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

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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

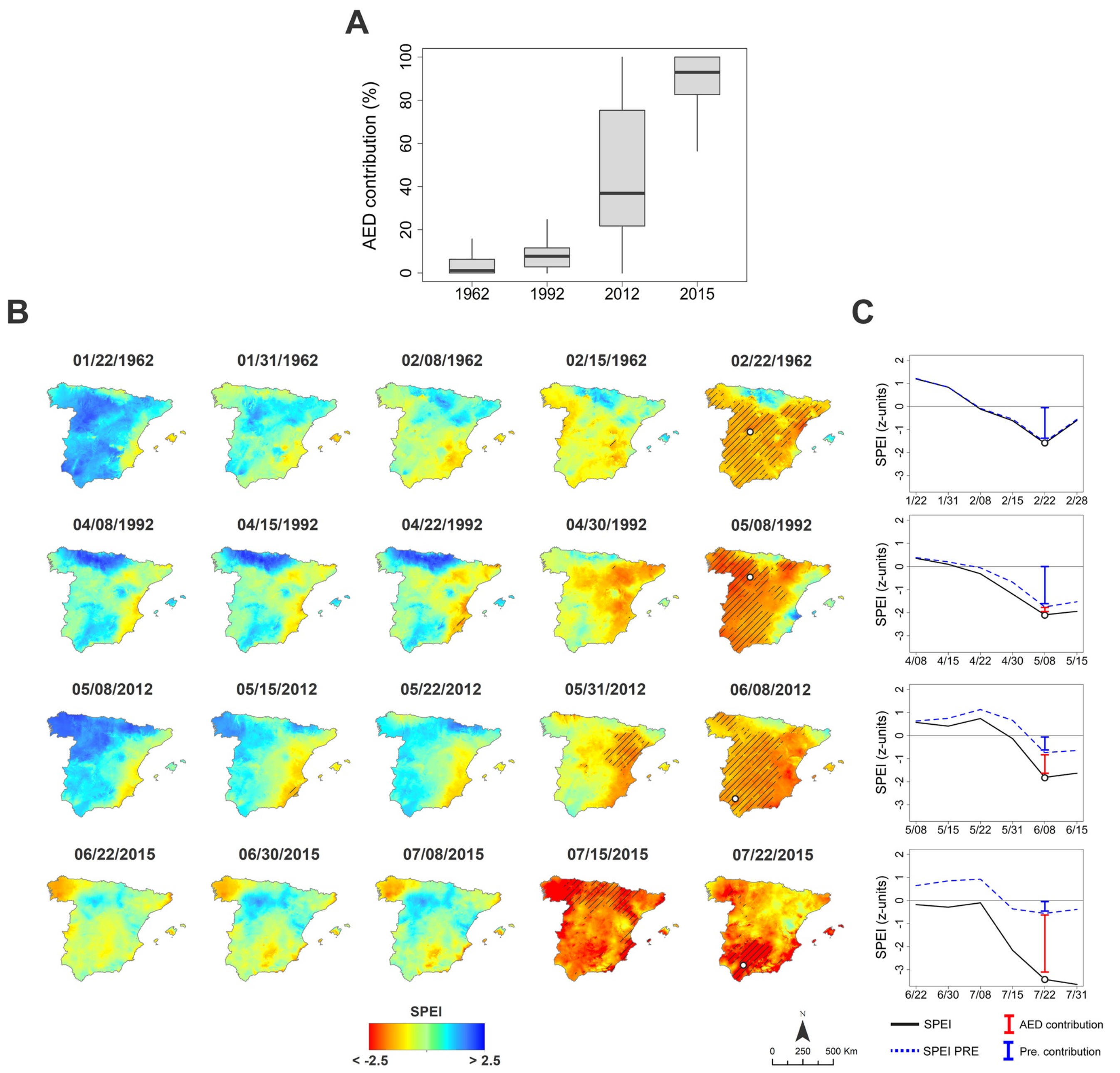

Figure 1. (a) Atmospheric evaporative demand (AED) contribution to flash drought events of 1962, 1992, 2012, and 2015, and (b) spatiotemporal evolution of SPEI at a 1-month time scale during these episodes, overlay areas represent the spatial extent of the flash drought; (c) examples of temporal evolution 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

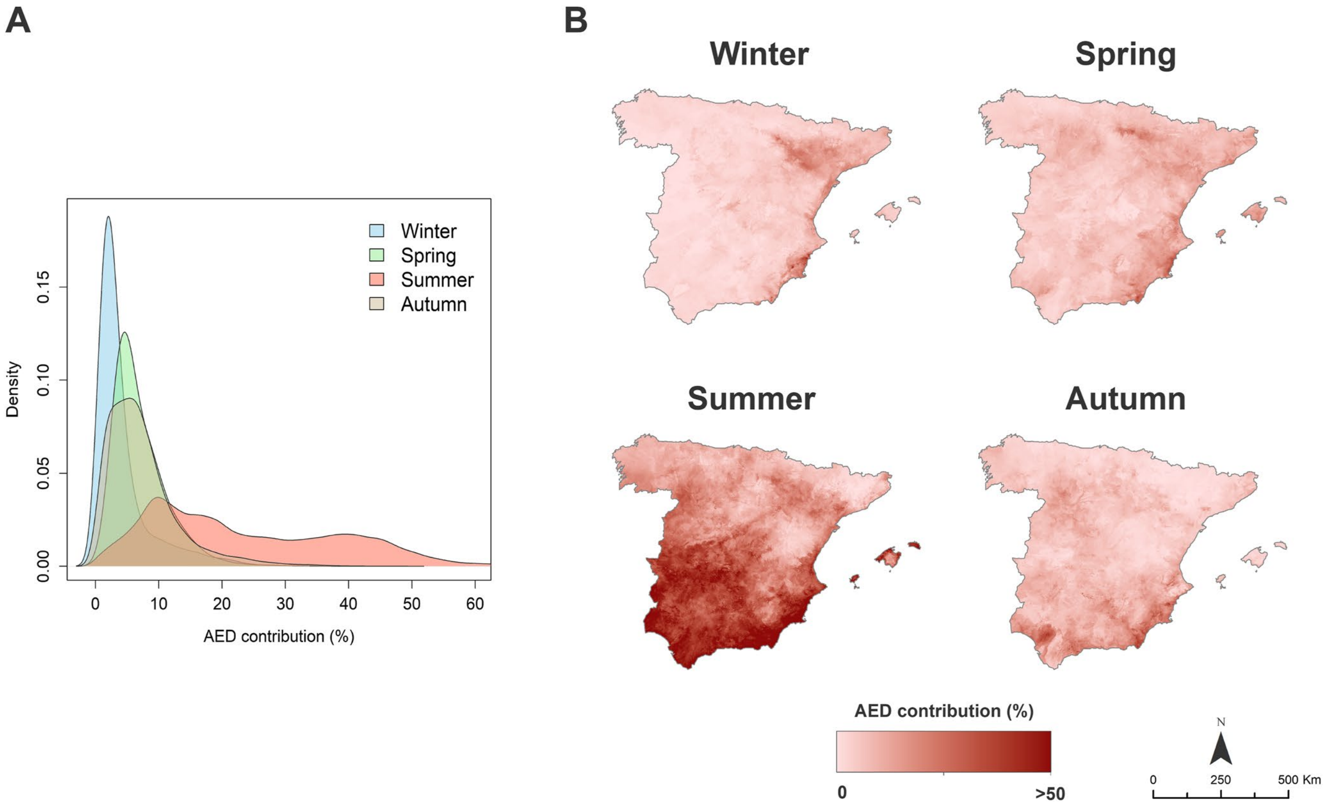

Figure 2. Seasonal (a) density of the average atmospheric evaporative demand (AED) contribution to the development of flash droughts and (b) its spatial distribution in mainland Spain and the Balearic Islands over the period 1961–2018.

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).

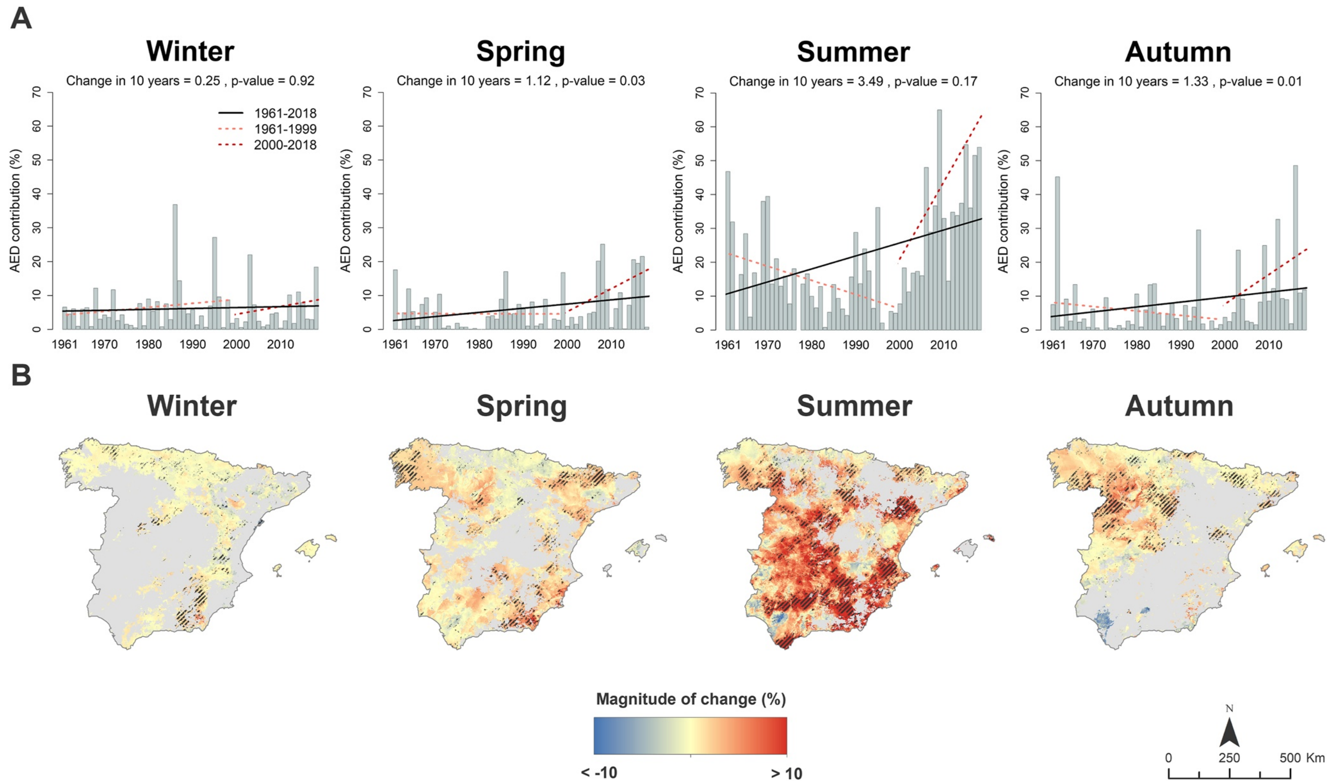

Figure 3. (a) Temporal evolution and (b) spatial distribution of seasonal magnitude of change (per decade) and significance in atmospheric evaporative demand (AED) contribution to flash droughts in mainland Spain and the Balearic Islands over the period 1961–2018. The dotted areas correspond to significant 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;

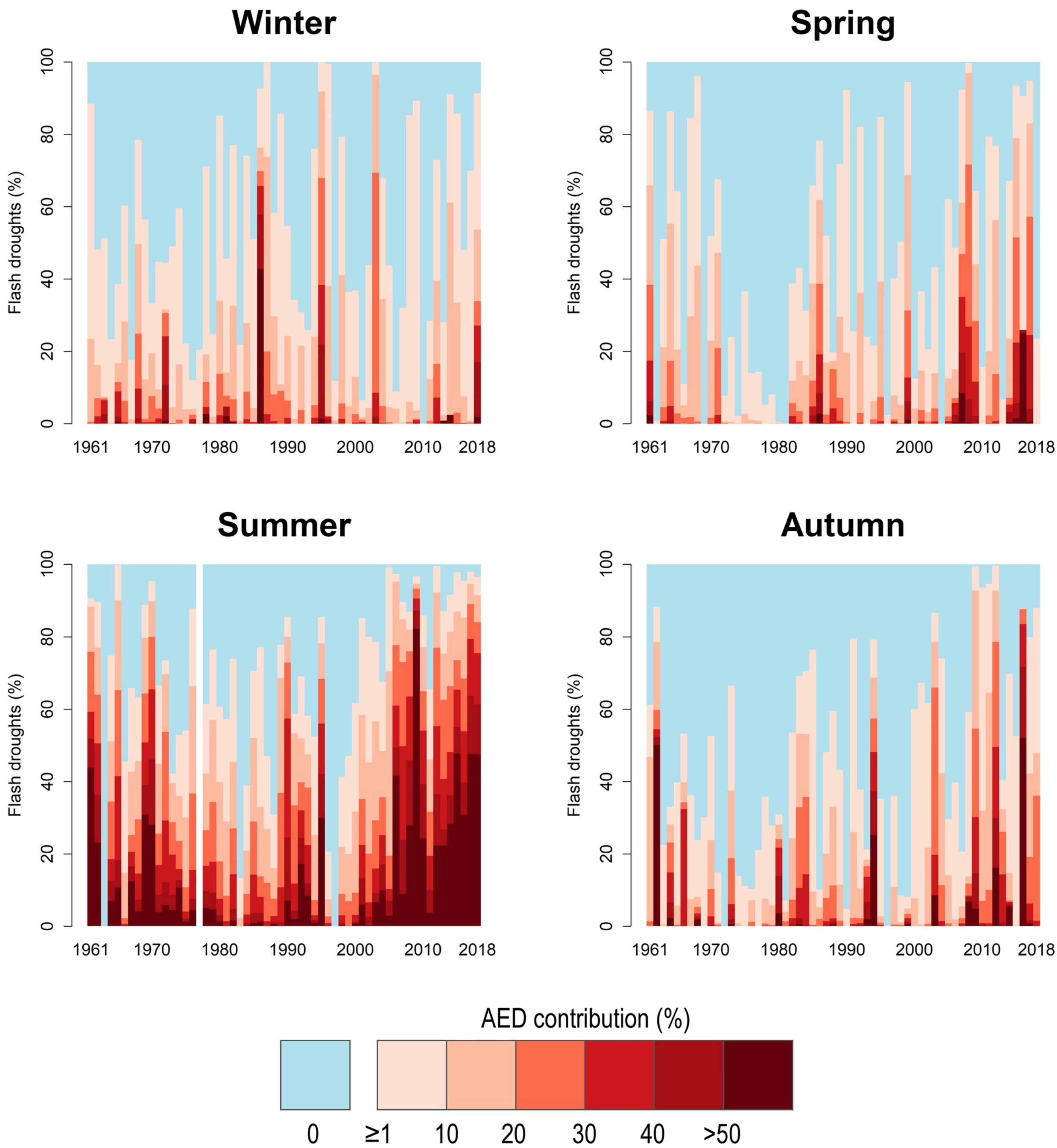

Figure 4. Temporal evolution of the seasonal percentage of flash droughts taking into account different atmospheric evaporative demand (AED) contribution thresholds in mainland Spain and the Balearic Islands over the period 1961–2018.

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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References

AEMET. (2012a). *Junio, extremadamente cálido y muy seco*. Retrieved from http://www.aemet.es/es/noticias/2012/07/climatologicojunio2012

AEMET. (2012b). *Mayo, extremadamente cálido y muy seco*. Retrieved from http://www.aemet.es/es/noticias/2012/06/climaticomayo2012

AEMET. (2015a). *Julio, extremadamente cálido y normal en precipitaciones*. Retrieved from http://www.aemet.es/es/noticias/2015/08/climticojulio2015

AEMET. (2015b). *Junio, muy cálido y húmedo*. Retrieved from http://www.aemet.es/es/noticias/2015/07/Junio_calido_y_humedo

Allen, C. D., Breshears, D. D., & McDowell, N. G. (2015). On underestimation of global vulnerability to tree mortality and forest die-off from hotter drought in the Anthropocene. *Ecosphere*, *6*(8), 1–55. https://doi.org/10.1890/ES15-00203.1

Allen, C. D., Macalady, A. K., Chenchouni, H., Bachelet, D., McDowell, N., Vennetier, M., et al. (2010). A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. *Forest Ecology and Management*, *259*(4), 660–684. https://doi.org/10.1016/j.foreco.2009.09.001

Allen, R. G., Pereira, L. S., Raes, D., & Smith, M. (1998). *Crop evapotranspiration: Guidelines for computing crop water requirements-FAO irrigation and drainage paper 56*.

Anderson, M. C., Zolin, C. A., Sentelhas, P. C., Hain, C. R., Semmens, K., Tugrul Yilmaz, M., et al. (2016). The evaporative stress index as an indicator of agricultural drought in Brazil: An assessment based on crop yield impacts. *Remote Sensing of Environment*, *174*, 82–99. https://doi.org/10.1016/j.rse.2015.11.034

Asseng, S., Ewert, F., Martre, P., Rötter, R. P., Lobell, D. B., Cammarano, D., et al. (2014). Rising temperatures reduce global wheat production. *Nature Climate Change*, *5*(2), 143–147. https://doi.org/10.1038/nclimate2470

Ault, T. R., Mankin, J. S., Cook, B. I., & Smerdon, J. E. (2016). Relative impacts of mitigation, temperature, and precipitation on 21st-century megadrought risk in the American Southwest. *Science Advances*, *2*(10), e1600873. https://doi.org/10.1126/sciadv.1600873

Beguería, S., Vicente-Serrano, S. M., Reig, F., & Latorre, B. (2014). Standardized precipitation evapotranspiration index (SPEI) revisited: Parameter fitting, evapotranspiration models, tools, datasets and drought monitoring. *International Journal of Climatology*, *34*(10), 3001–3023. https://doi.org/10.1002/joc.3887

Berg, A., & Sheffield, J. (2018). Soil moisture-evapotranspiration coupling in CMIP5 models: Relationship with simulated climate and projections. *Journal of Climate*, *31*(12), 4865–4878. https://doi.org/10.1175/JCLI-D-17-0757.1

Breshears, D. D., Adams, H. D., Eamus, D., Mcdowell, N. G., Law, D. J., Will, R. E., et al. (2013). The critical amplifying role of increasing atmospheric moisture demand on tree mortality and associated regional die-off. *Frontiers of Plant Science*, *4*, 266. https://doi.org/10.3389/fpls.2013.00266

Christian, J. I., Basara, J. B., Hunt, E. D., Otkin, J. A., Furtado, J. C., Mishra, V., et al. (2021). Global distribution, trends, and drivers of flash drought occurrence. *Nature Communications*, *12*(1), 6330. https://doi.org/10.1038/s41467-021-26692-z

Christian, J. I., Basara, J. B., Hunt, E. D., Otkin, J. A., & Xiao, X. (2020). Flash drought development and cascading impacts associated with the 2010 Russian heatwave. *Environmental Research Letters*, *15*(9), 094078. https://doi.org/10.1088/1748-9326/AB9FAF

Cook, B. I., Smerdon, J. E., Seager, R., & Coats, S. (2014). Global warming and 21st century drying. *Climate Dynamics*, *43*(9–10), 2607–2627. https://doi.org/10.1007/s00382-014-2075-y

Dai, A. (2011). Drought under global warming: A review. *WIREs Climate Change*, *2*(1), 45–65. https://doi.org/10.1002/wcc.81

Dai, A. (2012). Increasing drought under global warming in observations and models. *Nature Climate Change*, *3*(1), 52–58. https://doi.org/10.1038/nclimate1633

Dai, A., Zhao, T., & Chen, J. (2018). Climate change and drought: A precipitation and evaporation perspective. *Current Climate Change Reports*, *4*(3), 301–312. https://doi.org/10.1007/s40641-018-0101-6

Domínguez-Castro, F., Vicente-Serrano, S. M., Tomás-Burguera, M., Peña-Gallardo, M., Beguería, S., ElKenawy, A., et al. (2019). High spatial resolution climatology of drought events for Spain: 1961–2014. *International Journal of Climatology*, *39*(13), 5046–5062. https://doi.org/10.1002/joc.6126

Eamus, D., Boulain, N., Cleverly, J., & Breshears, D. D. (2013). Global change-type drought-induced tree mortality: Vapor pressure deficit is more important than temperature per se in causing decline in tree health. *Ecology and Evolution*, *3*(8), 2711–2729. https://doi.org/10.1002/ECE3.664

Furió, D., & Meneu, V. (2011). Analysis of extreme temperatures for four sites across Peninsular Spain. *Theoretical and Applied Climatology*, *104*(1–2), 83–99. https://doi.org/10.1007/s00704-010-0324-5

García-Herrera, R., & Barriopedro, D. (2018). Climate of the Mediterranean region. *Oxford Research Encyclopaedia of Climate Science*. https://doi.org/10.1093/acrefore/9780190228620.013.509

Garrido-Perez, J. M., García-Herrera, R., & Ordóñez, C. (2021). Assessing the value of air stagnation indices to reproduce PM10 variability in Europe. *Atmospheric Research*, *248*, 105258. https://doi.org/10.1016/j.atmosres.2020.105258

Grossiord, C., Buckley, T. N., Cernusak, L. A., Novick, K. A., Poulter, B., Siegwolf, R. T. W., et al. (2020). Plant responses to rising vapor pressure deficit. *New Phytologist*, *226*(6), 1550–1566. https://doi.org/10.1111/nph.16485

Hamed, K. H., & Ramachandra Rao, A. (1998). A modified Mann-Kendall trend test for autocorrelated data. *Journal of Hydrology*, *204*(1–4), 182–196. https://doi.org/10.1016/S0022-1694(97)00125-X

He, M., Kimball, J. S., Yi, Y., Running, S., Guan, K., Jensco, K., et al. (2019). Impacts of the 2017 flash drought in the US Northern plains informed by satellite-based evapotranspiration and solar-induced fluorescence. *Environmental Research Letters*, *14*(7), 074019. https://doi.org/10.1088/1748-9326/ab22c3

Hoffmann, D., Gallant, A. J. E., & Hobbins, M. (2021). Flash drought in CMIP5 models. *Journal of Hydrometeorology*, *22*(6), 1439–1454. https://doi.org/10.1175/JHM-D-20-0262.1

Hunt, E. D., Femia, F., Werrell, C., Christian, J. I., Otkin, J. A., Basara, J., et al. (2021). Agricultural and food security impacts from the 2010 Russia flash drought. *Weather and Climate Extremes*, *34*, 100383. https://doi.org/10.1016/j.wace.2021.100383

Hunt, E. D., Svoboda, M., Wardlow, B., Hubbard, K., Hayes, M., & Arkebauer, T. (2014). Monitoring the effects of rapid onset of drought on non-irrigated maize with agronomic data and climate-based drought indices. *Agricultural and Forest Meteorology*, *191*, 1–11. https://doi.org/10.1016/j.agrformet.2014.02.001

IPCC AR6 WGI. (2021). Weather and climate extreme events in a changing climate. In V. Masson & E. A. Delmotte (Eds.), *Climate change 2021: The physical science basis. Contribution of working group I to the sixth assessment report of the Intergovernmental Panel on Climate Change*. Cambridge University Press.

Jin, C., Luo, X., Xiao, X., Dong, J., Li, X., Yang, J., & Zhao, D. (2019). The 2012 flash drought threatened US midwest agroecosystems. *Chinese Geographical Science*, *29*(5), 768–783. https://doi.org/10.1007/S11769-019-1066-7

Kenawy, A. E., López-Moreno, J. I., & Vicente-Serrano, S. M. (2011). Recent trends in daily temperature extremes over northeastern Spain (1960–2006). *Natural Hazards and Earth System Sciences*, *11*, 2583–2603. https://doi.org/10.5194/nhess-11-2583-2011

Koster, R. D., Schubert, S. D., Wang, H., Mahanama, S. P., & Deangelis, A. M. (2019). Flash drought as captured by reanalysis data: Disentangling the contributions of precipitation deficit and excess evapotranspiration. *Journal of Hydrometeorology*, *20*(6), 1241–1258. https://doi.org/10.1175/JHM-D-18-0242.1

Lisonbee, J., Woloszyn, M., Skumanich, M., & Skumanich, M. (2021). Making sense of flash drought: Definitions, indicators, and where we go from here. *Journal of Applied and Service Climatology*, *2021*(1), 1–19. https://doi.org/10.46275/JOASC.2021.02.001

Lobell, D. B., Schlenker, W., & Costa-Roberts, J. (2011). Climate trends and global crop production since 1980. *Science*, *333*(6042), 616–620. https://doi.org/10.1126/SCIENCE.1204531

Lorenzo-Lacruz, J., Vicente-Serrano, S. M., López-Moreno, J. I., Beguería, S., García-Ruiz, J. M., & Cuadrat, J. M. (2010). The impact of droughts and water management on various hydrological systems in the headwaters of the Tagus River (central Spain). *Journal of Hydrology*, *386*(1–4), 13–26. https://doi.org/10.1016/j.jhydrol.2010.01.001

Martin-Vide, J., & Olcina-Cantos, J. (2001). *Climas y tiempos de España* (p. 43). Alianza Editorial.

McDowell, N. G. (2011). Mechanisms linking drought, hydraulics, carbon metabolism, and vegetation mortality. *Plant Physiology*, *155*(3), 1051–1059. https://doi.org/10.1104/PP.110.170704

McEvoy, D. J., Huntington, J. L., Hobbins, M. T., Wood, A., Morton, C., Anderson, M., & Hain, C. (2016). The evaporative demand drought index. Part II: CONUS-wide assessment against common drought indicators. *Journal of Hydrometeorology*, *17*(6), 1763–1779. https://doi.org/10.1175/JHM-D-15-0122.1

Miralles, D. G., Gentine, P., Seneviratne, S. I., & Teuling, A. J. (2019). Land-atmospheric feedbacks during droughts and heatwaves: State of the science and current challenges. *Annals of the New York Academy of Sciences*, *1436*(1), 19–35. https://doi.org/10.1111/NYAS.13912

Mo, K. C., & Lettenmaier, D. P. (2015). Heat wave flash droughts in decline. *Geophysical Research Letters*, *42*, 2823–2829. https://doi.org/10.1002/2015GL064018

Nguyen, H., Wheeler, M. C., Hendon, H. H., Lim, E. P., & Otkin, J. A. (2021). The 2019 flash droughts in subtropical eastern Australia and their association with large-scale climate drivers. *Weather and Climate Extremes*, *32*, 100321. https://doi.org/10.1016/J.WACE.2021.100321

Nguyen, H., Wheeler, M. C., Otkin, J. A., Cowan, T., Frost, A., & Stone, R. (2019). Using the evaporative stress index to monitor flash drought in Australia. *Environmental Research Letters*, *14*(6), 064016. https://doi.org/10.1088/1748-9326/ab2103

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

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

Otkin, J. A., Anderson, M. C., Hain, C., Mladenova, I. E., Basara, J. B., & Svoboda, M. (2013). Examining rapid onset drought development using the thermal infrared-based evaporative stress index. *Journal of Hydrometeorology*, *14*(4), 1057–1074. https://doi.org/10.1175/JHM-D-12-0144.1

Otkin, J. A., Anderson, M. C., Hain, C., Svoboda, M., Johnson, D., Mueller, R., et al. (2016). Assessing the evolution of soil moisture and vegetation conditions during the 2012 United States flash drought. *Agricultural and Forest Meteorology*, *218–219*, 230–242. https://doi.org/10.1016/j.agrformet.2015.12.065

Otkin, J. A., Haigh, T., Mucia, A., Anderson, M. C., & Hain, C. (2018a). Comparison of agricultural stakeholder survey results and drought monitoring datasets during the 2016 U.S. Northern plains flash drought. *Weather, Climate, and Society*, *10*(4), 867–883. https://doi.org/10.1175/WCAS-D-18-0051.1

Otkin, J. A., Svoboda, M., Hunt, E., Ford, T. W., Anderson, M. C., Hain, C., & Basara, J. B. (2018b). Flash droughts: A review and assessment of the challenges imposed by rapid-onset droughts in the United States. *Bulletin of the American Meteorological Society*, *99*(5), 911–919. https://doi.org/10.1175/BAMS-D-17-0149.1

Otkin, J. A., Zhong, Y., Hunt, E. D., Basara, J., Svoboda, M., Anderson, M. C., & Hain, C. (2019). Assessing the evolution of soil moisture and vegetation conditions during a flash drought-flash recovery sequence over the south-central United States. *Journal of Hydrometeorology*, *20*(3), 549–562. https://doi.org/10.1175/JHM-D-18-0171.1

Parker, T., Gallant, A., Hobbins, M., & Hoffmann, D. (2021). Flash drought in Australia and its relationship to evaporative demand. *Environmental Research Letters*, *16*(6), 064033. https://doi.org/10.1088/1748-9326/ABFE2C

Peña-Gallardo, M., Vicente-Serrano, S., Camarero, J., Gazol, A., Sánchez-Salguero, R., Domínguez-Castro, F., et al. (2018a). Drought sensitiveness on forest growth in Peninsular Spain and the Balearic Islands. *Forests*, *9*(9), 524. https://doi.org/10.3390/f9090524

Peña-Gallardo, M., Vicente-Serrano, S. M., Domínguez-Castro, F., Quiring, S., Svoboda, M., Beguería, S., & Hannaford, J. (2018b). Effectiveness of drought indices in identifying impacts on major crops across the USA. *Climate Research*, *75*(3), 221–240. https://doi.org/10.3354/cr01519

Peña-Gallardo, M., Vicente-Serrano, S. M., Hannaford, J., Lorenzo-Lacruz, J., Svoboda, M., Domínguez-Castro, F., et al. (2019a). Complex influences of meteorological drought time-scales on hydrological droughts in natural basins of the contiguous Unites States. *Journal of Hydrology*, *568*, 611–625. https://doi.org/10.1016/J.JHYDROL.2018.11.026

Peña-Gallardo, M., Vicente-Serrano, S. M., Quiring, S., Svoboda, M., Hannaford, J., Tomas-Burguera, M., et al. (2019b). Response of crop yield to different time-scales of drought in the United States: Spatio-temporal patterns and climatic and environmental drivers. *Agricultural and Forest Meteorology*, *264*, 40–55. https://doi.org/10.1016/j.agrformet.2018.09.019

Pendergrass, A. G., Meehl, G. A., Pulwarty, R., Hobbins, M., Hoell, A., AghaKouchak, A., et al. (2020). Flash droughts present a new challenge for subseasonal-to-seasonal prediction. *Nature Climate Change*, *10*(3), 191–199. https://doi.org/10.1038/S41558-020-0709-0

Potop, V., Možný, M., & Soukup, J. (2012). Drought evolution at various time scales in the lowland regions and their impact on vegetable crops in the Czech Republic. *Agricultural and Forest Meteorology*, *156*, 121–133. https://doi.org/10.1016/J.AGRFORMET.2012.01.002

Scheff, J. (2018). Drought indices, drought impacts, CO_2, and warming: A historical and geologic perspective. *Current Climate Change Reports*, *4*(2), 202–209. https://doi.org/10.1007/S40641-018-0094-1

Scheff, J., & Frierson, D. M. W. (2014). Scaling potential evapotranspiration with greenhouse warming. *Journal of Climate*, *27*(4), 1539–1558. https://doi.org/10.1175/JCLI-D-13-00233.1

Sherwood, S., & Fu, Q. (2014). A drier future? *Science*, *343*(6172), 737–739. https://doi.org/10.1126/science.1247620

Svoboda, M., LeComte, D., Hayes, M., Heim, R., Gleason, K., Angel, J., et al. (2002). The drought monitor. *Bulletin of the American Meteorological Society*, *83*(8), 1181–1190. https://doi.org/10.1175/1520-0477-83.8.1181

Tomas-Burguera, M., Beguería, S., & Vicente-Serrano, S. M. (2020a). Climatology and trends of reference evapotranspiration in Spain. *International Journal of Climatology*, *41*, E1860–E1874. https://doi.org/10.1002/joc.6817

Tomás-Burguera, M., Castañeda, A. J., Luna, M. Y., Morata, A., Vicente-Serrano, S. M., Gonzalez-Hidalgo, J. C., & Begueria, S. (2016). Control de calidad de siete variables del banco nacional de datos de AEMET. In *X Congreso Internacional AEC: Clima, sociedad, riesgos y ordenación del territorio*. (pp. 407–415). Retrieved from http://repositorio.aemet.es/handle/20.500.11765/8056

Tomas-Burguera, M., Vicente-Serrano, S. M., Peña-Angulo, D., Domínguez-Castro, F., Noguera, I., & ElKenawy, A. (2020b). Global characterization of the varying responses of the standardized precipitation evapotranspiration index to atmospheric evaporative demand. *Journal of Geophysical Research: Atmospheres*, *125*, e2020JD033017. https://doi.org/10.1029/2020JD033017

Vicente-Serrano, S. M., Beguería, S., & López-Moreno, J. I. (2010). A multiscalar drought index sensitive to global warming: The standardized precipitation evapotranspiration index. *Journal of Climate*, *23*(7), 1696–1718. https://doi.org/10.1175/2009JCLI2909.1

Vicente-Serrano, S. M., Camarero, J. J., & Azorin-Molina, C. (2014). Diverse responses of forest growth to drought time-scales in the Northern Hemisphere. *Global Ecology and Biogeography*, *23*(9), 1019–1030. https://doi.org/10.1111/geb.12183

Vicente-Serrano, S. M., Gouveia, C., Camarero, J. J., Begueria, S., Trigo, R., Lopez-Moreno, J. I., et al. (2013). Response of vegetation to drought time-scales across global land biomes. *Proceedings of the National Academy of Sciences of the United States of America*, *110*(1), 52–57. https://doi.org/10.1073/pnas.1207068110

Vicente-Serrano, S. M., & López-Moreno, J. I. (2005). Hydrological response to different time scales of climatological drought: An evaluation of the Standardized Precipitation Index in a mountainous Mediterranean basin. *Hydrology and Earth System Sciences*, *9*(5), 523–533. https://doi.org/10.5194/hess-9-523-2005

Vicente-Serrano, S. M., Lopez-Moreno, J. I., Beguería, S., Lorenzo-Lacruz, J., Sanchez-Lorenzo, A., García-Ruiz, J. M., et al. (2014). Evidence of increasing drought severity caused by temperature rise in southern Europe. *Environmental Research Letters*, *9*(4), 044001. https://doi.org/10.1088/1748-9326/9/4/044001

Vicente-Serrano, S. M., McVicar, T. R., Miralles, D. G., Yang, Y., & Tomas-Burguera, M. (2020). Unraveling the influence of atmospheric evaporative demand on drought and its response to climate change. *WIREs Climate Change*, *11*(2), e632. https://doi.org/10.1002/wcc.632

Vicente-Serrano, S. M., Tomas-Burguera, M., Beguería, S., Reig, F., Latorre, B., Peña-Gallardo, M., et al. (2017). A high resolution dataset of drought indices for Spain. *Data*, *2*(3), 22. https://doi.org/10.3390/data2030022

Wang, K., Dickinson, R. E., & Liang, S. (2012). Global atmospheric evaporative demand over land from 1973 to 2008. *Journal of Climate*, *25*(23), 8353–8361. https://doi.org/10.1175/JCLI-D-11-00492.1

Wang, L., & Yuan, X. (2018). Two types of flash drought and their connections with seasonal drought. *Advances in Atmospheric Sciences*, *35*(12), 1478–1490. https://doi.org/10.1007/S00376-018-8047-0

Wang, L., Yuan, X., Xie, Z., Wu, P., & Li, Y. (2016). Increasing flash droughts over China during the recent global warming hiatus. *Scientific Reports*, *6*(1), 30571. https://doi.org/10.1038/srep30571

Wilhite, D. A. (2000). *Drought as a natural hazard: Concepts and definitions*. Retrieved from https://digitalcommons.unl.edu/droughtfacpub/69/

Wilhite, D. A., Svoboda, M. D., & Hayes, M. J. (2007). Understanding the complex impacts of drought: A key to enhancing drought mitigation and preparedness. *Water Resources Management*, *21*(5), 763–774. https://doi.org/10.1007/s11269-006-9076-5

Will, R. E., Wilson, S. M., Zou, C. B., & Hennessey, T. C. (2013). Increased vapor pressure deficit due to higher temperature leads to greater transpiration and faster mortality during drought for tree seedlings common to the forest-grassland ecotone. *New Phytologist*, *200*(2), 366–374. https://doi.org/10.1111/NPH.12321

Williams, A. P., Cook, E. R., Smerdon, J. E., Cook, B. I., Abatzoglou, J. T., Bolles, K., et al. (2020). Large contribution from anthropogenic warming to an emerging North American megadrought. *Science*, *368*(6488), 314–318. https://doi.org/10.1126/science.AAZ9600

Williams, A. P., Seager, R., Abatzoglou, J. T., Cook, B. I., Smerdon, J. E., & Cook, E. R. (2015). Contribution of anthropogenic warming to California drought during 2012–2014. *Geophysical Research Letters*, *42*, 6819–6828. https://doi.org/10.1002/2015GL064924

Yuan, X., Ma, Z., Pan, M., & Shi, C. (2015). Microwave remote sensing of short-term droughts during crop growing seasons. *Geophysical Research Letters*, *42*, 4394–4401. https://doi.org/10.1002/2015GL064125

Yuan, X., Wang, L., & Wood, E. F. (2018). Anthropogenic intensification of southern African flash droughts as exemplified by the 2015/16 season. *Bulletin of the American Meteorological Society*, *99*(1), S86–S90. https://doi.org/10.1175/BAMS-D-17-0077.1

Yuan, X., Wang, L., Wu, P., Ji, P., Sheffield, J., & Zhang, M. (2019). Anthropogenic shift towards higher risk of flash drought over China. *Nature Communications*, *10*(1), 4661. https://doi.org/10.1038/s41467-019-12692-7

Yue, S., & Wang, C. Y. (2004). The Mann-Kendall test modified by effective sample size to detect trend in serially correlated hydrological series. *Water Resources Management*, *18*(3), 201–218. https://doi.org/10.1023/B:WARM.0000043140.61082.60

Zhang, M., & Yuan, X. (2020). Rapid reduction in ecosystem productivity caused by flash droughts based on decade-long FLUXNET observations. *Hydrology and Earth System Sciences*, *24*(11), 5579–5593. https://doi.org/10.5194/hess-24-5579-2020

Zhang, Q., Kong, D., Singh, V. P., & Shi, P. (2017). Response of vegetation to different time-scales drought across China: Spatiotemporal patterns, causes and implications. *Global and Planetary Change*, *152*, 1–11. https://doi.org/10.1016/j.gloplacha.2017.02.008

Zhao, M., AGVelicogna, I., Kimball, J. S., & Kimball, J. S. (2017). A global gridded dataset of GRACE drought severity index for 2002–14: Comparison with PDSI and SPEI and a case study of the Australia Millennium drought. *Journal of Hydrometeorology*, *18*(8), 2117–2129. https://doi.org/10.1175/JHM-D-16-0182.1

Zhao, T., & Dai, A. (2015). The magnitude and causes of global drought changes in the twenty-first century under a low-moderate emissions scenario. *Journal of Climate*, *28*(11), 4490–4512. https://doi.org/10.1175/JCLI-D-14-00363.1