

# Seasonal temperature trends on the Spanish mainland: A secular study (1916–2015)

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## Abstract

Trends in seasonal mean values of maximum and minimum temperature are analysed in the Spanish mainland from the new MOTEDAS\_century database. This new data set has been developed combining the digitalized archives from the Spanish Meteorological Agency (AEMET) with information retrieved from Annual Books published by the former Meteorological Agency dating back to 1916, and covers the period 1916–2015. In all four seasons, mean seasonal temperature of maximum ( $T_{max}$ ) and minimum ( $T_{min}$ ) increased. The raising occurred in two main pulses separated by a first pause around the middle of the 20th century, but differed among seasons and also between maximum and minimum temperature. Analysis of the percentage of land affected by significant trends in maximum temperature reveals two increasing phases in spring and summer for  $T_{max}$ , and in spring, summer, and autumn for  $T_{min}$ . However, winter  $T_{max}$  only rose during the recent decades, and autumn  $T_{max}$  in the first decades. Negative significant trends were found in extended areas in spring  $T_{max}$ , and in spring, autumn, and summer  $T_{min}$ , confirming the first pause around the 1940's–1960's. Trends of seasonal mean values of  $T_{max}$  and  $T_{min}$  are not significant for at least the last 25–35 years of the study period, depending on the season. The areas under significant positive trend are usually more extended for  $T_{min}$  than  $T_{max}$  at any season and period. Areas with significant trend expand and contract in time according to two spatial gradients: south-east to north-west (east-west) for  $T_{max}$ , and west to east for  $T_{min}$ . We hypothesize a relationship between atmospheric prevalent advection and relief as triggering factors to understand spatial and temporal differences in seasonal temperatures at regional scale during the 20th century in the Iberian Peninsula.

## KEYWORDS

MOTEDAS\_century database, seasonal trends, Spain, temperature maximum, temperature minimum

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## 1 | INTRODUCTION

Most temperature trend analyses face the problem of generalized poor data availability, which becomes particularly noticeable for the first half of the 20th century. To better understand current warming, however, a secular context or longer must be adopted better frame the current trends in perspective. Several studies have shown that temperature evolution during the 20th century was not monotonic but characterized by periods of rising temperature and periods in which temperature remained stable or even decreased, usually referred to as ‘pauses’ or ‘hiatus’ (Easterling and Wehner, 2009; Fyfe *et al.*, 2013; Kosaka and Xie, 2013; Dong and McPhaden, 2017). Temperature rise periods are usually identified between *circa* 1910–1940 and 1976–1997, while pauses have been reported between *circa* 1941–1975 and 1997–2013 (Folland *et al.*, 2018).

In the Western Mediterranean basin, and particularly in the Spanish mainland, there are only a few secular analyses, mostly carried out with a very low station density. Brunet *et al.* (2007) analysed the seasonal temperature evolution in 22 stations for the period 1850–2005. They found that the highest contribution to the annual mean increasing trend was in winter and autumn, with the rates of maximum temperature (diurnal time,  $T_{max}$ ) being stronger than those of minimum temperature (night-time,  $T_{min}$ ). They analysed the first rising period of the 20th century (1901–1949), also the first pause (1950–1972), and the second rising period (1973–2005). However, they did not provide any information regarding the second pause. They have shown, however, that temperature trends were not significant in several periods: in winter for  $T_{max}$  and  $T_{min}$ , and in summer and autumn for  $T_{min}$  over 1901–1949. Furthermore, negative and significant seasonal trends were found from 1950 to 1972, and during the final period analysed (1951–2005), autumn  $T_{max}$  and winter  $T_{min}$  trends were not significant. Different results were found by Staudt *et al.* (2007) who detected and corrected the urban effect in 43 stations, and suggested that  $T_{min}$  trend rates were higher than those of  $T_{max}$ . Unfortunately, these authors neither study sub-periods, nor combined the stations into a regional series. Other articles analysing the secular trends at sub-regional scale (see review in Gonzalez-Hidalgo *et al.*, 2015) agree with Brunet *et al.* (2007).

This situation contrasts with the large body of research covering post-1950 years, either using weather stations (del Río *et al.*, 2011, 2012), grids (Gonzalez-Hidalgo *et al.*, 2015; Herrera *et al.*, 2015; Gonzalez-Hidalgo *et al.*, 2018) or average regional and sub-regional series (Guijarro, 2013; Gonzalez-Hidalgo *et al.*, 2016).

Generally speaking, these papers analyse the period since the end of the first pause, thus covering only the second period of temperature rise, and in some cases detect the second pause. Still, they do not provide the secular of the evolution of temperature in the region. Gonzalez-Hidalgo *et al.* (2015) presented a more thorough review of these studies.

This paper presents an analysis of seasonal mean maximum and minimum temperature trends over the Spanish mainland, covering the period 1916–2015, and based on high spatial resolution information provided by the new MOTEDAS\_century database. The main objective is to explore the spatial variations of seasonal trends of  $T_{max}$  and  $T_{min}$  along the study period, by analysing their behaviour at different temporal windows.

## 2 | DATA AND METHODS

The recently presented MOnthly TEmpERature DATaset of Spain (acronym MOTEDAS\_century) combines information digitalized from the Annual Books (Libros Resúmenes Anuales, LRA) edited by the former Meteorological Agency of Spain, and digital data from the Banco Nacional de Datos del Clima (BNDC) of the National Meteorological Agency of Spain (AEMET). The data includes monthly maximum ( $T_{max}$ , diurnal-time) and minimum ( $T_{min}$ , night-time) temperature, and covers the 1916–2015 period. A general description of data rescue, station matching, quality control, and grid calculation are described in Gonzalez-Hidalgo *et al.* (2020), although the most critical information will be provided here. The resulting grid has been therefore obtained using the highest spatial information currently available, in particular for the period 1916–1949. Notwithstanding, the number of stations varies largely during the period of study, with a minimum of 228 in 1939 (end of the Spanish Civil War), and a maximum of 2030 in 1994. MOTEDAS\_century offers a spatial resolution of  $10 \times 10$  km.

Data rescued from the LRA filled gaps and extended back the BNDC series, because about 30% of data rescued from the LRA were not included in the BNDC. Thus, LRA data increased significantly the information available for the pre-1950 period. Nevertheless, data series from both, BNDC and LRA, present some drawbacks because there are a large number of stations with very short temporal records. For instance, 3,969 (75.5%) series from a total of 5,259 have less than 30 years (see tables 1 and 2 in Gonzalez-Hidalgo *et al.*, 2020). This characteristic is accentuated in the 1916–1950 period, when 13.2% of all stations (156) recorded data for only 1 year; 22% for only 2 years (259 stations); and 63% of the station (748)

for less than 10 years. Particularly, the LRA series tend to be very short: 351 stations from a total of 1107 (31.7%) recorded less than 3 year, and more than 70% (807) recorded less than 10 years.

The development of the grid was done considering that: (i) the number of stations changed year by year; and also (ii) that there were many changes in the location of some stations. In order to maximize the amount of information we decided to compute monthly fields independently using the total amount of data available each month, instead of reconstructing a selected number of time series. This approach is similar to the one described and used in the reanalysis project (Slivinski *et al.*, 2020), and we applied it after validating its adequacy by comparing alternative procedures using filled (reconstructed) and non-filled series. The interpolation procedure was a modification of the model suggested by Brunetti *et al.* (2006) that combines distance weighting and azimuth, after converting the original data into anomalies to avoid elevation effects. To do so, the difference between the observed values and the mean climatology was computed, using the 1951–2010 climatology computed by Peña-Angulo *et al.* (2016). Preliminary quality control of raw data was done to avoid suspicious data. Detailed information on the advantages and drawbacks of the procedure can be found in Gonzalez-Hidalgo *et al.* (2020).

Seasonal time series were obtained for each grid cell both for  $T_{max}$  and  $T_{min}$  using the classic aggregation (December–January–February for winter, March–April–May for spring, June–July–August for summer, and finally September–October–November for autumn). The sign and significance of the temporal trend were calculated by the Mann–Kendall test (Mann, 1945) using a significance level of  $\alpha = .05$ , after discarding any autocorrelation (see Gonzalez-Hidalgo *et al.*, 2015), and the rate of the trend was estimated following Sen (1968). Rates are shown as  $^{\circ}\text{C}$  per decade ( $^{\circ}\text{C}/\text{dec}$ ).

It is generally accepted that significance and rate in temperature trends depend on the chosen temporal window and length. However, there is no agreement on the minimum length required to robustly discriminate a trending signal from natural variability or noise. In our case, we set the minimum temporal span at 20 years, largely in excess of the recommendations of studies such as those of Knight *et al.* (2009), who suggested a minimum of 15 years, or Santer *et al.* (2011), who suggested a minimum of 17 years. More recently Huang (2013) noticed that ‘the most detectable secular trend signals appear in the  $\text{CO}_2$  band and the time it takes to see these radiance changes is much less than 12 years’, with similar opinions expressed by Loehle (2009), Liebmann *et al.* (2010) and McKittrick (2014).

Following the aforementioned research, temporal variations in trends were analysed by using increasing temporal windows spanning a minimum of 20 years (1916–1935), until covering the entire period 1916–2015. Additionally, decreasing temporal windows were also used, starting from the 1916–2015 window to the most recent 1996–2015 one (again, using a minimum length of 20 years). Increasing and decreasing temporal window trend analyses enabled us to find the effects of selected periods and temporal lengths on the resulting trends. In the first case, the effect of increasing the size of the period of analysis is similar to the process of updating a database year by year. The results, therefore, take into consideration the cumulative effect on the trend on both magnitude and significance. When the temporal windows decrease, the effect is equivalent to decreasing the age of the records, and it informs on the most recent period, mostly the second pause, and identifies its beginning, temporal length, and spatial variation, among other features. Finally, 30-years moving windows were also used to avoid the effect of the length of the windows on the confidence intervals of the trends (size effect).

### 3 | RESULTS

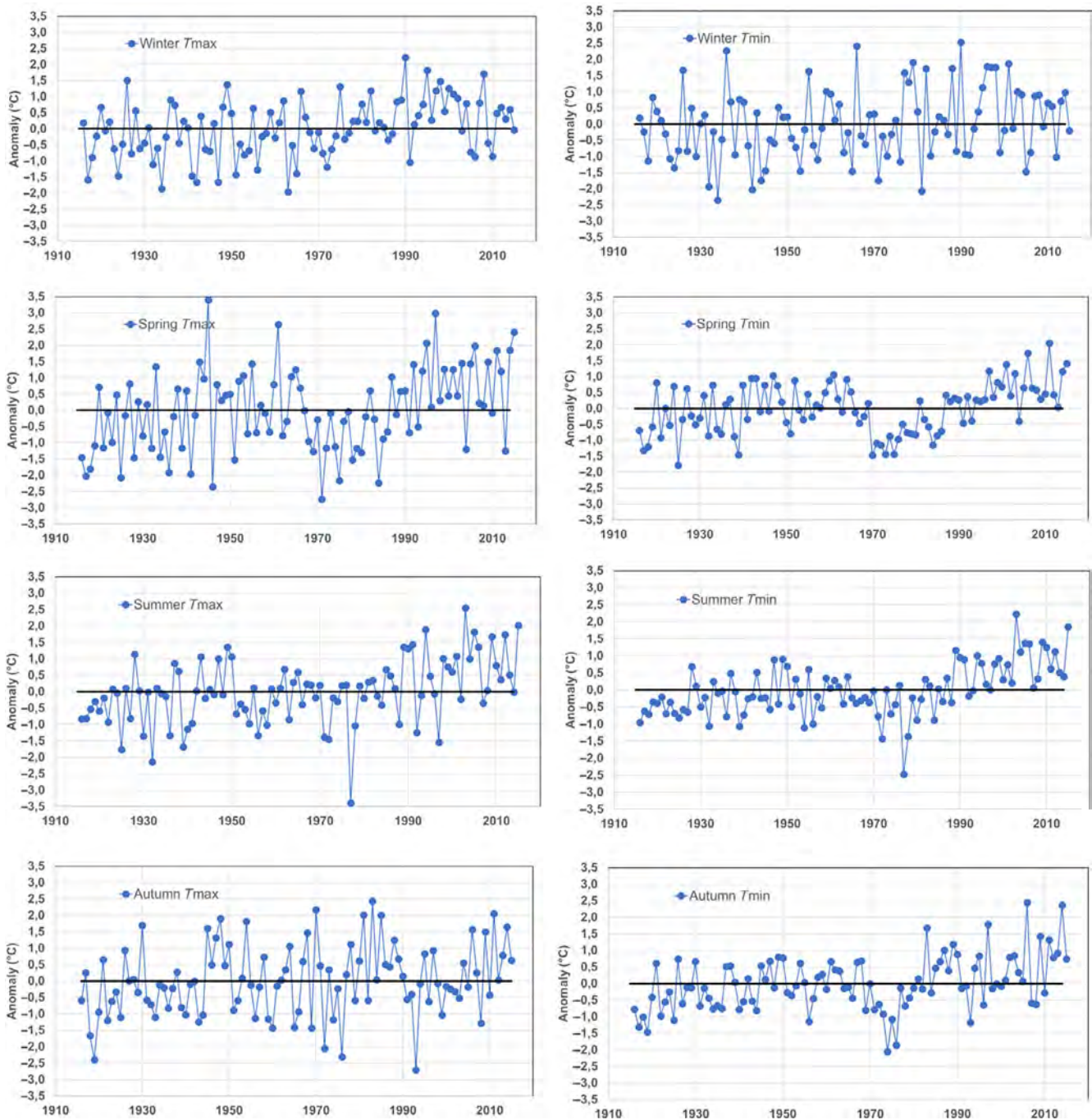
#### 3.1 | Seasonal temporal evolution of $T_{max}$ and $T_{min}$ on the Spanish mainland 1916–2015

The time series of mean seasonal  $T_{max}$  and  $T_{min}$  (as anomalies over the period 1916–2015) for the whole Spanish mainland are shown in Figure 1. The main result is that  $T_{min}$  shows lower temporal variability than  $T_{max}$ , except during winter.

The series shows a generalized increase in temperature during the study period, both in  $T_{max}$  and  $T_{min}$  and in the four seasons. It was easy to identify the different periods detected at a global scale. Also, we noted the extremely low temperature recorded in the summer of 1977.

The highest trend rate for the 1916–2015 period corresponds to  $T_{max}$  in spring ( $0.16^{\circ}\text{C}/\text{dec} \pm 0.08$ ) and summer ( $0.13^{\circ}\text{C}/\text{dec} \pm 0.06$ ). For  $T_{min}$  the highest rates occurred in summer ( $0.13^{\circ}\text{C}/\text{dec} \pm 0.04$ ) and autumn ( $0.11^{\circ}\text{C}/\text{dec} \pm 0.05$ ). Table 1 shows seasonal rates for different periods of regional series.

Global  $T_{max}$  rates are not significant for winter since the 1965–2015 window, and since 1945–2015 for  $T_{min}$ . For spring the not significant periods are 1985–2015 and 1992–2015, respectively. For summer they are 1981–2015 and 1987–2015. For autumn there is no clear behaviour



**FIGURE 1** Regional seasonal mean series (Spanish mainland) for  $T_{max}$  and  $T_{min}$ . Values as anomalies over 1916–2015 [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

in  $T_{min}$  because rates have changed to significant over the last few decades, while no significant trend were detected in  $T_{max}$ .

The highest seasonal trend rates occurred around the 1970s, and in recent decades the rates of both variables decreased for all seasons.  $T_{max}$  trend rates were higher than  $T_{min}$  in spring and winter when they were significant. In summer and autumn,  $T_{min}$  rates were usually higher than winter  $T_{max}$ , and higher in summer.

In general, the significance of rates remained for longer periods for  $T_{min}$  than  $T_{max}$ .

### 3.2 | Spatial variation in trends using 30-years moving windows

The evolution of the surface percentage according to the trend sign and significance at 30-years moving windows

**TABLE 1** Selected seasonal *T*<sub>max</sub> and *T*<sub>min</sub> trend rates in different temporal windows (10-year intervals)

		Sig.	Winter	(±)	Sig.	Spring	(±)	Sig.	Summer	(±)	Sig.	Autumn	(±)
Maximum	1916_2015_100	***	0.11	0.06	***	0.16	0.08	***	0.13	0.06	*	0.09	0.07
	1926_2015_90	**	0.12	0.07	*	0.13	0.10	***	0.13	0.07		0.05	0.09
	1936_2015_80	**	0.13	0.09	*	0.15	0.12	***	0.16	0.09		0.07	0.11
	1946_2015_70	**	0.15	0.11	*	0.19	0.15	***	0.18	0.11		0.03	0.14
	1956_2015_60	**	0.17	0.13	**	0.31	0.18	***	0.27	0.14		0.13	0.17
	1966_2015_50		0.13	0.16	***	0.52	0.21	***	0.33	0.17		0.07	0.25
	1976_2015_40		0.04	0.22	***	0.57	0.28	**	0.41	0.27		0.03	0.31
	1986_2015_30		-0.16	0.42		0.36	0.44		0.27	0.48		0.18	0.43
	1996_2015_20		-0.51	0.57		0.36	0.89		0.53	0.78		0.69	0.81
		Sig	Winter	(±)	Sig	Spring	(±)	Sig	Summer	(±)	Sig	Autumn	(±)
Minimum	1916_2015_100	*	0.08	0.07	**	0.09	0.05	***	0.13	0.04	***	0.11	0.05
	1926_2015_90	*	0.09	0.09	*	0.08	0.06	***	0.13	0.05	**	0.09	0.06
	1936_2015_80		0.09	0.11	*	0.08	0.07	***	0.15	0.07	*	0.09	0.08
	1946_2015_70		0.09	0.12	**	0.12	0.09	***	0.18	0.08	*	0.10	0.10
	1956_2015_60		0.09	0.16	***	0.21	0.13	***	0.27	0.09	**	0.19	0.13
	1966_2015_50		0.08	0.23	***	0.45	0.13	***	0.38	0.12	***	0.31	0.17
	1976_2015_40		-0.01	0.33	***	0.48	0.16	***	0.44	0.18	*	0.30	0.25
	1986_2015_30		-0.06	0.46	**	0.33	0.26	*	0.30	0.25		0.13	0.42
	1996_2015_20		-0.59	0.66		0.06	0.53		0.30	0.52		0.65	0.77

Note: Significance expressed by (\*\*\*)  $p < .001$ , (\*\*)  $p < .01$ , and (\*)  $p < .05$ . Rate values in °C/dec.

is presented in Figure 2. Two main rising periods are identified, and also intermediate and a final pause. The periods differ between *T*<sub>max</sub> and *T*<sub>min</sub> for season and annual values.

The first rise in *T*<sub>max</sub> affected less than 50% of land in spring, summer, and autumn, and did not occur in winter. On the other hand, the second rise was more extended in winter and started earlier than spring and summer, while being practically absent in autumn. Also the first pause is clearly detected in *T*<sub>max</sub>, when significant negative trends affected extended areas (>50%) in spring, and to a lesser extent in summer (c. 25%) and autumn (c. 10%). Meanwhile, the second pause is detected in the last decades in the four seasons.

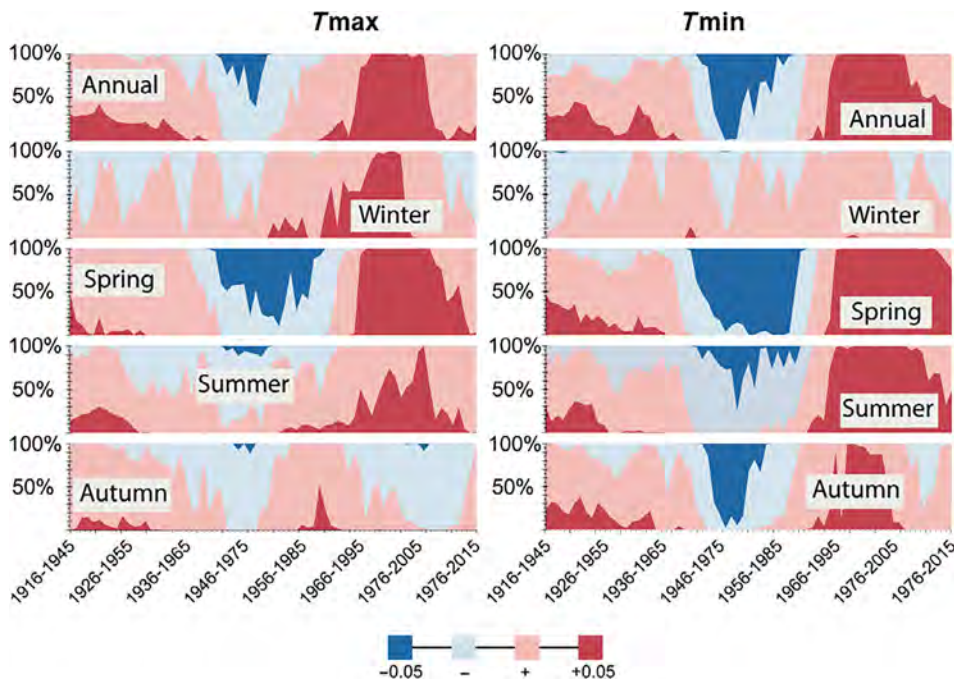
No clear evidences of winter rise are detected in *T*<sub>min</sub> during the study period, while two rising periods are identified in spring, summer, and autumn *T*<sub>min</sub>. During the first rising period the area under significant trend was around 25% (higher values than *T*<sub>max</sub>), and during the second positive phase it extended to almost the entire area in spring and summer, but also in autumn during some decades around the 1970's. Extended areas with significant negative trend have been identified (>75%) during the first pause in spring and autumn and to a lesser extent in summer, and no significant negative trend areas

have been detected in winter. No significant trends have also been detected during the last decades in *T*<sub>min</sub>, again showing the recent pause over extended areas.

These results suggest that the trend observed in the mean annual *T*<sub>max</sub> depend mostly on spring, summer, and autumn during the first rising period; and winter, spring and summer during the second one. For *T*<sub>min</sub>, on the other hand, spring, summer, and autumn defined the two rising periods.

The spatial evolution of trends according to 30-year moving windows is presented in Figure 3. In *T*<sub>max</sub> the first positive period until the mid-1950's mostly affects the south-eastern areas in spring, summer and autumn, while the second period begun around the 1960's and lasted until 2010 at most, being more extended. The Figure also shows that, for more than 30 years, no significant trend is detected for *T*<sub>max</sub>. With respect to the first pause, the negative significant trend is only detected in spring over extended areas.

The spatial evolution of *T*<sub>min</sub> trend sign and significance also shows two different positive phases, lasting the second in spring and summer until the final window (1986–2015) over extended areas and particularly to the east. No significant trends are found in any part of the study area in winter and autumn in the period



**FIGURE 2** The surface percentage under positive/negative trend and significance ( $p < .05$ ); 30-years moving windows.  $T_{max}$  (left),  $T_{min}$  (right) [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

1980–2015. Significant trends tended to appear in the central-western areas during the first positive period, while during the second one the area affected was more extended and shifted to the east. Extended areas of negative and significant trends are found around the period 1945–1985, when around 100% of the study area was affected by significant cooling. This period was more extended in spring than in summer and autumn, and mostly affected central-western areas.

The percentage of land affected by significant trends during the two positives periods and the first pause is higher in  $T_{min}$  than  $T_{max}$  in the four seasons. The above results seem to be an improved descriptor of warming than simple annual mean rates from a regional series.

### 3.3 | Spatial variations in trends using increasing temporal windows

Figure 4 presents the variation of the percentage of land affected by positive and negative, significant and non-significant trends under increasing temporal windows. The first temporal window (20 years, on the left side) corresponds to 1916–1935, and the last one (on the right side) includes the entire 1916–2015 period, thus there exists a cumulative effect along the chart that must be considered. The total area affected according to the sign and significance of the trend differs by seasons throughout the temporal windows. Globally, winter  $T_{max}$  trends were positive and significant and affected more than 50% of the area after the 1916–1982 window, increasing

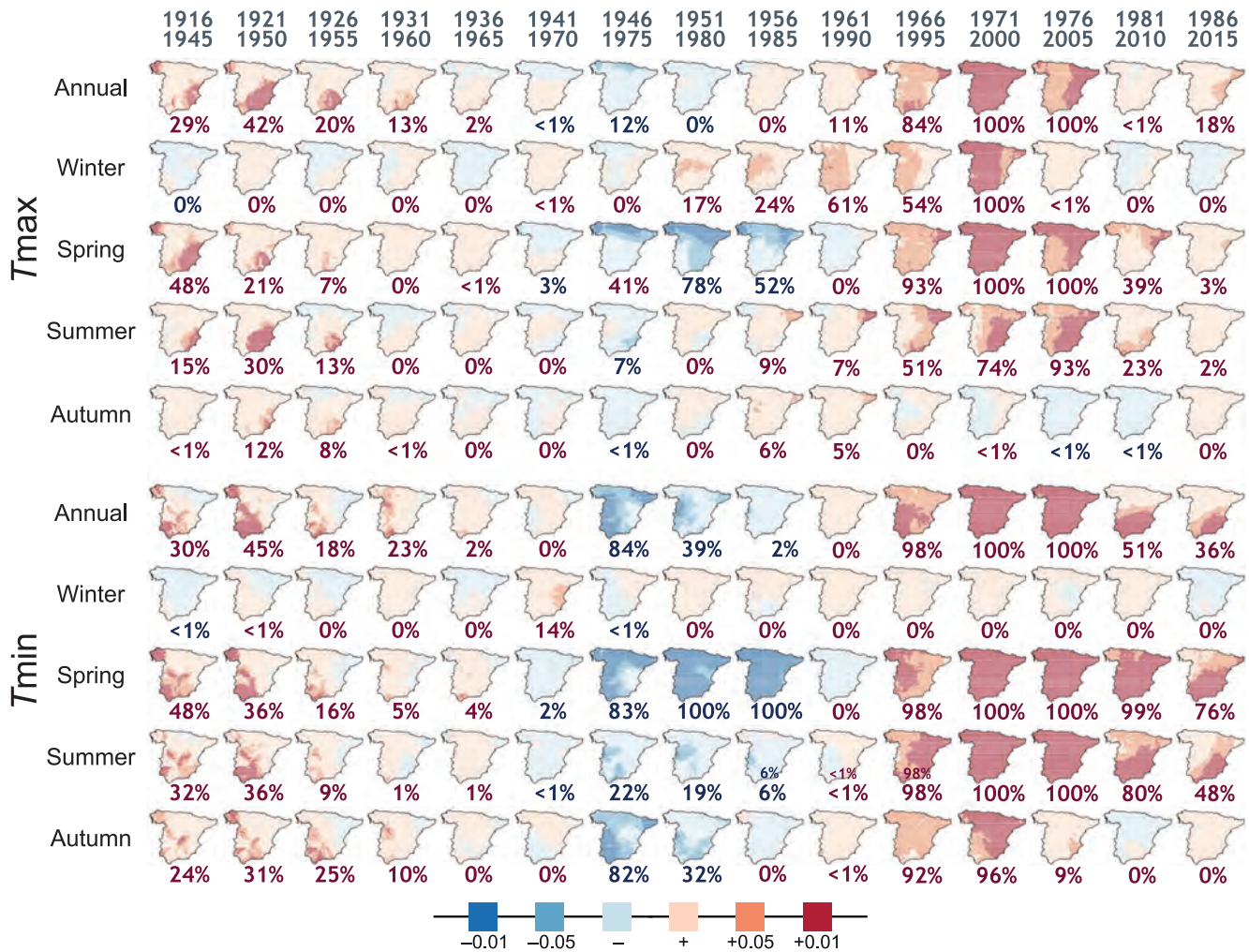
progressively to cover up to 94% of the territory in 1916–2015.

Spring and summer  $T_{max}$  also showed a generalized positive trend in the entire period, in accordance with previous studies (see Brunet *et al.*, 2007). In spring, the evolution of the percentage of land displays two pulses. The first one started in the temporal windows from 1916–1944 to 1916–1974, where positive and significant trends affected more than 50% of the area. Subsequently, given the effect of negative and significant trends detected in the first pause, no significant trends were detected until 1916–1987, when the area affected by positive trend in  $T_{max}$  starts again to increase to cover 93.4% of the area at the end of the study period.

The spatial evolution of land affected by positive and significant trends in summer was similar to spring except that, during the first pulse, the affected area was smaller. In the second raising pulse, starting in 1916–1994 up to the present, the area affected by positive and significant trends covered the study area almost completely. The positive and significant trends in summer affected more than 20% of the area in the intermediate period, whereas it was close to 0% in spring.

Evolution of the area affected by positive and significant trends in autumn differed: two pulses were detected in which the area under positive and significant trends increased (similar to spring and summer), but at no time covered more than 50% of the area (only one pulse of increase).

The results suggest that the use of annual mean values of  $T_{max}$  may mask important differences among



**FIGURE 3** Spatial variation in seasonal mean trends in  $T_{max}$  and  $T_{min}$  according to 30-years moving windows (5-year intervals). The figure includes the percentage under positive/negative predominant significant trend (Mann–Kendall test  $p < .05$ ) [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

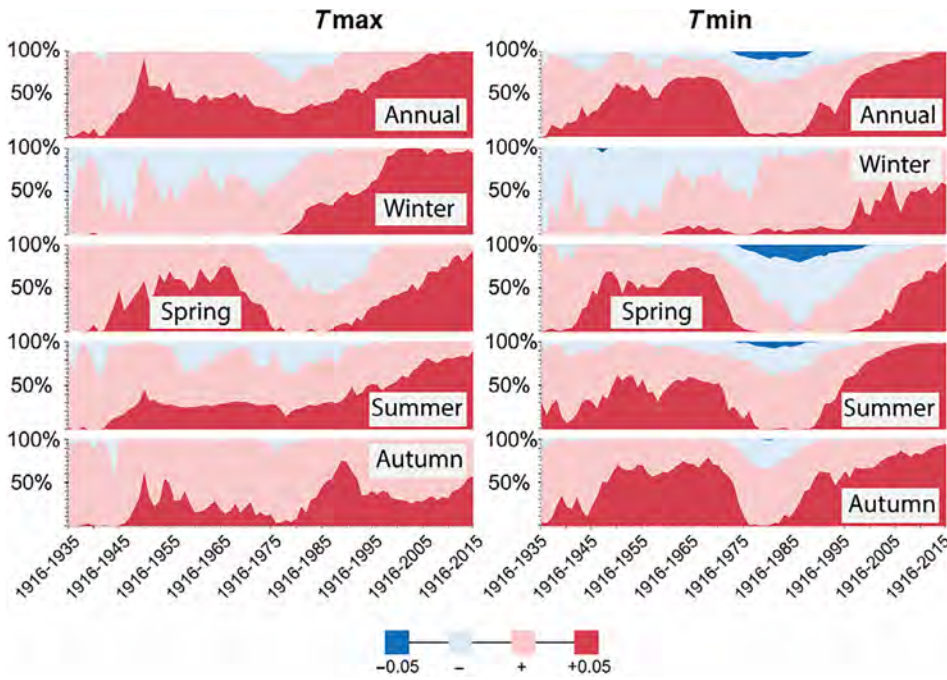
seasons and along time. Temperature rise until the 1970's, for instance, seems to be driven mostly by the evolution of spring and summer temperatures and, to a lesser extent, autumn. On the other hand, temperature evolution during the last few decades seems to be related with all seasons, albeit a lesser contribution of autumn.

The temporal evolution of  $T_{min}$  was quite similar in spring, summer and autumn. All of these seasons show  $T_{min}$  increasing in two pulses throughout the 20th century, with a high percentage of land affected by positive and significant trends (>50% of total land in the first case and >75% in the second one). Also, the first pulse is clearly represented with negative significant trends detected in spring and to a lesser extent in summer. Winter, however, showed a different behaviour again, and the percentage of land affected by positive and significant trends was less than 10% until 1990's, and the final maximum value reached 50%. These results agree with those

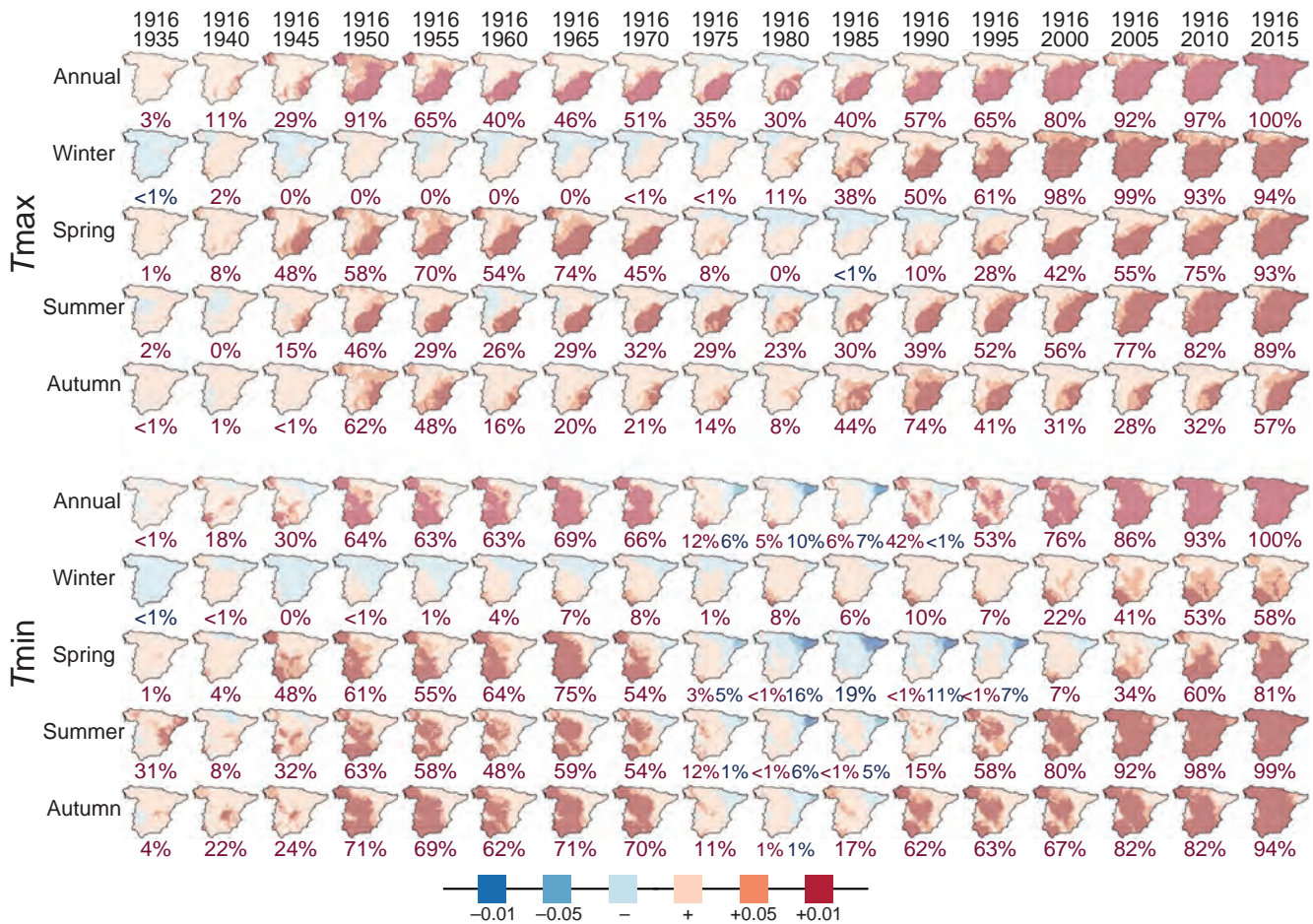
previously presented and show that the first rise in  $T_{min}$  was mostly driven by spring, summer, and autumn and the second one by winter, spring, summer, and autumn.

Figure 5 shows a sequence of maps with time steps of 5 years, and the percentage of land affected by positive-significant trends. Generally, the percentage of land affected by significant positive trends is higher for  $T_{min}$  than  $T_{max}$  in both periods of temperature rise, and particularly in summer and autumn. The figures show the importance of conducting detailed spatial analyses, because regional mean rates as those presented in Table 1 hide the rich spatial variability of temperature trends in the region. In Spanish mainland significant positive  $T_{min}$  trends have been more extended and prolonged than  $T_{max}$  in both rising periods.

Two gradients of spatial variation dominate the development of trends along the temporal windows. The areas affected by positive-significant trends in  $T_{max}$  expand



**FIGURE 4** The surface percentage under positive and negative trends and their significance ( $p < .05$ ); increasing temporal windows. Tmax (left), Tmin (right) [Colour figure can be viewed at wileyonlinelibrary.com]



**FIGURE 5** Spatial variation in seasonal mean trends in Tmax and Tmin according to increasing temporal windows (5-year intervals). The figure includes the surface percentage under positive/negative significant predominant trend (Mann-Kendall test  $p < .05$ ) [Colour figure can be viewed at wileyonlinelibrary.com]



and contract from the east (Mediterranean coastland) to the west (inland), while the reverse is true for  $T_{min}$  from west Atlantic-coastland to the east-inland. The two opposing gradients can be detected during the rising periods both in  $T_{max}$  and  $T_{min}$  in spring, summer, and autumn, while only the second one prevails in winter.

The first pause is apparent in a wide area in spring  $T_{max}$ , when positive significant trends were practically absent, whereas a small significant positive trend area remained in the eastern coastland in summer and autumn. For  $T_{min}$ , spring and summer showed a significant cooling period mostly located to the north-east, longer-lasting in spring than in summer.

### 3.4 | Spatial variation in trends using decreasing temporal windows

Figure 6 shows the temporal evolution of the percentage of land with significant positive and negative trends under decreasing temporal windows. From left to right, the plots confirm a global rise in temperature during the 20th century in  $T_{max}$  at the annual and seasonal scales. The presence of the second pause is, however, very marked, since temperature ceased to rise significantly in all four seasons. Taking the 20% of total land affected by a significant trend as a threshold, the starting date of the second pause can be identified precisely for  $T_{max}$ : in winter in 1965–2015; in spring and summer in 1985–2015 and 1983–2015. In autumn, the area affected by significant trends is less than 20% since 1933, but there is a brief recovery period around 1983. The same is true for  $T_{min}$ .

However, the winter pause started very early (1946–2015), while dates for the onset of the hiatus were 1992–2015 for spring, and 1988–2015 for summer; the autumn pause started in 1978–2015.

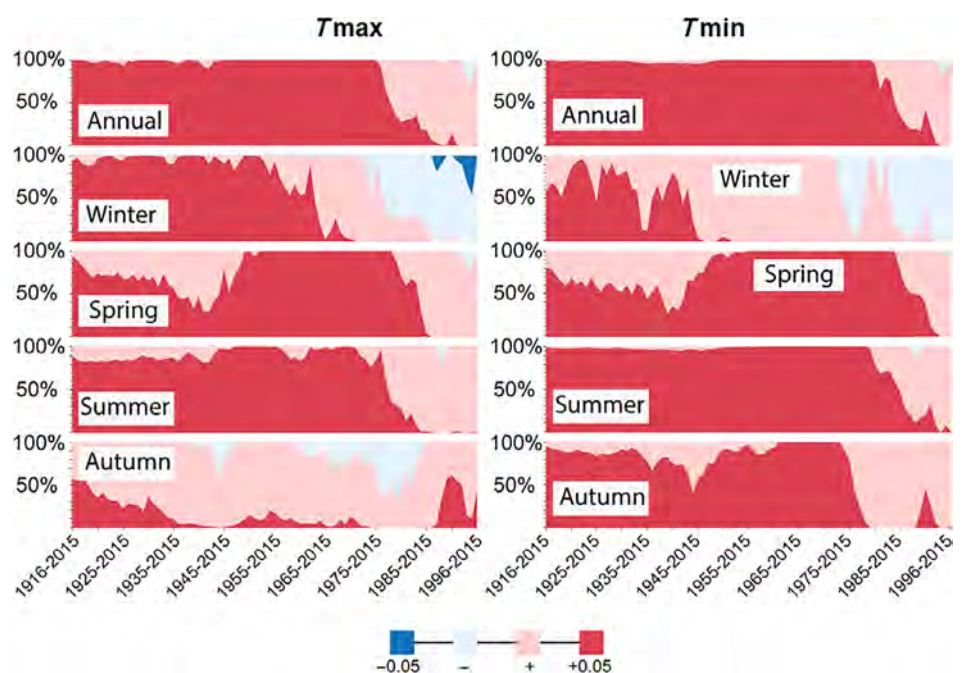
## 4 | DISCUSSION

### 4.1 | General comments

It has been assumed that global temperature rise has been controlled by the evolution of  $T_{max}$ , mostly in winter (Jones *et al.*, 1999). However, the negative trend of the diurnal temperature range since mid-century does not confirm this hypothesis (Rohde *et al.*, 2013; Sun *et al.*, 2018a,b). On the other hand, discrepancies arise in regional studies at the seasonal scales as those presented here.

There is detailed information for mainland Spain on temperature evolution from 1950 onward, characterized by a global rise, mostly in summer and spring (Brunet *et al.*, 2007; del Rio *et al.*, 2011, 2012; Rios *et al.*, 2012; Guijarro, 2013; Gonzalez-Hidalgo *et al.*, 2015). However, there is no agreement on whether the increase was stronger for  $T_{max}$  or  $T_{min}$ . On the other hand, less information exists for the first decades of the 20th century.

Our results show that, globally, seasonal mean values of  $T_{max}$  and  $T_{min}$  on the Spanish mainland rose between 1916 and 2015, in a similar sequence of periods as in the global data set and in previous research in the study area (see Brunet *et al.*, 2007). Also, the results confirm that differences exist among  $T_{max}$  and  $T_{min}$  at the



**FIGURE 6** The surface percentage under positive/negative trend and significance ( $p < .05$ ); decreasing temporal windows.  $T_{max}$  (left),  $T_{min}$  (right) [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

seasonal scale and at different temporal windows. Considering the whole period 1916–2015 and the regional series, spring and summer temperature rise was more pronounced than winter and autumn, both in  $T_{\max}$  and  $T_{\min}$ , and differences can be detected between  $T_{\max}$  and  $T_{\min}$  according to the temporal windows selected. Seasonal rates from MOTEDAS\_century are lower than those previously published for Spanish mainland, particularly in recent decades (see review in Gonzalez-Hidalgo *et al.*, 2015).

MOTEDAS\_century shows spatial detail and the research identifies spatial differences in the evolution of  $T_{\max}$  and  $T_{\min}$  along the time at the highest possible spatial resolution achieved. In spring and summer, we found two warming periods for  $T_{\max}$ , but only one in winter and autumn. On the other hand, for  $T_{\min}$ , we detected two positive pulses in spring, summer, and autumn and only one in winter. This means that temperature rise was mostly an effect of the evolution of spring and summer  $T_{\max}$  and  $T_{\min}$ , and to a lesser extent to winter  $T_{\max}$  and autumn  $T_{\min}$ , up to the 1970's.

MOTEDAS\_century also offers spatial information about the area affected by significant trend and this results can characterize better the warming than isolated regional or series for the whole Spain. In Spanish mainland, given the percentage of land affected by significant trend in both measurements at seasonal scale, the effect of  $T_{\min}$  on global warming seems to be more important than  $T_{\max}$ , on the contrary of previous results published (see table 5 in Gonzalez-Hidalgo *et al.*, 2020; also review in Gonzalez-Hidalgo *et al.*, 2015).

Finally, the seasonal analyses found non-significant trends in the last 30 years in both  $T_{\max}$  and  $T_{\min}$ . These results suggest that the second pause in mainland Spain, detected previously up to 2010 (Gonzalez-Hidalgo *et al.*, 2016), lasted until 2015. The analyses also confirm that the onset of the hiatus was before 2000, the date that is usually stated. This second pause has received closer attention because climate change models did not anticipate it (Soon *et al.*, 2004; Rahmstorf *et al.*, 2007; Stockwell, 2009; Lüdecke *et al.*, 2011; Cohen *et al.*, 2013; Fyfe *et al.*, 2016), and the discussion is not over on the causes, duration and eventual persistence (Chen and Tung, 2014; Schmidt *et al.*, 2014; Trenberth *et al.*, 2014; Li and Zha, 2019; Treloar, 2019). Different theories about its nature and cause have been suggested: (i) whether it appeared as a consequence of the natural variability of the climatic system (Foster and Rahmstorf, 2011; Fyfe *et al.*, 2016; Medhaug *et al.*, 2017; Tung and Chen, 2018); (ii) whether it was an artefact due to low-quality of data control (Karl *et al.*, 2015) and (iii) whether it even occurred at all (Risbey *et al.*, 2018), and also presents different local behaviours. According to the results

presented here the second pause has occurred whatever the reason, and futures updating processes will inform about its persistence, ending, spatial distribution, and so on.

Finally, the two spatial gradients in the seasonal temperature trends evolution along the time need to be explained.

## 4.2 | A hypothesis

The global temperature rise during the 20th century does not seem to respond to a single cause. The review by Folland *et al.* (2018) suggested that the first rising temperature pulse in the 20th century could be attributed to a combination of total solar irradiance (TSI), absence of volcanic eruptions, and the combined effects of two of the most prominent low-variability atmospheric patterns: El Niño Southern Oscillation (ENSO) and Atlantic Multidecadal Oscillation (AMO). These factors remained relevant during the second pulse of rising temperatures (1975–2005), when human emissions became the dominant factor. They suggested that the main causes of the first pause were the 60–80-year cycle of natural variability associated with the low intensity of the AMO pattern and an increase in volcanic activity as the leading causes. In contrast, for the second pause they suggested the reduction in TSI and increasingly frequent La Niña events as the main drivers. Fyfe *et al.* (2016) and Dong and McPhaden (2017) pointed out the coincidence of both pauses with negative phases of the Interdecadal Pacific Oscillation, and recent revision and attribution of this pause can be found in Medhaug *et al.* (2017) and Tung and Chen (2018), among many others.

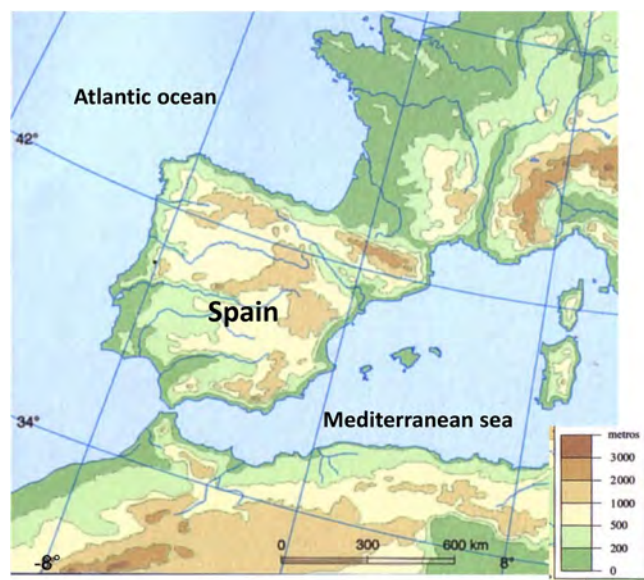
In Europe, spatial and temporal variations of temperature have been attributed partially to atmospheric variability modes and ocean-atmospheric coupling (Arguez *et al.*, 2009; Gámiz-Fortis *et al.*, 2011). Trigo *et al.* (2002) found, for the Iberian Peninsula, a positive relationship between NAO+ phase (westerly advection) and  $T_{\max}$  and negative with  $T_{\min}$ , while under NAO– conditions  $T_{\min}$  increased due to more prevalent cloudy conditions. Beranová and Huth (2008) identified spatial variation in  $T_{\max}$  and NAO across Europe. Lüdecke *et al.* (2020) have studied inter-annual variability of monthly mean temperature over 1901–2015, being NAO the dominant pattern in winter months, and the AMO pattern the triggering factor of summer months. They also pointed out that the relationship with atmospheric patterns is not so clear at the Iberian Peninsula latitudes as it is in the north European area, because of variations in time of the NAO dipole (Castro-Díaz *et al.*, 2002).

In the Iberian Peninsula, previous research analysed the relationship of temperature and prevalent flows by using pressure fields (Fernández-Montes and Rodrigo, 2012; Fernández-Montes *et al.*, 2012); Peña-Angulo *et al.*, 2016) or atmospheric indices that represent the prevalent flows, as teleconnection pattern such as North Atlantic Oscillation (NAO), East Atlantic, Western Mediterranean Oscillation (WeMO), among others (see, e.g., Ríos-Cornejo *et al.*, 2015). With respect to the relationship between NAO and temperature, contradictory results have been found. Sáenz *et al.* (2001a, 2001b) and Rodríguez-Puebla *et al.* (2010) did not find significant relationships, while Ríos-Cornejo *et al.* (2015), Favà *et al.* (2016), Fernández-Montes and Rodrigo (2012), Fernández-Montes *et al.* (2012), and Espíritu Santo *et al.* (2014) found significant relationships. Generally speaking, the effect of NAO decreases from west to east in the Iberian Peninsula, and is more prominent in winter than summer. A second interesting pattern in the western Mediterranean basin is the WeMO, defined by Martín-Vide and López-Bustins (2006). It is mostly related to precipitation, but its effects on temperature have not been analysed until present in detail, with some contribution in Ríos-Cornejo *et al.* (2015) and El Kenawy *et al.* (2012). As a general rule, WeMO has a strong influence on temperature from April to September (except in August) in two opposite areas: the northern coastland (under positive phase), and the eastern coastland (under negative phase).

Given the spatial differences observed in temperature trends, attribution of any global factor to temperature evolution in the study area should be combined with local factors, assuming that the latter can also vary

spatially. This is especially true considering the spatial gradients of evolution for the significance signal for  $T_{max}$  and  $T_{min}$  throughout the 20th century. These facts suggest that the effects of different factors on temperature, such as low-variability atmospheric patterns, for example, are not generalized in the study area as was indicated by Ríos *et al.* (2012). Furthermore, they may not be constant in time as Illes and Hegerl (2017) indicated in mid-latitudes of the northern hemisphere where the NAO effect on winter temperature rise fell to 43% between 1920–1971 and 45% in 1963–1995.

A hypothesis under research at present is that the two spatial gradients of positive and significant trends in  $T_{max}$  and  $T_{min}$  detected along the temporal windows, are related to different advection flows and their relationship with relief, because of the spatial alignment of the main mountain chains in the Iberian Peninsula (from west to east, and north-south to the east, see Figure 7). In previous research, it was identified an asymmetrical behaviour of temperatures under westerly/easterly flows, as westerly flows refresh and cool the Atlantic coastland while they warm the Mediterranean coastland (to the leeward of the mountain chains); and vice versa under easterly flows in a generalized adiabatic processes (Peña-Angulo *et al.*, 2016). These results agree with different comments in Favà *et al.* (2016) and Fernández-Montes and Rodrigo (2012), Fernández-Montes *et al.* (2012). If this hypothesis was correct, the effect of different atmospheric patterns as NAO or WeMO would be better understood, and then the positive trend of diurnal temperature should be located in areas not affected by the NAO pattern, that is, in the Mediterranean coastland to



**FIGURE 7** Relief of Iberian Peninsula. <https://mapswire.com/maps/countries/spain-physical-map-large.jpg> [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

the leeward of mountain chains, while the reverse should be true for eastern advection from the Mediterranean under WeMO negative phase. Many questions remain, and current analyses on the temporal variation of these relationships at the monthly scale should help us solve these questions.

In both gradients, the effect of an atmospheric low-variability pattern suggests that the predominant direction of flow varies in the positive and negative phases along time which, combined with relief alignment, could favour expansion or contraction of trends with different effects on  $T_{max}$  and  $T_{min}$ . It is interesting to note that the relationships between atmospheric patterns and temperature varies among cold season (NAO) and warm season (WeMO), while for precipitation Cortesi *et al.* (2013) described them in the winter months.

To summarize, in the western Mediterranean basin, mainland Spain, the spatial variation in time of seasonal mean values of  $T_{max}$  and  $T_{min}$  trends show differences that could be related to a combination of local factors (such as relief) with prevalent flows, probably linked to low-variability atmospheric patterns and their variation along the study period.

## 5 | CONCLUSION

The analyses of trends of the seasonal averages of  $T_{max}$  and  $T_{min}$  on the Spanish mainland show temporal and spatial differences between the two thermometric variables. Average seasonal maximum and minimum temperature increased during the period 1916–2015. This increase was, however, not continuous. In the case of  $T_{max}$ , two rising pulses were recorded in spring, summer and to a lesser extent in autumn. In winter, rise in maximum temperature was only detected in the most recent decades. For  $T_{min}$ , we detected an increase in two pulses in spring, summer, and autumn, and only recently in winter. The first pause which separates the two ascending pulses is also recognized in the regional temperature, record particularly in  $T_{min}$  (spring, autumn, and summer). The seasonal averages of trends have not been significant in almost the whole of the final three decades of the study period. If we consider the percentage of land affected by significant trends and the time under this conditions, the warming processes in Spanish mainland seems to depend more on  $T_{min}$  than  $T_{max}$ .

In time, for  $T_{max}$ , the areas with a positive and significant trend expand and contract inland from the east Mediterranean coast. For  $T_{min}$ , the areas with a positive and significant trend expand from the west to the interior of the peninsula. We suggest that a general process at the peninsular scale could cause both gradients, linked to

prevalent flow advection and then perhaps coupled to the prominent low-variability atmospheric patterns in the area (NAO and WeMO), at present under research. These results highlight the effect that local factors can have on the evolution of temperatures in the Iberian Peninsula.

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