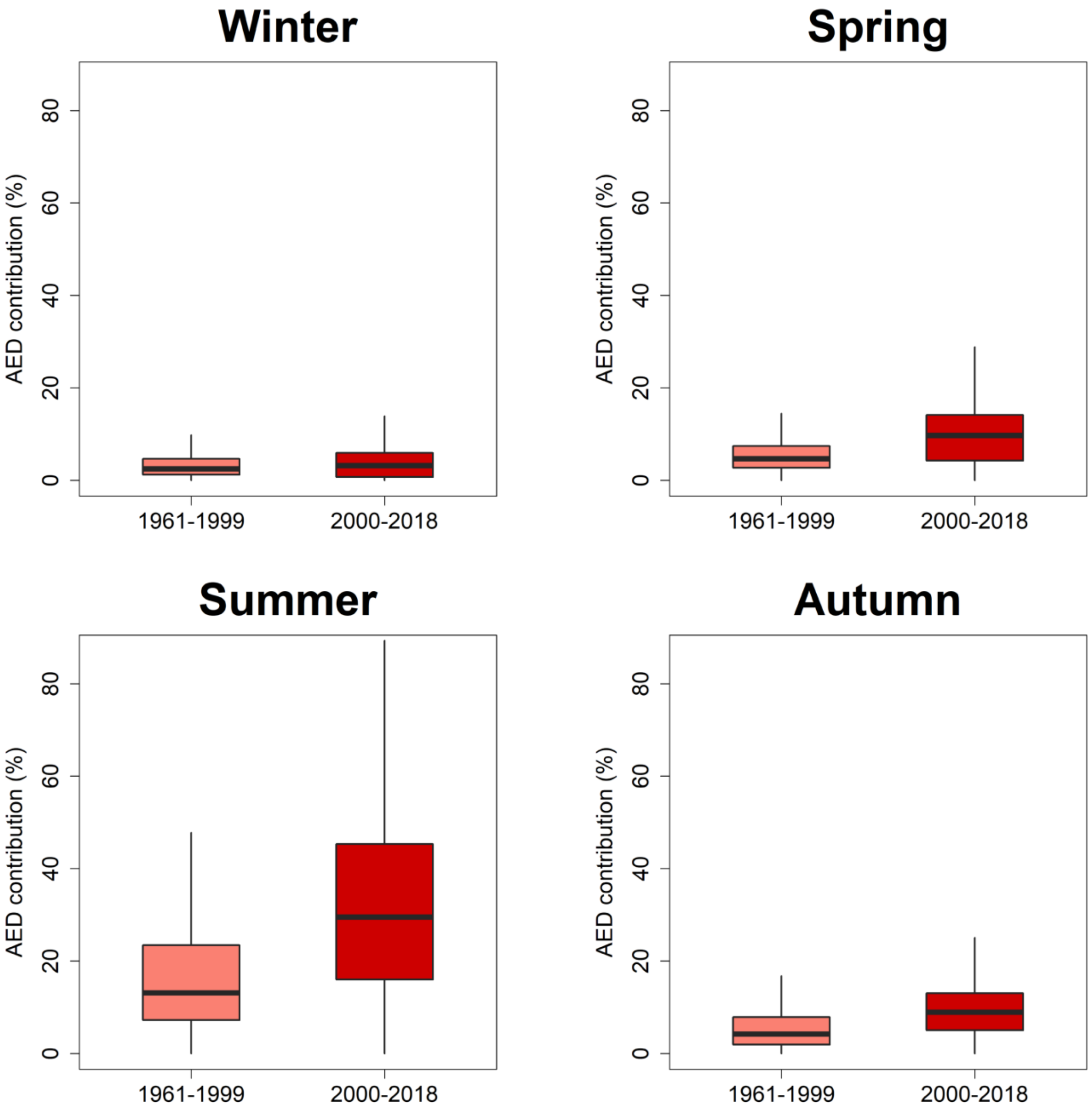

Figure S2. Comparison between the seasonal average AED contribution to the development of flash drought in mainland Spain and the Balearic Islands calculated for the period 1961-1999 and 2000-2018.

4. Supporting information for Chapter 6

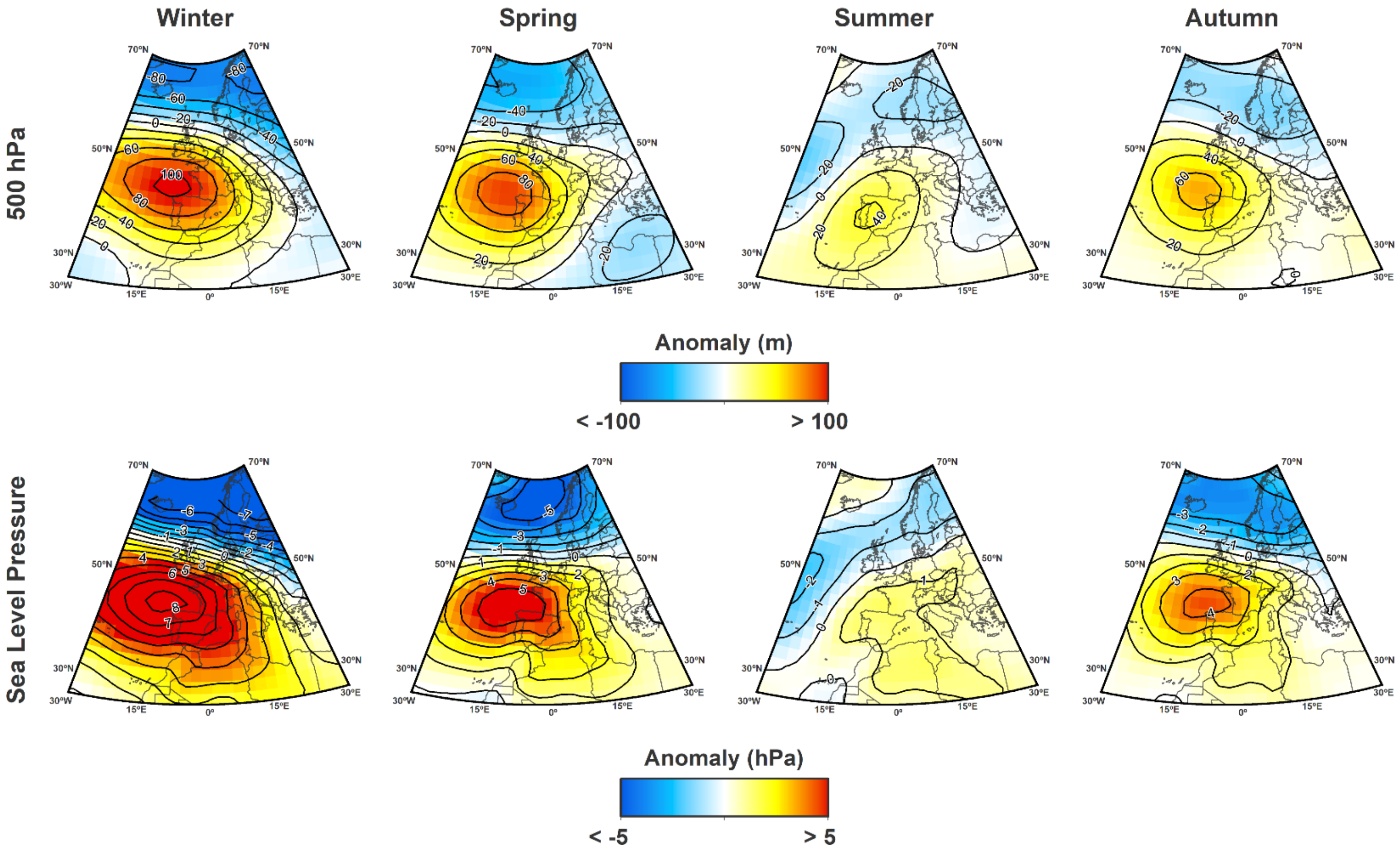

Figure S1. Composite of the anomalies in 500 hPa geopotential heights (meters) and sea level pressure (hPa) during top-10 flash drought (surface affected) development (i.e., onset week and previous three weeks) in each season over the period 1961-2018. Data obtain from National Centers for Environmental Prediction (NCEP)–National Center for Atmospheric Research (NCAR).

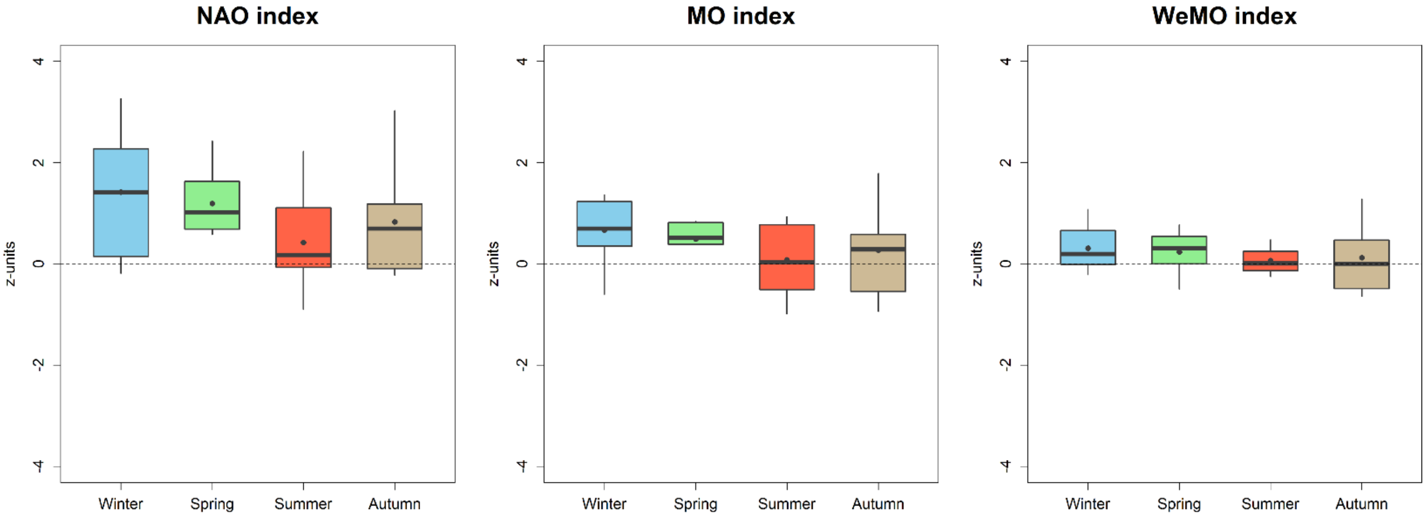

Figure S2. North Atlantic Oscillation (NAO), Mediterranean Oscillation (MO) and Western Mediterranean Oscillation (WeMO) indices values during top-10 flash drought (surface affected) development (i.e., onset week and previous three weeks) in each season over the period 1961-2018. Lines in the boxplot represent the median, while the points represent the average. Data obtain from National Centers for Environmental Prediction (NCEP)–National Center for Atmospheric Research (NCAR). We calculated NAO index follow the aproach proposed by Jones et al. (1997), which is based on the differences between normalized sea level pressure at the point 35°N, 5°W (Gibraltar) and that at the point 65°N, 20°W (Iceland). To calculated the MO index we employed the method suggest by Palutikof (2003) based on the differences between normalized sea level pressure at the point 35°N, 5°W (Gibraltar) and that at the point 30°N, 35°E (Lod). Finally, to computed WeMO index we adopt the original approach proposed by Martin-Vide and Lopez-Bustins (2006), which is based on the difference between normalized sea level pressure at the point 35°N, 5°W (San Fernando/Gibraltar) and that at the point 45°N, 10°E (Padova).