LA EVOLUCIÓN DE LOS ESTUDIOS SOBRE SEQUÍAS CLIMÁTICAS EN ESPAÑA EN LAS ÚLTIMAS DÉCADAS

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Resumen: Este estudio revisa la evolución de la investigación sobre las sequías climáticas en España en las últimas décadas. La complejidad de este fenómeno natural y su importante incidencia en España ha supuesto un elevado interés por parte de los científicos españoles, con una apreciable producción científica durante las últimas dos décadas. Los estudios han evolucionado desde el predominio de los análisis descriptivos hasta la década de 1990, a la cobertura de una alta diversidad de temas, que incluyen el desarrollo de índices, herramientas y bases de datos, el estudio de la probabilidad de ocurrencia de sequías, el estudio de la variabilidad y tendencias de la sequía, incluyendo la investigación sobre reconstrucciones y análisis de sequías a largo plazo mediante datos instrumentales, la evaluación de los mecanismos físicos de la sequía y su modelización desde una base física. Este último aspecto incluye la forma en que los modelos representan las sequías, y sus aplicaciones para la predicción de las sequías y el establecimiento de proyecciones futuras. El estudio de las sequías climáticas en España muestra un elevado grado de internacionalización; la mayoría de los estudios científicos actuales se publican en revistas internacionales de alto impacto, y los estudios no solo cubren España, sino también otras regiones del mundo así como estudios continentales y globales.

Palabras clave: Sequía, España, índices de sequía, riesgo de sequía, circulación atmosférica, cambio climático.

The evolution of climatic drought studies in Spain over the last few decades

Abstract: This study reviews the evolution of scientific research on climatic droughts in Spain over the last few decades. The complexity of this na-

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tural hazard and the wide incidence of droughts in Spain have led to great interest from scientists in Spain, and generated a significant amount of scientific work on the topic over the last two decades. Climatic drought studies have evolved from predominantly descriptive studies up to the 1990s to highly diverse research topics, which include the development of indices, tools and datasets, the study of drought hazard probability, the analysis of drought variability and trends, including research on long term drought reconstructions and analysis with instrumental data, an assessment of drought mechanisms and drivers, and drought modeling, including how models represent droughts, and applying models to drought forecasting and future projections. The study of climatic droughts in Spain is highly internationalized, since most of the current scientific studies are published in high-impact international journals and, nowadays, do not only cover Spain, but also other world regions as well as continental and global studies.

Keywords: Drought, Spain, drought indices, drought risk, atmospheric circulation, climate change.

1. Introduction

Drought is one of the main natural hazards affecting Spain. It causes economic impacts, environmental damage, contributes to land degradation in arid ecosystems and even affects human health and has several ramifications for society. The impacts are not exclusive to Spain, but as a consequence of the strong interannual variability of precipitation and characteristic summer dryness, drought is an intrinsic climatic phenomenon in the country. Droughts are a root cause of socioeconomic crises in the history of Spain (Cuadrat *et al*., 2016a), and affect land and water management. It is usual for populations in the dry regions of Spain to be concerned about droughts given the dependence of crop yields on the interannual variability in precipitation (Gil and Amorós, 1996; Morales *et al*., 2001). The relevance of droughts in Spain has changed over the last century as a consequence of socioeconomic transformations, since agriculture and livestock activities have lost economic weight. Transformations have also changed the perception of drought in the country, since not only are the hydrological implications of drought much more significant these days (Morales *et al*., 2001; Ruiz Sinoga and León Gross, 2013), but the environmental and ecological perspective has also gained weight in recent years (Vicente-Serrano *et al*., 2020e).

Drought is probably the most complex climatic hazard, and different studies have addressed theoretical and conceptual aspects of the issue (Olcina, 2001; Pita, 1989, 1990; Vicente-Serrano *et al*., 2020a, 2017b; Vicente-Serrano, 2016). Droughts are dependent on both physical and human factors (Pita, 1989) although their origin is fundamentally climatic and principally caused by an abnormal decrease in precipitation, which may be aggravated by other factors, such as an increase in atmospheric evaporative demand (AED) (Vicente-Serrano *et al*., 2020d). In Spain, droughts have been addressed from various disciplines, with a growing body of scientific literature analyzing hydrological, agricultural and ecological droughts. As a brief summary, hydrological drought studies carried out in Spain include, drought propagation throughout the hydrological cycle (López-Moreno *et al*., 2009; Lorenzo-Lacruz *et al*., 2013; Peña-Gallardo *et al*., 2019), the development of hydrological drought indices (Vicente-Serrano *et al*., 2012b), the impact on groundwater (Lorenzo-Lacruz *et al*., 2017), an assessment of drought policies (Kahil *et al*., 2016), the development of drought management plans (Estrela and Vargas, 2012) and optimization of drought early warning in regulated rivers (Haro *et al*., 2016). Droughts have also been addressed from an ecological perspective, which includes an analysis of the impact of drought on tree-ring growth (Camarero *et al*., 2015; Pasho *et al*., 2012; Sánchez-Salguero *et al*., 2017), an assessment of drought resilience factors (Gazol *et al*., 2017, 2018b), evaluations based on remote sensing data (Gazol *et al*., 2018a; Rita *et al*., 2020; Vicente-Serrano *et al*., 2015a), and impacts on land degradation (Vicente-Serrano *et al*., 2012c), among several other studies.

Although the perspectives are diverse, in this article I shall review studies on climatic droughts by Spanish scientists which can be also be considered as a multidisciplinary research topic given the many perspectives involved. The research has evolved from descriptive studies for particular drought episodes, to studies that include advanced analysis of the atmospheric mechanisms of drought, the development of long-term drought reconstructions based on rescuing documentary sources and other proxy data, the evaluation of future drought scenarios using model outputs, and development of climatic indices and tools to analyze and monitor droughts. Moreover, research teams working on droughts in Spain have evolved from carrying out studies exclusively focused on Spain, or specific Spanish regions, to those in other regions of the world and even global research. There are previous revisions of drought studies in Spain (Hernández and Torres, 2001) and collective volumes containing different perspectives (Gil and Morales, 2001). In this article, I shall review how the study of climatic droughts in Spain has changed over the last few decades, including the main topics addressed, the most important findings and the current challenges in research on a very important subject within climate sciences.

2. Development of indices, tools and datasets

Given the difficulties in quantifying droughts, the scientific community has made an effort to develop drought indices in order to determine the severity, duration and spatial extent of drought episodes from a climatic point of view, which enables comparison among regions with very different climatic characteristics. These indices apply to drought analysis and monitoring, and can also be used to analyze drought variability and trends and assess future scenarios based on the climate projections by Earth models. The prime requirement in analyzing climatic droughts is having the tools for quantification, so I shall start by describing the advances made by Spanish researchers in the field.

Work on climatic drought indices in Spain had a late start in the early 2000s. The first approach was to develop the Standardized Drought-Precipitation Index (IESP) (Pita, 2001), which is based on precipitation data and follows a similar procedure to the Standardized Precipitation Index (SPI). The IESP is not calculated on different time scales, which is an essential characteristic in assessing drought severity and impacts (Vicente-Serrano *et al.*, 2011a). Other statistical drought indices were proposed in the decade of 2000, such as the drought frequency index (DFI) (González and Valdés, 2006), which was designed to characterize extreme drought events based on the statistical significance of extreme and persistent deviations, and is an estimation of the mean drought return period. A Poisson cluster process methodology comprising three series of random variables (duration, deficit, and maximum intensity) was proposed to represent the occurrence of drought (Abaurrea and Cebrian, 2002; Cebrián and Abaurrea, 2006).

A landmark in the development of drought indices was the design of the Standardized Precipitation Evapotranspiration Index (SPEI) (Beguería *et al.*, 2014; Vicente-Serrano *et al.*, 2010a), based on a standardization of the difference between precipitation and the AED. This includes the role of the AED in drought severity and can be calculated on different time scales to determine a variety of possible drought impacts. This index has gained use globally during the last decade, with advantages over other indices in drought quantification (Vicente-Serrano *et al.*, 2012a) and provides a suitable response to the spatial and temporal variability of precipitation and AED (Vicente-Serrano *et al.*, 2015c). In the SPEI, the main influence of the AED is recorded during low precipitation periods and regions (Tomas-Burguera *et al.*, 2020); it also provides a good characterization of the tails of the distribution of the variable (Vicente-Serrano and Beguería, 2016), thus enabling robust temporal and spatial comparability of drought severity.

Another index developed recently is the standardized evapotranspiration deficit index (SEDI) (Vicente-Serrano *et al.*, 2018b), which is based on a temporal standardization of the evapotranspiration deficit (evapotranspiration minus AED), which may have advantages over other indices in identifying situations of plant stress and reduced forest activity and growth. Standardized drought indices like the SPEI, SEDI or others are the best metrics for accurate quantification of drought (Slette *et al.*, 2020), although it has been suggested that relative indices should be used when working with climate change projections (Marcos-Garcia *et al.*, 2017; Vicente-Serrano *et al.*, 2020c).

Other authors have developed combined drought indices that include climate, soil moisture and vegetation data (Jiménez-Donaire *et al.*, 2020). Moreover, although they are not exclusively climatic indices, I must also mention the great advances made in the development of drought indices based on soil moisture anomalies obtained from remote sensing data. Soil moisture deficits have serious implications and not only from the hydrological, agricultural or ecological points of view, since they are highly relevant in climate studies given the land-atmosphere feedbacks that can affect AED. Temporal variability of soil moisture in Spain is related to climatic drought indices (Scaini *et al.*, 2015), and soil moisture observations are close to estimations based on remote sensing data (Gumuzzio *et al.*, 2016), which led to the development of a soil water deficit index (SWDI) which provides a good representation of the wilting point and anomalies in plant activity (Martínez-Fernández *et al.*, 2015). The Soil Moisture Agricultural Drought Index (SMADI) was developed by combining data from the Moderate Resolution Imaging Spectroradiometer (MODIS) and the Soil Moisture and Ocean Salinity (SMOS) satellites (Sanchez *et al.*, 2018; Sánchez *et al.*, 2016). These indices were shown to be appropriate for implementing reliable drought monitoring systems (Martínez-Fernández *et al.*, 2016; Pablos *et al.*, 2017).

To be effective and useful, new drought methodologies must be developed in tandem with the generation of tools for calculation and/or drought datasets that can be used in different scientific disciplines, to create a real climate service. Spanish researchers have been pioneers in the delivery of publicly available tools to quantify droughts (Beguería *et al.*, 2014) and develop several drought datasets not only on a global scale (Beguería *et al.*, 2010; Vicente-Serrano *et al.*, 2010b, 2018b), but also for Europe (Domínguez-Castro *et al.*, 2020), Africa (Peng *et al.*, 2020), and specifically and at high spatial resolution for Spain (Domingo-Marimon, 2016; Vicente-Serrano *et al.*, 2017c). These datasets and tools are the main source in implementing operative services for drought monitoring (e.g., https://lcsc.csic.es/).

3. Probability studies on drought hazard

The assessment of possible spatial differences in the probability of drought hazard has been a recurrent topic addressed by Spanish scientists. Conceptually, this issue is difficult to solve, since droughts are fully dependent on their related impacts (Vicente-Serrano, 2016) and drought impacts are recorded in areas with very different climatic characteristics (i.e., humid and dry regions). In Spain, there are examples of severe droughts recorded in humid regions of northern Spain that badly affected hydrological (Cuadrat, 2001) and ecological systems (Peguero-Pina *et al.*, 2007). Thus, the probability of drought hazard is strongly related to the average climate conditions, and long drought periods (e.g. determined by means of time series of dry spells) are usually recorded in the driest sites. The hazard probability is not a good metric for drought risk since for example, vegetation in dry sites is usually adapted to long and severe dry periods, but vegetation types in humid areas are generally less well adapted to water shortages. Thus, short drought periods may have a strong effect on humid vegetation activity and growth (Vicente-Serrano *et al.*, 2013).

There are several studies that have analyzed the probability of dry spells in Spain by means of different methodologies. Early studies were based on daily precipitation series and empirical approaches (Ortigosa Izquierdo, 1987), and Markov chains (Lana and Burgueño, 1998a; Martin-Vide and Gomez, 1999; Pérez Manrique *et al*., 1984), although from the very beginning parametric approaches were also applied, e.g. based on the exponential distribution (Creus *et al*., 1978). Using Markov chains, Martin-Vide and Gomez (1999) regionalized mainland Spain based on the duration of dry spells. All these studies obtained the probability for dry spells of different lengths, regardless of their extreme nature. Nevertheless, the heaviest impacts from drought are usually associated with the longest dry spells, which are poorly modeled using the above-mentioned approaches (Martin-Vide and Gomez, 1999).

Early approaches to modeling the upper tails of the distribution were based on the Gumbel distribution (Ascaso and Casals, 1981; Lana and Burgueño, 1998b), which used samples of annual maximum dry spell duration for the estimations. However, this approach also underestimated the hazard probability for the most extreme dry spells, mostly due to sample selection. This problem was mainly solved by adapting the selection through peaks over threshold (POT) to series of dry-spells. Vicente-Serrano and Beguería-Portugués (2003) showed that the use of POT series obtained from different thresholds, and modeled by the Generalized Pareto distribution, provided better results than series of annual maximum dry spell duration and the Gumbel distribution. This method has been successfully applied in Catalonia (Lana *et al*., 2006a), Spain (Lana *et al*., 2006b) and Europe (Serra *et al*., 2016). Other studies also show good assessment of the probability of dry spell hazard using the Wakeby (Pérez-Sánchez and Senent-Aparicio, 2018) and Weibull distributions (Lana *et al*., 2008a, 2008b).

Recently, a new approach has emerged to assess drought hazard probability. A lacunarity drought index, which determines maximum dry spell duration and the time structure of dry spells was developed and tested globally (Monjo *et al*., 2020). Dry spell fractality and autoregressive methods have also been implemented to predict long dry spells (Lana *et al*., 2017), but are highly uncertain for Europe. Also, methods for the assessment of drought risk based on monthly precipitation data have been developed, with special focus on the spatial dependence on hazard probability (Kallache *et al*., 2013) and Bayesian approaches (Avilés *et al*., 2016).

Using standardized indices, new methods have been developed to assess the probability of drought hazard. Domínguez-Castro *et al*. (2018b) used high spatial resolution SPI and SPEI data to characterize drought duration and magnitude at different timescales over Spain. To this end, they applied the extreme value theory and tested various thresholds to generate peak-over-threshold (POT) drought duration and magnitude series. They showed that the generalized Pareto (GP) distribution performs well in estimating the frequencies of drought magnitude and duration, with good agreement between the observed and modeled data when using upper percentiles. The application of this method obtained, for the first time, maps of drought hazard probability across Spain, which are not dependent on the mean climatology. The maps suggest a higher probability of extreme drought events in southern and central Spain compared to the northern and eastern regions, and large differences among drought time scales, which have important implications for drought risk assessment.

4. The study of drought variability and trends

Knowledge on spatial and temporal variability of droughts has been a significant study topic among Spanish researchers, whose early studies on droughts focused on the subject, with a spatial description of the droughts affecting Spain in 1944-1945 (Lorente, 1945) and 1974 (Roldan, 1975). Since the 1980s, multiple studies have analyzed the spatial and temporal variability of droughts, first in Spain, but several studies have appeared for other territories in the last two decades, which are highly relevant under the current climate change scenario. Thus, there is an international discussion on how droughts are changing in response to global warming, with high uncertainty on the issue (Vicente-Serrano *et al*., 2020d).

Great effort has been invested in the study of drought from a long-term perspective, including pre-instrumental periods by means of documentary sources and tree-ring data (Cuadrat *et al*., 2016b). These studies are very important in assessing whether drought episodes recorded in the last few decades have precedents over the centuries in order to find a possible anthropogenic cause. Dominguez-Castro and García-Herrera (2016) reviewed the main documentary sources used in Spain for drought reconstruction. The studies are mostly based on ecclesiastical rogation ceremonies (Barriendos, 1997; Cuadrat, 2012; Cuadrat *et al*., 2002; Domínguez-Castro *et al*., 2008, 2010, 2012; Martín-Vide and Barriendos, 1995; Vicente-Serrano and Cuadrat, 2007), Arab chronicles (Domínguez-Castro *et al*., 2014), diaries and crop price statistics (Fernández-Fernández *et al*., 2015; García-Herrera *et al*., 2003b, 2003a), and early instrumental records (Prohom *et al*., 2016). The findings suggest that there were very severe drought episodes in the last millennium at least equivalent to, if not worse than, those recorded over the last few decades (Barriendos and Llasat, 2003; Martín-Vide and Barriendos, 1995; Tejedor *et al*., 2018). Tree-ring reconstructions suggest severe drought periods affected various Spanish regions in the XVII and XVIII centuries (Andreu-Hayles *et al*., 2017; Tejedor *et al*., 2017). Spanish researchers also collaborated in European research networks to reconstruct drought from documentary sources (Pfister *et al*., 1999; Wetter *et al*., 2014) and early instrumental observations (Camuffo *et al*., 2013), and studies have also extended to South America (Domínguez-Castro *et al*., 2018).

There is a vast scientific literature examining drought variability and trends using instrumental observations. The majority of studies focused on analyzing precipitation data, but recent ones have considered the possible role of the AED on drought severity. In general, studies stress the strong spatial complexity of drought in Spain, as it is very common to find reduced rainfall in some regions, but others may experience normal or even humid conditions (Olcina, 1994; Pérez-Cueva and Escrivá, 1982). This issue was illustrated by Raso *et al.* (1981) and Sales *et al.* (1982) when analyzing the patterns of drought episodes in Spain at the beginning of the 1980s. The spatial complexity of droughts has also been identified at the regional level, in areas such as the Community of Valencia (Estrela *et al.*, 2000; Vicente-Serrano *et al.*, 2004), Andalusia (Pita, 1987), the central Ebro basin (Cuadrat, 1991; Vicente-Serrano and Cuadrat-Prats, 2007), Catalonia (Martín-Vide, 2001), the Balearic Islands (Lorenzo-Lacruz and Morán-Tejeda, 2016) and the north of Spain (Cuadrat, 2001). In general, four main drought regions in terms of drought behavior have been identified (Vicente-Serrano, 2006a), although this pattern strongly depends on the drought time scale, since patterns are more complex for long drought time scales (Vicente-Serrano, 2006b).

Although it is not possible to consider a single type of behavior for drought in Spain, regional series identified the main drought periods over the last 150 years. Raso (1993) stressed the severity of the drought periods identified at the beginning of the twentieth century, but also heavy droughts in 1949-1950 (Esteban-Parra *et al.*, 1998; Olcina, 1994), the beginning of the 1980s (Pérez Cueva, 1983; Raso *et al.*, 1981), but also between 1990 and 1995 and 2005 (Vicente-Serrano, 2013). More recent studies suggest that an examination of precipitation series has not found any drought trends since at least 1870 (Coll *et al.*, 2017; Vicente-Serrano *et al.*, 2020b). An analysis based on high spatial resolution drought datasets has shown no relevant trends in drought magnitude and duration since 1961 (Domínguez-Castro *et al.*, 2019b). Recently, new concepts are emerging since, although droughts have usually been considered as a slow developing and long duration phenomenon, recent drought events and related impacts suggest that some may evolve quickly, triggering flash droughts. Noguera *et al.* (2020) characterized flash drought events in Spain at a very detailed spatial resolution, but they showed no relevant trend over the last six decades.

Nowadays, there is a debate on the possible role of global warming on the severity of climatic droughts. This influence could be driven by increased AED, mostly due to temperature and reduced relative humidity in most continental regions (Vicente-Serrano *et al.*, 2018a). Stronger AED would imply more stressful conditions on natural systems and hydrological bodies, although the assessment of the effects of AED on drought are complex and depend on the drought type and general humidity conditions (Vicente-Serrano *et al.*, 2020d). Based on the SPEI, it has been suggested that AED may have contributed to the increase in severity of drought episodes in comparison to the evolution of precipitation (González-Hidalgo *et al.*, 2018; Vicente-Serrano *et al.*, 2014c). This issue arises from the recorded increase in temperature and decrease in relative humidity (Vicente-Serrano *et al.*, 2014a), which has caused a clear rise in AED observed with both physical models (Azorin-Molina *et al.*, 2015; Vicente-Serrano *et al.*, 2014b) and observations (Sanchez-Lorenzo *et al*., 2014). The heavy effect of AED on drought severity was observed during the drought event in mainland Spain in 2017, when extreme temperatures were the main contributor to intensifying the drought (García-Herrera *et al*., 2019).

Over the last decade, Spanish researchers have studied drought variability and trends in other regions of the world, including global analysis (Vicente-Serrano *et al*., 2017b), studies on a European level (Serra *et al*., 2014; Vicente-Serrano *et al*., 2020b), in other European countries like Portugal (Santos *et al*., 2010) and Italy (Baronetti *et al*., 2020), and in other areas, including Syria (Mathbout *et al*., 2018), Iran (Karimi *et al*., 2020), Bolivia (Maillard *et al*., 2020; Vicente-Serrano *et al*., 2015b), Ethiopia (El Kenawy *et al*., 2016), Oman (El Kenawy *et al*., 2020), Mexico (Serrano-Barrios *et al*., 2016), and Vietnam (Stojanovic *et al*., 2020).

5. Drought mechanisms and drivers

The drivers determining drought variability and trends have received close attention from Spanish researchers. The study of drought mechanisms has probably been the most common drought-related research in the last few decades, including several studies by Spanish researchers on different regions of Spain, but also at European and global scales.

This topic was approached in diverse ways, including studies on the atmospheric mechanisms controlling drought variability over time, through drought reconstructions from documentary sources. For example, these studies have confirmed the important role of the variability of the North Atlantic Oscillation (NAO) in explaining drought severity in different regions of Spain, extending over the last four centuries (Bravo-Paredes *et al*., 2020; Tejedor *et al*., 2018; Vicente-Serrano and Cuadrat, 2007). However, most studies were based on instrumental information, mainly focused on understanding the mechanisms of drought in Spain.

The literature has mostly followed two approaches. The first focused on identifying the role of different atmospheric circulation drivers on drought severity to explain the atmospheric situations and mechanisms causing droughts in Spain, and included synoptic situations. Several studies used qualitative approaches, which generally suggest that drought conditions in Spain are mostly driven by the persistence of atmospheric conditions characterized by stability, high pressure and subsidence (Esteban-Parra *et al*., 1998; Olcina, 2001), although the importance of spatial differences in the main synoptic situation affecting drought in Spain has also been emphasized (Olcina, 2001), which would explain the spatial differences in drought variability described in section 4 of this review. This subject has also been analyzed through quantitative approaches, in which automatic synoptic classification relates the frequency of weather types to drought indices (Romero *et al*., 1999; Vicente-Serrano and López-Moreno, 2006). However, most analyses focused on the role of the main low-frequency atmospheric circulation patterns, principally the NAO (Martín-Vide and Fernández, 2001; Merino *et al.*, 2015; Muñoz-Díaz and Rodrigo, 2003; Rodó *et al.*, 1997; Rodriguez-Puebla *et al.*, 1998), in addition to other patterns characteristic of the North Atlantic region (Manzano *et al.*, 2019; Rodriguez-Puebla *et al.*, 1998; Rodríguez-Puebla *et al.*, 2001), and global atmosphere-ocean coupled mechanisms, such as the El Niño-Southern Oscillation (Muñoz-Díaz and Rodrigo, 2005; Rodó *et al.*, 1997; Vicente-Serrano, 2005).

The second approach focused on the analysis of specific drought events, and a detailed analysis of the different drivers that could have caused the event. The first example analyzed the drought in regions of Spain in 1988-1989, and the atmospheric configurations at synoptic scale during this period (Capel, 1989). Subsequent studies included complex evaluation of different factors including not only synoptic configurations, but also anomalies in the low-frequency mechanisms, changes in storm-track directions, blocking conditions and anomalies in humidity sources and moisture transport, among other factors. These studies focused on analyzing recent very severe drought periods, including those of 2005 (García-Herrera *et al.*, 2007), 2012 (Trigo *et al.*, 2013) and 2017 (García-Herrera *et al.*, 2019), as well as on specific regions, such as the 2015/2016 drought in the Balearic islands (Ramis *et al.*, 2017). These studies made it clear that very severe drought episodes in Spain, affecting most of the territory can be explained by very different atmospheric mechanisms, an issue that highlights the difficulties in understanding drought behavior in Spain.

As mentioned above, studies of drought mechanisms by Spanish researchers also cover other regions. In the Mediterranean area, Sousa *et al.* (2011) analyzed trends in drought indices and the influence of the main low-frequency atmospheric circulation in the North Atlantic region. Vicente-Serrano *et al.* (2011c) used the SPEI to make a detailed study of the role of the NAO on Mediterranean droughts, and López-Moreno *et al.* (2008) showed the spatial and temporal differences of the NAO on droughts in Europe. Thus, there is a spatial complementarity of different atmospheric circulation mechanisms to explain drought on a European level (Vicente-Serrano *et al.*, 2016). Furthermore, García-Herrera *et al.* (2019) analyzed the mechanisms of the drought in Europe inf 2016/2017, and Ayarzagüena *et al.* (2018) its connection with the stratosphere. In Africa, studies have connected drought variability with sea surface temperature (SST) anomalies and decadal drought variability linked to the Atlantic Multidecadal and the Interdecadal Pacific Oscillations (Mohino *et al.*, 2011; Rodriguez-Fonseca *et al.*, 2015; Villamayor and Mohino, 2015). In Asia, Barriopedro *et al.* (2012) analyszd the mechanisms of the drought in China in 2009/2010. In South America, there are studies showing the complex influence of ENSO on droughts in Ecuador (Vicente-Serrano *et al.*, 2017a; Zambrano Mera *et al.*, 2018) and the River Plate basin (Cavalcanti *et al.*, 2015). Finally, global studies also analyzed the connection of droughts with SST (Schubert *et al.*, 2016), and specifically Vicente-Serrano *et al.* (2011b) illustrated the mechanisms of propagation of the effects of ENSO on droughts on a global scale.

As a final point, a novel research line has emerged in the last decade, in which Spanish researchers were pioneers. The study of humidity sources and moisture transport showed that they have a heavy influence on drought events (Drumond *et al.*, 2016), and that humidity sinks may change considerably during these, with alterations in the relative contribution from different regions, as demonstrated in the Mediterranean (Drumond *et al.*, 2017), the Fertile Crescent region (Salah *et al.*, 2018), the Danube river basin (Stojanovic *et al.*, 2017), central Europe (Stojanovic *et al.*, 2018a, 2018b) and the Congo basin (Sorí *et al.*, 2017). A recent study has linked to anomalous moisture transport and drought episodes globally, by examining the different IPCC reference regions and main drought events over the last four decades (Drumond *et al.*, 2019).

6. Drought modeling: drought representation, forecasting and future projections

The last research topic reviewed here is the latest one developed in Spain. However, increasing computing capacity has enabled some Spanish research teams to work on developing model simulations to forecast droughts. There are also recent studies using the outputs from global climate models (GCMs) (e.g., from the CMIP experiments by the IPCC) or regional climate models (RCMs) to analyze anychanges in droughts in future projections.

Droughts are highly complex to analyze and characterize, even with robust instrumental datasets. Therefore, some of the studies focused on assessing how the models represent droughts. (Barella-Ortiz and Quintana-Seguí, 2018) examined how RCMs represent meteorological droughts and their propagation over different parts of the hydrological cycle, demonstrating that RCMs represent meteorological droughts well; other studies reveal the lack of capacity of RCMs, as they return large differences between models and regions (Domínguez *et al.*, 2013; Giraldo and García, 2012). In addition, these models have drawbacks in reproducing how meteorological anomalies propagate to soil moisture and streamflow. In these simulations, the current model structure seems to be a major cause of considerable uncertainty (Quintana-Seguí *et al.*, 2019).

Studies on drought forecasting based on seasonal forecasting models have also emerged recently, with the development of prototypes to be used in operative model forecasting (Sutanto *et al.*, 2020). In general, the studies suggest high uncertainty in seasonal drought forecasting in mid-latitude regions, although some models are said to be useful for ENSO events (Frías *et al.*, 2010). Nevertheless, the capacity of the models is still low. Turco *et al.* (2017) analyzed summer drought predictability and compared statistical and dynamic models, and although they showed a source of predictability, they suggested that this is mostly attributable to the observed initial conditions and mainly as a consequence of the autoregressive character of droughts, which limit any practical operability of the forecasts. Thus, the ability of possible drought forecasting is restricted to the AED component (Solaraju-Murali *et al*., 2019), which has little influence on drought severity in comparison to precipitation (Tomas-Burguera *et al*., 2020).

Finally, various studies have analyzed future drought changes based on model simulations. Sanchez *et al.* (2011) studied projections of dry spells in Spain based on RCMs and GCMs. In general, they showed predominantly increased dry conditions in Spain in future scenarios, in agreement with Giraldo and García (2013) and López-Franca *et al.* (2015), but they also suggested that GCMs were limited in reproducing dry spells in comparison to the best performance of the RCMs. The general increase in dryness by projections in Spain has also been suggested when using different metrics (Barrera-Escoda *et al*., 2014), including standardized drought indices (Gaitán *et al*., 2020; Lopez-Bustins *et al*., 2013), and not only in Spain, but also in other regions such as the River Plate basin (Sordo-Ward *et al*., 2017). In any case, the ability of the models to project droughts in future scenarios is still highly uncertain with a debate between the use of online simulation outputs from the earth models (e.g., soil moisture and runoff) or drought indices calculated by offline simulations. (Vicente-Serrano *et al*., 2020c) showed better convergence among these different drought metrics on a global scale if using comparable statistical calculations and drought time scales.

7. Conclusions: new challenges for drought research

This review shows the recent evolution of Spanish research on climatic droughts. The research has evolved from very descriptive studies of particular drought episodes to a wide variety of research topics. The international character of drought research has also greatly increased, not only because the majority of contributions over the last few decades have been published in international journals, but also because Spanish researchers have worked on developing methods and datasets that are used worldwide. They have covered regions other than Spain, including continental and global studies, and participated in international networks that have advanced in the study and knowledge of droughts. In other words, Spanish researchers have made a significant contribution to the general progress in knowledge on droughts, establishing novel research topics, and making very significant contributions with noticeable international scientific impact.

In addition to the several challenges faced by the research topics reviewed above, important new ones are emerging: i) assessment of drought attribution, including any anthropogenic attribution to specific drought events, but also possible drought trends, ii) to find the relative contribution of land atmospheric feedbacks on drought development and intensification; this requires accurate quantification of land evapotranspiration, which means new instrumental networks must be installed and modeling approaches improved, iii) to unravel the mechanisms of drought under future climate change projections, including an assessment of the relative contribution of the radiative and fertilizing effects of CO2 on drought severity, and iv) the use of the vast historical information available in archives of documentary sources and early instrumental records, for which purpose, automatic methods based on artificial intelligence need to be explored in the future.

Climatic droughts are complex, cause strong impacts and very high uncertainty remains on what may happen in the future in response to global warming processes. Societies need an answer to several related questions. The effort expended by Spanish researchers working in the field and the societal and scientific importance of the topic, in addition to the several challenges posed nowadays, makes me optimistic about the future evolution of research on climatic droughts in Spain, a subject in which the Spanish researchers will continue to gain importance in the field of international science.

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