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AN UPDATED REVIEW ON RECENT TRENDS IN OBSERVATIONAL SURFACE ATMOSPHERIC VARIABLES AND THEIR EXTREMES OVER SPAIN

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ABSTRACT. *This article reviews the state-of-the-art findings on recent trends in observed atmospheric variables and their extremes in Spain. Our study screened peer-reviewed articles, published within the last decade, on recent climate variability in Spain, with a particular focus on a range of the essential atmospheric variables. The review focusses on the recent evolution of precipitation and air temperature, but also on other meteorological variables such as solar radiation, wind speed, surface humidity and evapotranspiration. While this review highlights results on changes in the mean state of climate in Spain, it also gives equal attention to findings on extreme weather events like rainstorms, heat waves and droughts. A detailed review of studies focusing on recent changes in the surface climate of Spain revealed some key findings. Studies demonstrate an overall increase of solar radiation since the 1980s. A similar behaviour was observed for surface air temperature since the 1960s, on the order of +0.3ºC decade^{-1}, with rapid warming rates during summer. Different seasonal trend patterns of wind speed were noted over Spain, with declines in winter-spring and increases in summer-autumn. A remarkable decrease (-5%) in relative humidity was observed from 1961 to 2011. For precipitation, studies suggested a strong variability over both space and time, with a moderate decrease of the annual total precipitation. In accordance with changes in the mean conditions of climate, studies of extreme weather events stressed a notable warming in warm extremes, while changes in cold extremes were generally insignificant.*

Revisión actualizada sobre las tendencias recientes de variables atmosféricas superficiales y sus extremos en España

RESUMEN. *Este artículo revisa el actual estado de conocimiento sobre las tendencias recientes de diferentes variables atmosféricas y sus extremos en*

España. El estudio se centra en las aportaciones publicadas en revistas arbitradas por revisión entre pares y publicadas en la última década, especialmente en la evolución reciente de la precipitación y la temperatura del aire, pero también en la de otras variables meteorológicas como la radiación solar, velocidad de viento, humedad atmosférica y evapotranspiración. Pero además de incluir una revisión sobre los cambios en las condiciones medias de estas variables, también se muestran los más recientes resultados sobre la evolución de los eventos meteorológicos más extremos (por ejemplo, precipitaciones extremas, olas de calor o sequías). La revisión muestra algunos aspectos destacables. Los estudios realizados hasta la fecha demuestran un notable incremento de la radiación solar desde la década de 1980. Se observa un comportamiento similar para la temperatura del aire desde 1960, con un incremento de alrededor de +0.3ºC década^{-1}, con un rápido calentamiento durante el verano. Se han identificado también diferencias estacionales en las tendencias de velocidad de viento, con descensos dominantes en invierno-primavera e incrementos en verano-otoño. Existe un notable descenso en los niveles de humedad relativa (-5%) entre 1961 y 2011. Respecto a la precipitación, los estudios existentes sugieren una importante variabilidad en el tiempo y el espacio, con un moderado descenso en los valores de precipitación anual. Respecto a los cambios en los eventos más extremos de temperatura, se asiste a un notable incremento en la frecuencia de eventos cálidos, mientras que los cambios de los eventos más fríos resultan no significativos.

Key words: climate variability, precipitation, air temperature, solar radiation, wind speed, atmospheric evaporative demand, drought, Spain.

Palabras clave: variabilidad climática, precipitación, temperatura del aire, radiación solar, velocidad del viento, demanda atmosférica, sequía, España.

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1. Introduction

The climate of the Iberian Peninsula is mainly controlled by the geographic location of the peninsula, orography and the influences of different air masses (e.g. Atlantic, Mediterranean and sub-tropical) and circulation patterns (e.g. North Atlantic Oscillation, Mediterranean Oscillation). Accordingly, the Iberian climate is highly variable over space and time, with clear spatial and temporal differences in many climate variables (Ramis *et al*., 1997; De Castro *et al*., 2005; Vicente-Serrano and López-Moreno, 2006; Beguería *et al*., 2009; López-Moreno *et al*., 2010; El Kenawy *et al*., 2013).

Earlier attempts to report changes in the climate of Spain in peer-reviewed journals occurred in the 1990s, with a particular focus on precipitation (García *et al*., 1995; Esteban-Parra *et al*., 1998; Rodriguez *et al*., 1999) and air temperature (Esteban-Parra *et al*., 1995). Bladé and Castro-Diez (2010) provided a comprehensive review on climate trends in the Iberian Peninsula during the instrumental period, with a special focus on precipitation and air temperature. According to this review, Spain witnessed a general air temperature increase during the 20th century. This increase was more pronounced during the last decades of the 20th century: a finding that is consistent with other regions of Europe. The review of Bladé and Castro-Diez (2010) indicated a strong spatial, seasonal and inter-annual variability of precipitation over Spain, with a general negative trend between 1960 and 2010. The tendency towards drying affected the frequency and intensity of extreme precipitation events, which tended to diminish during the same period. Nevertheless, Bladé and Castro-Diez (2010) did not include any updates on variability and changes of other essential atmospheric variables (e.g. relative humidity, wind speed, drought and atmospheric evaporative demand). These variables are relevant to the Spanish climate context, due to their environmental and socioeconomic impacts. Given their strong influence on evapotranspiration processes, changes in these variables may have impacts on the hydrological cycle and water resources (McVicar *et al*., 2012).

Chapter 2 of the IPCC2013 (Hartmann *et al*., 2013) focused on the observed atmospheric changes at the global scale, including a detailed review of current trends in air temperature and the hydrological cycle, especially large-scale changes in precipitation. This report also stressed the importance of analysing possible changes in air temperature and precipitation extreme events, as one of the main features of climate change processes, as well as changes in other atmospheric variables needed for understanding the complex characteristics of climate change (e.g. evapotranspiration, solar radiation, wind speed, cloud coverage, surface humidity). For example, Wild *et al.* (2013) concluded that a global assessment of brightening is necessary, as it gives indications on recent changes in solar radiation. Similarly, Vautard *et al.* (2010) suggested an investigation of changes in stilling, as an indicator of changes in near-surface wind speed, at the global scale. More recently, Willet *et al.* (2014) showed a recent decrease in relative humidity over large regions of the world.

Although there are several studies that have analysed changes in the chemical composition of the atmosphere (e.g., Fernández-Fernández *et al*., 2011), the overriding aim of this article is to review literature on recent changes in atmospheric variables over Spain. In particular, we revised peer-reviewed articles on changes in solar radiation, near-surface wind speed, surface humidity and evapotranspiration. With respect to surface air temperature and precipitation, we restricted our review only to those studies published after Bladé and Castro-Díez (2010).

2. Changes in solar radiation

Together with the anthropogenic alteration of the atmospheric composition as a consequence of higher greenhouse gasses concentrations, incoming solar radiation that reaches the surface is another relevant forcing that may affect the magnitude of warming processes at the global scale (Wild *et al*., 2013). Hartmann *et al.* (2013) documented a general decrease of surface solar radiation at the global scale from the 1950s to 1980s, a period known as "global dimming", followed by a partial recovery from the 1980s onward ("brightening period"). A number of studies support this behaviour in Europe, and updates on surface solar radiation data since 2000 suggest a continuation of the brightening. A detailed assessment of changes in the surface solar radiation in Spain is difficult since available solar radiation series from radiometers are generally short and very sparse (Sánchez-Lorenzo *et al.,* 2013). For this reason, long-term variability and changes in surface solar radiation have been usually analysed by means of sunshine duration series - obtained by means of Campbell-Stokes recorder- spanning the period from the beginning of the 20th century. Sanchez-Lorenzo *et al.* (2009) analysed changes in sunshine duration and cloud cover in Spain between 1964 and 2004, suggesting a strong correlation between both variables. Nevertheless, they found some discrepancy from 1960s to 1980s: a behaviour that concurs with the "global dimming period" reported by the IPCC (2013). Over this period, the decrease in sunshine duration was not associated with cloud coverage increase. On the contrary, from the early 1980s to 2004, an upward trend or ''brightening" was recorded across Spain seasonally and annually. The observed pattern from the 1980s agrees with the few available observations of solar radiation. Sánchez-Lorenzo *et al*. (2013) developed a homogeneous dataset of surface solar radiation in Spain, demonstrating a significant upward trend between 1985 and 2010 on the order of 3.9 $Wm^{-2}decade^{-1}$. Similar significant increases were observed in the mean seasonal series, with the highest rate of increase during summer (6.5 Wm^{-2} $decade^{-1}$). These results confirm the "brightening" phenomenon in Spain over the last decades, a pattern that was recently confirmed by Perdigao *et al*. (2016) using reanalysis datasets.

To account for the possible mechanisms responsible for brightening, Mateos *et al.* (2013) analysed data of shortwave radiation from 13 locations over Spain, with the aim of determining the radiative effects of clouds and aerosols in the period 1985-2010. They found a significant decrease of the radiative effects of clouds and aerosols. More recently, Mateos *et al*. (2014) quantified the contribution of each of clouds and aerosols to "brightening" processes in Spain, indicating that clouds are the key factor responsible for explaining "brightening" trends, as they explain approximately 75% of the solar radiation changes, while a possible reduction of aerosol concentrations explains 25% of "brightening" trends.

3. Air temperature variability and change

3.1. Mean air temperature

Although radiative forcing caused by more intense surface solar radiation can contribute to the observed air temperature trends, there is a strong confidence that thermal forcing, driven by changes in the chemical composition of the atmosphere, is the main driver of air temperature variability and change (Hartmann *et al*., 2013). Based on a range of global air temperature datasets, the IPCC2013 reported a general agreement on the sign (i.e. positive) of changes in air temperature since the mid of the 19th century, though being more accelerated since the 1970s. A similar temporal pattern was already confirmed by Bladé and Castro-Díez (2010) for Spain, albeit with an enhanced air temperature increase in recent decades (0.48ºC decade^{-1}), which is 50% higher than the trend observed in the northern hemisphere.

The most recent studies analysing air temperature trends in Spain gave new insights on warming rates over the past decade. Some articles employed high density databases (e.g. Brunet *et al*., 2006; Hofstra *et al*., 2009). The use of these dense databases is advantageous in the sense that the temporal variability of air temperature over Spain is highly variable, and air temperature trends can thus be better expressed by using regional series for different territories, both for maximum and minimum air temperatures (Peña-Angulo *et al*., 2015).

For peninsular Spain, some studies have analysed changes in air temperature using a highly dense network of observatories. One example is Del Río *et al.* (2011) who analysed the evolution of mean air temperature using 473 meteorological stations between 1961 and 2006. They showed dominant positive trends, mainly in spring and summer months, suggesting an annual increase between 0.1 and 0.2ºC decade^{-1}, which was statistically significant in the entire peninsular Spain. Later, Del Río *et al.* (2012) employed the same dataset to analyse the evolution of maximum and minimum air temperatures for the same period. They found an identical rate of increase (0.3ºC decade^{-1}) for maximum and minimum temperatures, particularly in summer and spring months. The average of increase in maximum temperature was 0.37ºC and 0.43ºC decade^{-1} during summer and spring, respectively. For minimum temperature, the warming rate was 0.34ºC (summer) and 0.41ºC decade^{-1} (spring). Recently, Gonzalez-Hidalgo *et al.* (2015) developed a dense dataset, composed of 1358 homogeneous temperature series from 1951 to 2010, over peninsular Spain. They demonstrated that maximum temperature has risen in late winter/early spring and summer, while minimum temperature has increased in summer, spring and autumn, especially in Spain southern regions. Moreover, they showed that trends in the daily temperature range had a clear north-south gradient during summer, with positive trends in the north and negative trends in the south. The overall signal in maximum temperature showed a positive trend over more than 75% of land, and the strongest signal was detected in June, in which 87% of land exhibited a statistically significant positive trend. Also, changes in maximum temperature showed a different spatial structure with reference to minimum temperature. In particular, rapid changes in minimum temperature were identified in the Mediterranean area (central-southern areas and eastern coastland) in March, April, May, September and October; while significant positive trends extend over the whole continental Spain, except the north-west northern plateau, in June, July and August.

Overall, results of changes in air temperature across Spain agree on a strong temperature increase affecting the whole territory. Nonetheless, recent studies also suggest that the warming rate has noticeably decreased in the past two decades in comparison to the strong increase recorded in the preceding decades. This temporal pattern has been identified at the global scale and called "warming hiatus" (Fyfe *et al.,* 2013), requiring different mechanisms to explain this phenomenon (Trenberth, 2015). In Spain, although the recent findings of the long-term temperature evolution have shown a strong temperature increase since 1850 (Sigró *et al*., 2015), recent studies also suggest a slowdown of temperature trends in the past two decades. In particular, temperatures in the past two decades would show a lower rate of temperature increase than that shown between 1970 and 1995 (González-Hidalgo *et al.,* 2016).

At a more detailed scale, several studies were more specific to assess changes in air temperature over particular regions in Spain. For example, El Kenawy *et al.* (2012) employed a long-term (1920-2006) dataset of 19 homogenized observatories and a denser dataset of 126 observatories for the period 1960-2006 to assess changes in air temperature over northeastern Spain. They identified an average increase of 0.11 ºC decade^{-1} between 1920 and 2006, which was more pronounced for minimum (0.14ºC decade^{-1}) than for maximum air temperature (0.08ºC decade^{-1}). Seasonally, summer exhibited the largest warming trend (0.22ºC decade^{-1}). They also showed a clear spatial gradient in the warming processes, as coastal areas warmed at higher rates compared with mainland areas. In Catalonia, Martínez *et al.* (2010) indicated higher air temperature increase during the warm season (JJA). In accordance, Homar *et al.* (2009) found a very strong summer warming trend in the Balearic Islands from 1976 to 2006 (+0.73ºC decade^{-1}). The magnitude of change was similar to that found in the Canary Islands for the period 1981-2010, varying from 0.40 to 0.46ºC decade^{-1} (Cropper and Hanna, 2014). In their assessment of air temperature changes in the island of Tenerife, Martín *et al.* (2012) found a strong spatial contrast between high mountains, which showed a higher increase than coastal areas, where the effect of the Atlantic Ocean modulated the general air temperature rise. In the Valencia region, Miro *et al.* (2015) found a remarkable warming tendency in mountain areas, with less pronounced warming in valleys and coastal plains, particularly for minimum air temperature. In contrast, the tendency for increasing maximum temperature was more generalized for the period 1948-2011.

Martínez *et al.* (2010) analysed trends of temperature in Catalonia, indicating a clear breakpoint in the temperature increase around 1995 and no significant warming trends from 1995 to 2004, mainly recorded for minimum temperature. Recently, González-Hidalgo *et al.* (2016) suggested that the warming rate in both maximum and minimum temperatures was more pronounced over the Spanish mainland between 1970 and 1990, followed by a decrease in the intensity of warming until the present. Furthermore, they found that the slowdown of warming rates in maximum temperature has been higher than in minimum temperature for the last three decades, suggesting that recent annual warming is mainly driven by changes in minimum temperature than those of maximum temperature. According to González-Hidalgo *et al.* (2016), there is a general warming from 1970 and a recent warming hiatus from the mid-1990s to the present. Nevertheless, although this hiatus is more specific to the cold season (DJF), temperature has also shown some increase in summer and spring during the 1990s and 2000s, mainly caused by changes in minimum temperature. Again, this pattern suggests that current warming processes are more controlled by night-time temperature than by daytime temperature. Overall, an assessment of the links between El Niño phenomenon and the Spanish temperature in 2015 and 2016 can confirm the hypothesis of Kosaka and Xie (2013), in which the hiatus phenomenon is related to the anomalous period of cold temperature in the Eastern Pacific region. Thus, recent analyses pointed out that the internal climate variability is important to explain the slowdown of air temperature trends as well as the robust warming projections despite the recent hiatus (England *et al*., 2015; Wehner and Easterling, 2016).

3.2. Changes in daily temperature extremes

Although the IPCC2013 report suggested a slowdown in the frequency of warm nights and warm days since the mid1990s (Hartmann *et al*., 2013), Beniston (2015) showed that extreme maximum temperatures in Europe exhibit sharp increases since 2000, despite a slowdown in the rise of mean temperatures. Thus, Barriopedro *et al.* (2011) showed a high frequency of record temperature events in Europe in the last decade (2000-2010), with no precedents in the last two centuries. This pattern is confirmed also in Spain in recent studies that indicate a strong increase in the frequency and magnitude of high temperatures in the last decade.

A number of recent studies have analysed changes in daily temperature extremes over Spain, using a range of percentile-based indices. In general, Spain exhibited a decrease in the frequency of winter cold events and a general increase in the frequency of summer warm events and heat waves (e.g. Garcia-Herrera *et al*., 2005; El Kenawy *et al*., 2011). A range of regional studies confirm this pattern over Spain, including: central (Labajo *et al*., 2012; Labajo *et al*., 2014) and northeastern Spain (El Kenawy *et al*., 2011, 2013a and 2013b; López-Moreno *et al*., 2014). Rodríguez-Puebla *et al.* (2010) analysed changes in warm days and cold nights over the whole Iberian Peninsula for the period 1950-2006, using a threshold of the 90th percentile of daily maximum temperature distribution to define warm days, and the 10th percentile of daily minimum temperature distribution to define cold nights. They indicated that warm days increased by 1.1% of decade^{-1} on average, while cold nights exhibited a decrease on the order of -1.3% decade^{-1}. This study also defined two sub-periods: 1950-1979 and 1980-2006, with remarkable changes in the frequency distribution of cold nights and warm days. Nevertheless, Acero *et al.* (2014) analysed summer extreme temperatures over Spain using non-urban station data and the extreme value theory, suggesting that temperature extremes are increasing, but not as much as the mean temperature. Also, recent studies by Fernández-Montes and Rodrigo (2012) and Fernandez-Montes *et al.* (2013) employed data from 1929 to 2005 and indices of daily temperature extremes to give evidences on a significant decreasing trend (–0.6 days decade^{-1}) in the frequency of frost days for coastal stations, especially from 1965 onwards. These investigations also reveal significant increasing trends from 1980 onwards, particularly for tropical nights in southeast (3.8 days decade^{-1}), and summer days in southern stations (2.3 days decade^{-1}). Thus, the observed warming has impacts on the definition of the warm season in Spain.

Peña-Ortiz *et al.* (2015) analysed changes in the onset, end and length of summer season using temperature thresholds. They found an increase in the length of summer season, mainly between 1979 and 2012. This increase ranges between 5 and 12 days decade^{-1}, and has been mainly driven by an earlier onset in June.

The increase in the frequency of warm temperature extremes was continuous during the past two decades. Sánchez-Lorenzo *et al*. (2012) confirmed that the average frequency of tropical nights showed a continuous increase since the beginning of the 1970s, with the most extreme values recorded during the 2000s, independently of the region of Spain. A similar temporal pattern was observed over the Iberian Peninsula (Fernández-Montes and Rodrigo, 2012), the central plateau (Labajo *et al.*, 2014) and northeastern Spain (El Kenawy *et al*., 2012).

4. Changes in surface winds

Given the lack of dense networks of surface wind, the IPCC2013 stressed that the confidence in surface wind trends is low. Nevertheless, a weakening of seasonal and annual mean wind speed, referred to as "global stilling", has been reported over many continental regions from 1960s onwards, with direct energetic and hydrological implications (Vautard *et al*., 2010). Since wind speed is one of the main variables controlling the atmospheric evaporative demand, their declining trends could noticeably affect the complete hydrological cycle (McVicar *et al*., 2012b). Numerous studies have analysed the spatial and temporal variability of wind speed over Spain. Lorente-Plazas *et al*. (2015) showed a strong spatial variability of the direction as well as the magnitude of wind speed over the whole Spain. Nevertheless, albeit the dense dataset of wind stations (>500), the temporal coverage of these series was very short (2002-2006). Thus, it has not been possible to assess long-term trends in wind characteristics, making results on wind speed trends highly uncertain. In addition, assessing changes in wind speed is also impacted by the measurement procedure. Recently, Azorín-Molina *et al*. (2017) showed significant differences in the magnitude of wind speed over Spain, when considering synoptic-time intervals and 24 hours run measurements. Nevertheless, this study also concluded that there are no differences in wind speed trends from 1961 to 2011, regardless of the measurement procedure. Azorín-Molina *et al*. (2014) have also used 67 monthly average wind speed series in Spain and Portugal from 1961 and 2011, showing a generally slight downward trend for the period 1961-2011 (-0.016 ms^{-1} $decade^{-1}$). However, they have found seasonal differences, with a declining trend in winter and spring and an increasing trend in summer and autumn. Over Spain, wind "stilling" affected almost 77.8% of the stations in winter and 66.7% in spring. Nonetheless, roughly 40% of the declining trends were statistically significant. On the contrary, increasing tendency appeared in 51.9% of the stations in summer and 57.4% in autumn, from which only 40% of stations showed statistically significant positive trends Nevertheless, changes in the magnitude of wind speed did not show a clear spatial structure, either at the seasonal or the annual scales. Azorin-Molina *et al*. (2016) analysed trends of daily peak wind gusts in Spain between 1961 and 2014 by means of the frequency (90th percentile) and the magnitude of the wind speed maxima of daily peak wind gusts. Results revealed less frequent and declining daily peak wind gusts during the cold half (November-April) of the year, compared to more frequent and increasing wind gusts during the warm half (May-October) of the year.

5. Changes in surface humidity

Possible changes in surface humidity can be important, as this variable affects the quantity of water vapour that a parcel of air can store and thus the atmospheric evaporative demand. IPCC2013 indicates the likely widespread increase of specific humidity from 1973 to 2012 at the global scale, suggesting that relative humidity would remain constant according to Clausius-Clapeyron relationship, given the unlimited available moisture at the global scale. Nevertheless, new observations suggest that this principle could not drive the evolution of surface relative and specific humidity in large regions of the world, mainly in semiarid regions (Simmons *et al*., 2008; Willet *et al*., 2014; Sherwood and Fu, 2014).

In Spain there are few studies analysing recent atmospheric humidity trends. Mattar *et al*. (2011) used radiosonde data to analyse changes in column integrated water vapour from 1973 to 2003, suggesting statistically significant negative trends (<–0.04 mm year^{-1}; $p < 0.05$) in the south of the Iberian Peninsula. More recently, Moratiel *et al.* (2016) assessed changes in wet-bulb and dew point temperature across Spain at different temporal scales between 1981 and 2010. These measurements give indirect assessments of humidity changes. Moratiel *et al*. (2016) showed strongly different trends derived from air temperature and wet-bulb temperature data, suggesting indirectly noticeable changes in the relative air humidity during the study period.

Vicente-Serrano *et al*. (2014) calculated surface relative and specific humidity and assessed their trends between 1961 and 2011. Results showed a large decrease in relative humidity over mainland Spain from 1961 to 2011, which was more pronounced in spring and summer (-1.02% and -1.56% decade^{-1}, respectively). On average, the decrease was on the order of -5.1% at the annual scale between 1961 and 2011. In contrast, there was no overall change in the specific humidity in this period, except in spring that exhibited an increase. Spatially, while the decrease in relative humidity affected the entire country, changes in specific humidity were less homogeneous. These results suggest an increase in the water holding capacity of the atmosphere, as a consequence of warming during recent decades. Nonetheless, this increase was not accompanied by an increase in surface water vapour content, probably because the supply of water vapour from the main terrestrial land/oceanic areas has been constrained, as suggested by Sherwood and Fu (2014).

6. Changes in the hydrological cycle: precipitation and evapotranspiration

The Spain report on Climate and Ocean: Variability, Predictability and Change (CLIVAR) project in 2010 made a detailed review of precipitation changes in Spain over the past decades (Bladé and Castro-Díez, 2010), stressing the high number of studies on this issue. However, these studies provided different results, as a consequence of the different homogenization tests applied to precipitation time series, varying study periods and the spatial density of rain gauges. In particular, Bladé and Castro-Díez (2010) indicated a general reduction in the total precipitation over the period 1960-2008, which affected most of the Iberian Peninsula. Nevertheless, they concluded that the magnitude of changes differed considerably, as a function of the database used and the study period. In the same context, there are a number of recent studies that have analysed precipitation trends in Spain, but with various methodological approaches, as some studies analysed long term magnitude (i.e. seasonal and annual), while others assessed changes at more fine (i.e. daily and sub-daily) scales.

6.1. Monthly, seasonal and annual precipitation changes

Considering a long-term perspective, Camuffo *et al*. (2013) analysed precipitation changes from two observatories in Spain (Barcelona and San Fernando), with long (>200 yrs) instrumental records. Both stations showed that the precipitation decrease between the 1960s and 2005 in spring and summer is unprecedented since the beginning of the 19th century. Different regional studies analysed precipitation trends covering different periods, but in general they recorded dominant negative trends during the past decades, including:, Altava-Ortiz *et al*. (2011) for three meteorological stations in the Mediterranean, De Luis *et al*. (2009) in the Mediterranean Iberian Peninsula, Fernández-Montes and Rodrigo (2015) in southeast Spain, Homar *et al.* (2010) in the Balearic Islands, Guerreiro *et al*. (2014) in the basins of the Douro, Tagus and Guadiana rivers and Ruiz-Sinoga *et al*. (2011) in southern Spain. Other studies did not show significant trends in precipitation at the seasonal and annual scales, such as Cropper and Hanna (2014) for the Canary Islands.

There are also studies that have analysed precipitation trends in Spain, but using dense network of meteorological rain gauges. One example is González-Hidalgo *et al.* (2011) who employed 2670 complete and homogeneous series for the period 1946-2005. They demonstrated that monthly precipitation trends show high monthly variability, with coherent spatial trend patterns in March, June (both with a general and significant negative trend) and October (general positive trends). More localized trend patterns were noted in July, February and April. Their results suggest that these local patterns are mainly controlled by topography. Del Río *et al*. (2011b) also analysed the spatial distribution of rainfall trends (1961-2006) using a dense database of 553 weather stations. This study revealed a decrease in rainfall in more than 28% of the Spanish territory during summer and winter. Although regional patterns of rainfall changes are complex, regional series over the whole Spain showed a precipitation decrease in winter and at the annual scale (Rodríguez-Puebla and Nieto, 2010). Vicente-Serrano *et al*. (2014) created an average precipitation series using 50 series over the Iberian Peninsula between 1961 and 2011, suggesting a statistically significant decrease on the order of -18.7 mm decade^{-1}, which was linked directly to the generalized streamflow decrease in the Iberian Peninsula since the 1950s (Lorenzo-Lacruz *et al*., 2012).

In addition to changes in precipitation magnitude, some studies also analysed possible changes in the temporal variability of precipitation and in precipitation regimes. Some studies showed an increase in the interannual precipitation variability. Over the Mediterranean region of Spain, De Luis *et al*. (2009) found an increase of precipitation variability in winter (+23.5%) and summer (+11.4%) and a decrease in autumn (−14.9%) and spring (−16.8%), with a global mean value of +7.8%. García-Barrón *et al.* (2011) analysed the evolution of annual rainfall irregularity in the southwest of the Iberian Peninsula, showing a progressive increase towards stronger interannual fluctuations of precipitation. In contrast, Guerreiro *et al*. (2014) did not find clear and generalized patterns toward higher or lower interannual variability in monthly precipitation series in central Spain. Therefore, more studies are still needed to increase confidence in assessments of changes in the temporal variability of precipitation over Spain.

In the same context, De Luis *et al*. (2011) analysed precipitation concentration changes in Spain (1946-2005), indicating an increase in precipitation concentration across most of the Iberian Peninsula, mainly driven by the increase in precipitation concentration during the wet season (October-March). Also, González-Hidalgo (2010) showed a general redistribution of precipitation throughout the year, with a reduction in the length of the wet season (due to the negative trend in March) and a concentration of precipitation at the beginning of the wet season in October. These results concur with García-Barrón *et al*. (2013) who found rapid changes in the most intense rainy periods during autumn and a consequent decrease in precipitation during spring across southwest Iberian Peninsula. Likewise, De Luis *et al*. (2010) analysed possible changes in traditionally described seasonal rainfall regimes in Spain during 1946-2005. They found that the percentage of territory in which winter constitutes the dominant precipitation season decreased from 51.1% to 42.7% of the total study area. While this area decreased in spring from 36.1% to 15.1%, it increased notably in autumn from 10.8% (restricted to the Mediterranean coast) to 41.4% of the territory. Overall, this study demonstrated that the wet season was shortened, inducing a concentration of the water input at the onset of the hydrological year (i.e. September-October).

6.2. Changes in daily extreme precipitation

Given their impacts on natural environments (e.g. water resources, biodiversity, hydrology, etc.) and human communities (e.g. energy, health, agriculture, etc.), recent studies focused not only on changes in the total precipitation magnitude, temporal variability and seasonality in Spain, but they also accounted for the frequency, intensity and duration of daily precipitation records. Bladé and Castro-Díez (2010) showed that daily precipitation intensity might have been reduced in the past 50 years, inducing an increase in the frequency of days recording low precipitation and a decrease in the frequency of intense precipitation events. Recent studies confirmed this pattern, although the strong spatial variability of intense precipitation events and the difficulties of analysing daily rainfall series make it difficult to assess whether precipitation intensity has noticeably changed in Spain.

With respect to precipitation frequency, Acero *et al*. (2012) analysed multi-day (1 to 7 days) rainfall trends in the Iberian Peninsula for the period 1958-2004. They found significant negative trends for a great part of the Iberian Peninsula in winter. In contrast, significant positive trends were observed over small areas in the southeast. According to this study, spring also showed negative trends for a great part of the Iberian Peninsula. Different studies analysed trends in daily precipitation indices at regional and national scales. For example, López-Moreno *et al*. (2010) assessed changes in daily precipitation indices for the northeastern Iberian Peninsula for the period 1955-2006, indicating a general decrease in the number of rainy days and precipitation intensity, and an increase in the duration of dry spells. Heavy rainfall events generally decreased in the west of the region during winter and in the east during autumn, concluding that these areas are more prone to hazards related to extreme rainfall. Valencia *et al*. (2012) also analysed changes in extreme rainfall indices for the Ebro River Basin using 14 meteorological stations from 1957 to 2002, showing a weakly but significant reduction of the extreme values in areas of high precipitation and near to the Mediterranean Sea. Homar *et al*. (2009) showed a different pattern for the Balearic Islands between 1950 and 2006, given that light (<4 mm) and heavy (>64 mm) daily precipitation contributed largely to the annual total precipitation, while the share from moderate-heavy (16-32 mm) precipitation decreased. Turco and Llasat (2011) investigated changes in indices of daily precipitation extremes over Catalonia, confirming that only the consecutive dry day index at annual scale showed a locally coherent spatial trend pattern, with around 30% of Catalonia experiencing an increase of 2-3 days decade^{-1}.

At the national level, there are a number of studies that analysed trends in high precipitation events. For example, Gallego *et al.* (2011) analysed trends in frequency indices of daily precipitation during the last century (1903-2003), using data from 27 stations in Portugal and Spain. They found that the total number of rainy days and that of light (≥0.2 and <0.25 mm) rainfall increased at many observatories over the Iberian Peninsula for all seasons. Nevertheless, some studies suggest a concentration of precipitation in a fewer number of days. Cortesi *et al.* (2012) assessed the statistical structure of daily precipitation over Europe from 1971 to 2010 using the daily precipitation concentration index (CI), suggesting significant positive trends in most of observatories south of Spain and along the Mediterranean coasts. More recently, Merino *et al.* (2016) defined regions that exposed to extreme precipitation hazards over the Iberian Peninsula and assessed trends of extreme precipitation index from 1960 to 2011, based on the 99th percentile of daily precipitation distribution.

The application of extreme value theory to assess trends in the most severe precipitation events is difficult given the irregularity of these extreme events and the common short length of their series. Albeit these limitations, some recent studies analysed this issue in Spain. A representative example is Acero *et al.* (2011) who used a peaks-over-threshold approach to study trends in extreme rainfall over the Iberian Peninsula. They indicated a high variability of extreme events over the Mediterranean coastline. The calculation of the trends for a 2-yr return period yielded a large proportion of negative trends for the considered seasons: 58% for winter, 63% for spring, and 69% for autumn. Nevertheless, the parametric approach also revealed an increase in the area with positive trends for a 20-yr return level, relative to a 2-yr return period. This feature could give indications on certain increase of intense precipitation events. Extreme value theory was also used by Beguería *et al.* (2011) to assess trends in the intensity and magnitude of extreme precipitation events using a set of 64 daily rainfall series in northeastern Spain from 1930 to 2006. Statistical significance was achieved only in less than 5% of the stations at the annual scale, suggesting no evidence of a generalized trend in extreme precipitation in the region. Also, Rodrigo (2010) analysed changes in the probability of daily precipitation observed from 1951 to 2002 in the Iberian Peninsula using a simple statistical model of daily precipitation based on the gamma distribution. This study showed that the trend of the probability of daily rainfall less than the 5th percentile is positive, mainly to the north and to the south of the Iberian Peninsula. In contrast, the probability of daily rainfall higher than the 95th percentile is negative, which would suggest a decrease of rainfall intensity during this period.

6.3. Snow precipitation

There are very few studies that analysed trends in snow precipitation, which is highly variable in time and space (Navarro-Serrano and López-Moreno, 2017). Overall, results are inconclusive and seem to be highly affected by the period of analysis. Pons *et al.* (2010) analysed snow trends in northern Spain using daily snow occurrence data from a network of 33 stations. They showed a significant decreasing trend in the annual number of snow days since the mid-1970s to 2001, with a reduction of about -50%. These changes were of similar magnitude for both low- and highly-elevated stations during winter and spring. In contrast, Buisan *et al.* (2015) investigated the spatial and temporal variability of winter snow in the western and central Spanish Pyrenees over the period 1961-2013, concluding that the definition of the study period can markedly influence the observed trends. In particular, they showed a statistically significant decrease in the number of snow days for the period 1971-2000, while trends were statistically insignificant for the periods 1961-2013 and 1980-2010.

6.4. The atmospheric evaporative demand

In addition to precipitation, evapotranspiration is a very relevant atmospheric variable to the hydrological cycle. However, it is necessary to distinguish between the actual evapotranspiration (ETa), which corresponds to the transferred water to the atmosphere in the form of vapor, and the potential evapotranspiration (PET), which corresponds to total water that would evaporate assuming that water supply from land is unlimited (see further details in Katerji and Rana, 2011). PET is difficult to determine since it depends on land conditions and vegetation types. For this reason, the concept of reference evapotranspiration (ETo) is alternatively used, which refers to a reference surface and it can be compared across different climate regimes and land surface conditions (Allen *et al.*, 1998). ETa is even more difficult to measure and there are no long term observations of this variable. As a supplementary source of data, land surface models and remote sensing images are used to quantify spatio-temporal variability of this variable, but with caution given their high uncertainty, particularly at the global scale (Hartmann *et al.*, 2013). The long term evolution of the Atmospheric Evaporative Demand (AED) has been usually assessed by means of evaporation pans. Nevertheless, IPCC2013 indicates only a medium confidence in the assessment of the AED changes at the global scale.

There are recent studies that have analysed AED trends in Spain using evaporation observations and robust physical models, based on the ETo Penman-Monteith scheme (e.g. Azorín-Molina *et al.*, 2015; Vicente-Serrano *et al.*, 2016). This method is based on different meteorological variables (e.g. wind speed, solar radiation, relative humidity and air temperature), providing accurate quantification of the AED (Allen *et al.*, 1998).

Espadafor *et al.* (2011) analysed ETo trends from 1960 to 2005 at eight stations in southern Spain, suggesting a general increase, mainly in summer months. More recently, Vicente-Serrano *et al.* (2014b) analysed temporal variability and trends in ETo over the whole Spain from 1961 to 2011, based on quality controlled and homogeneous series of various meteorological variables. On average, they found a strong increase (24.4 mm decade^{-1}) in the magnitude of ETo at the annual scale across Spain, with the main increase in summer (12 mm decade^{-1}). Using the same dataset, Vicente-Serrano *et al.* (2014c) analysed the sensitivity of ETo to the observed changes in a set of meteorological parameters (e.g. relative humidity, air temperature, wind speed, etc). They found that the aerodynamic component is more important in determining ETo, with respect to the radiative component. They also found that ETo trends were mainly explained by the decrease in relative humidity and the increase in maximum temperature since the 1960s, particularly during summer months. Sánchez-Lorenzo *et al.* (2014) developed, for the first time, an evaporation dataset for Spain based on long-term series of Piché atmometer and pan measurement records. Both the mean annual Piché and pan series showed evaporative increases over Spain during the study period (1985–2011). Furthermore, using the annual Piché records since the 1960s, an evaporation decline was detected from the 1960s to the mid-1980s, which resulted in a non-significant trend over the entire period 1961–2011, with the exception of summer season. More recently, Azorín-Molina *et al*. (2015) analysed the spatio-temporal evolution of evaporation observations from Piché atmometer and pan evaporimeters, and compared both measurements with evaporation estimates obtained by four physical models. They found that annual and seasonal trends of evaporation estimates showed a statistically significant increase for the period 1961-2011. This temporal evolution did not agree with long-term Piché evaporation trends; e.g. a discontinuity was found around the 1980s. They stressed that radiative and aerodynamic driving factors suggest that this discontinuity, and the observed evaporation trends across Spain, could be associated with the abrupt increase in air temperature observed at the beginning of the 1980s.

6.5. Droughts

IPCC2013 indicated low to medium confidence in assessments of drought trends at the global scale, given the few objective drought metrics, lack of direct observations, geographical inconsistencies of trends and dependencies of inferred trends on the chosen index and period (Hartmann *et al*., 2013). Moreover, determining drought trends under the current warming scenario is not an easy task, given the influence of different factors (e.g. precipitation and atmospheric evaporative demand) (Vicente-Serrano, 2016). In Spain, there are objective metrics that suggest increased drought severity, based on a dense and long database of streamflow records (Lorenzo-Lacruz *et al*., 2013). Using precipitation data, Vicente-Serrano (2013) analysed the evolution of droughts in Spain for the period 1910-2011, and stressed strong spatial variability. This study indicated that some regions showed a decrease in drought severity (e.g. Galicia and the southeast), whereas other regions showed increased severity (e.g. southwest, Catalonia and the central Ebro basin) (Coll *et al*., 2016). Thus, south Spain showed a large increase in the duration and magnitude of the drought events (Peña-Gallardo *et al*., 2016). Using a climate aridity index in Extremadura, Moral *et al*. (2016) found a general increase of land aridity annually, in summer and spring between 1951 and 2000. Lorenzo-Lacruz and Moran-Tejeda (2016) analysed droughts in the Balearic Islands between 1974 and 2014 based on the Standardized Precipitation Index, showing a strong temporal variability, but with no clear trends in this region. In the same context, Vicente-Serrano *et al.* (2014d) showed evidence on increasing drought severity, as driven mainly by the temperature rise in the Iberian Peninsula. They confirmed that drought severity increased in the past five decades, as a consequence of greater atmospheric evaporative demand resulting from temperature rise. They also stressed that recent positive trends in the atmospheric water demand had a direct influence on the temporal evolution of streamflow, particularly during the warm season, in which higher evapotranspiration rates are recorded.

7. Conclusions

This article reviewed the international scientific literature published within the last ten years on atmospheric trends in Spain, with a particular emphasis on the new released findings after the review of Bladé and Castro-Díez (2010). There are a number of studies dealing with trends in the different surface climate variables, including solar radiation, humidity, wind speed, air temperature and precipitation. While some studies covered the whole Spain, others focused on particular regions in the country. Although recent climate trends are determined by the used datasets and mostly the selected periods for analysis, it is possible to draw some concluding remarks for the different variables, which are illustrated in Figure 1:

i) There is a strong solar radiation increase from the 1980s, which has been caused by cloud cover trends (75% of solar radiation changes) and aerosols concentrations (25% of changes).

ii) Temperatures showed strong increases (around +0.3ºC decade^{-1}) since the 1960s, which were stronger in summer months. A slowdown of the mean temperature increase was recorded from the end of the 1990s, mainly driven by the evolution of maximum temperature. Nevertheless, the frequency of extreme warm temperature events (heat waves) noticeably increased from 2000.

iii) There are no noticeable changes in surface wind speed. A slight downward trend has been recorded but it is not statistically significant. Moreover, a different seasonal trend pattern of wind speed has been identified, with declines in winter-spring and increases in summer-autumn.

iv) Strong decrease in relative humidity was recorded (-5% between 1961 and 2011). In contrast, no changes in absolute humidity were identified.

v) There is a strong spatial and seasonal variability in precipitation trends, although average annual precipitation over Spain showed a moderate decrease in the past five decades. Studies on temporal trends in variability revealed different results and a change in the precipitation regime was recorded, indicating a trend toward shortened wet season and a higher percentage of autumn precipitation in the annual total.

vi) There is a strong uncertainty on trends in extreme precipitation events at daily scales, although most studies suggest an increase in the days recording low precipitation.

vii) There is no robust evidence on trends in snow occurrence, as the selection of the study period can noticeably influence the observed trends.

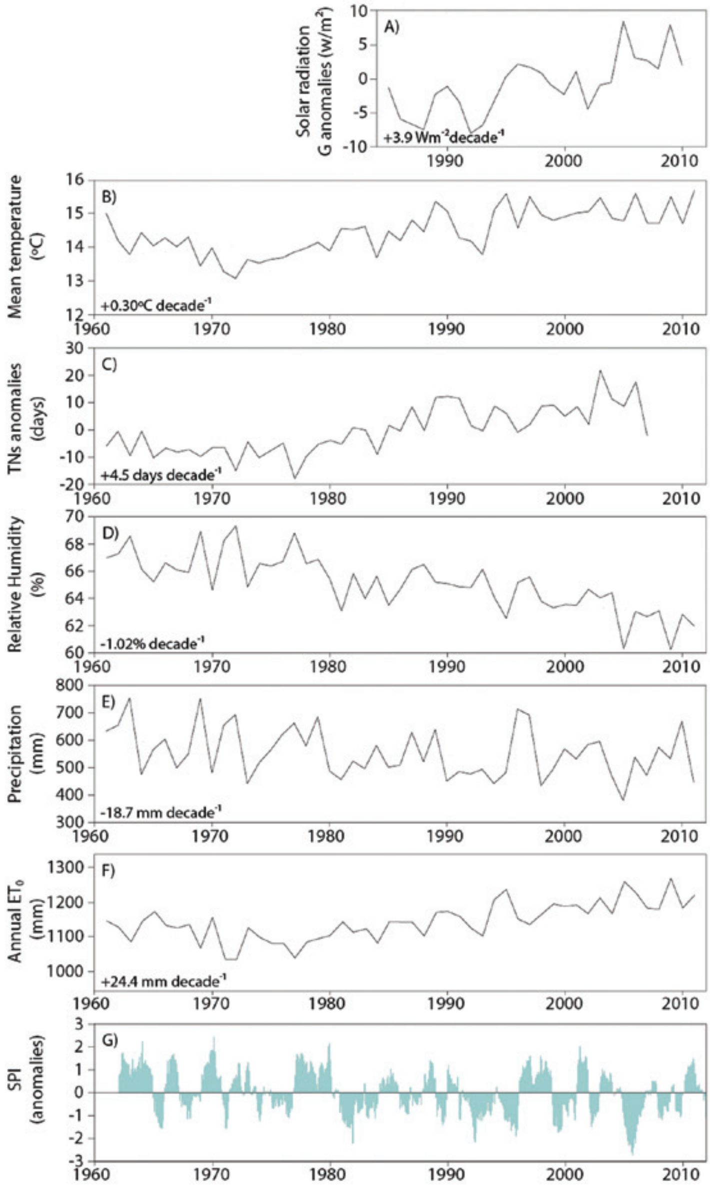

Figure 1. Meteorological variables for Iberian Peninsula analysed in the text (A) Mean annual G series expressed as anomalies from the 1991-2010 mean (modified from Sánchez-Lorenzo et al., *2013). (B) Evolution of annual mean temperature (1961-2011) (modified from Vicente-Serrano* et al., *2014) (C) JJAS temporal evolution of Tropical nights (Sánchez-Lorenzo* et al., *2012) (D) Evolution of annual RH (1961-2011) (modified from Vicente-Serrano* et al., *2014) (E) Evolution of annual precipitation) (modified from Vicente-Serrano* et al., *2014) (F) Evolution of annual ET_0 computed by Penman-Monteith method (modified from Vicente-Serrano* et al., *2014b) (G) Monthly evolution of standardized precipitation index (SPI) (modified from Vicente-Serrano* et al., *2014d).*

viii) The atmospheric evaporative demand increased in the past five decades (+24.4 mm decade^{-1}), mainly in summer months. This has been mainly driven by the decrease in relative humidity, besides the temperature increase.

ix) Drought frequency and severity increased in most of Spain, not only due to precipitation decrease, but also as a consequence of the increase in atmospheric evaporative demand.

Trends observed in some of the variables are in agreement with observations in some neighbour Mediterranean areas (Hartman *et al*., 2013). Nevertheless, although this is mostly valid for precipitation and temperature, it is difficult to establish robust comparisons for other variables such as wind speed, humidity or solar radiation, as there are very few studies on recent trends in these atmospheric variables over other Mediterranean regions. Overall, the recent climate trends observed for Spain clearly suggest a warmer and drier scenario in comparison to past decades. This finding is compatible with observations in other Mediterranean areas, where there is a tendency toward a climate scenario characterized by lower water availability (García-Ruiz *et al*., 2011) and the occurrence of more severe and frequent drought events (Hoerling *et al*., 2012).

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