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RESEARCH ARTICLE

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Variability of maximum and minimum monthly mean air temperatures over mainland Spain and their relationship with low-variability atmospheric patterns for period 1916–2015

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Abstract

The analysis of monthly air temperature trends over mainland Spain during 1916–2015 shows that warming has not been constant over time nor generalized among different months; it has not been synchronous for maximum and minimum air temperatures; and it has been heterogeneous in space. Temperature rose during two characteristic pulses separated by a pause around the middle of the 20th century in some months. In other months, only the second rising period is identified, or no warming can be found. In all months, and both for maximum and minimum air temperatures, a stagnation of the increasing trend is observed in the last two decades of the study period. High spatial variability exists in trend signal and significance, and two contrasting temporal patterns of advance over the study area are identified for maximum and minimum air temperatures. These patterns can be related to prevalent flow directions and relief disposition with respect to the flows associated with low-variability meteorological patterns North Atlantic Oscillation (NAO) and Western Mediterranean Oscillation (WEMO). The results show that warming is a complex phenomenon at regional and sub-regional scales that can only be analysed using high-spatial-resolution data and considering global and local factors.

KEYWORDS

monthly mean maximum air temperature, monthly mean minimum air temperature, MOTEDAS_century database, NAO, Spain, trends, WEMO

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1 | INTRODUCTION

Regional and local-scale climate research requires information of high spatial density. Notwithstanding, climate datasets often face problems related to the quality and homogeneity of the observational series and the low and varying spatial density of the observations (Janis *et al*., 2004). Jones *et al*. (2012) and Jones (2016) indicated that the increase in the number of observatories would only increase redundancy in the data sets. Still, an opposite opinion has been raised by Folland *et al*. (2018), Thorne *et al*. (2005, 2017a, 2017b) and Rao *et al*. (2018). It has been demonstrated that substantial differences exist among global datasets that can be related to differences in the spatial density of information and the interpolating models (Beguería et al., 2016). In any case, as a general rule, the results of these database analyses tend to disagree among regional and local scales (Vose *et al*., 2005; Menne *et al*., 2010; Hartmann *et al*., 2013; Thorne *et al*., 2016; Rao *et al*., 2018). Remote sensing improved surface station networks' deficiencies, mainly because they cover the Earth's whole surface, but they still require surface records for their validation.

The number of surface stations in global datasets has decreased since the 1980s (Hansen *et al*., 2010). This reduction has been most remarkable in rural areas and high altitudes (highland and mountain areas), and latitudes (Peterson and Voose, 1997; Menne and Williams, 2009). Furthermore, station location is biased towards specific land uses consistently over-represented in the regional and global datasets (Duveiller *et al*., 2018). The effects of these biases must be evaluated (see Montandon *et al*., 2011). These considerations are relevant at detailed spatial scales where the long-term context of warming is unknown because information from the early 20th century decades is scarce (Sun *et al*., 2018). Thus, the rescue of climate data that has not been previously considered is precious (Thorne *et al*., 2017a, 2017b; Folland *et al*., 2018) and even required to understand air temperature behaviour at detailed spatial scales (Fernández-Montes and Rodrigo, 2015).

The spatial and temporal variations of air temperature in Europe during the 20th century have been related to atmospheric-ocean coupling (Arguez *et al*., 2009; Gámiz-Fortis *et al*., 2011) and modes of atmospheric variability (Beranová and Huth, 2008). Trigo *et al*. (2002) described the advection of moist and warm air masses to the continent under positive North Atlantic Oscillation conditions (NAO+; http://www.cru.uea.ac.uk/data) due to a generalized westerly advection to the southern areas. In the Iberian Peninsula latitude, this advection increases diurnal air temperature (Tmax) because of sunny conditions, while night air temperatures (Tmin) tend to decrease. On the contrary, under NAO-, south-west advection causes increased Tmin air temperatures over the Iberian Peninsula due to prevalent cloudy conditions. Beranová and Huth (2008), on the other hand, found temporal changes in the correlation between NAO and Tmax in the Iberian Peninsula during the second half of the 20th century, showing that this relationship is dynamic. Recently, Lüdecke *et al*. (2020) studied the interannual variability of monthly mean air temperature (1901–2015). They found an effect of the atmospheric non-forced variability by the NAO pattern during the cold months (particularly February) and the Atlantic Ocean temperature (expressed by the Atlantic Multidecadal Oscillation [AMO] pattern between March and November, but especially during summer). They also observed that the intensity of the relationship between NAO and air temperature decreases at low latitudes, suggesting that in southern Europe, the relationship between NAO and the air temperature was highly complex because of spatial variation of the centre of actions of NAO dipole according to previous research (Castro-Díaz *et al*., 2002; Esteban-Parra *et al*., 2003).

The western Mediterranean basin is a nice example of the high spatial variability of air temperature evolution, and the case of the Iberian Peninsula is particularly well known (Brunet *et al*., 2007; del Río *et al*., 2011, 2012; Guijarro, 2013; Gonzalez-Hidalgo *et al*., 2015). This variability has been related to atmospheric circulation patterns as described by weather types defined from surface pressure fields (see Fernández-Montes *et al*., 2012, 2013; Peña-Angulo *et al*., 2016), and also as described by atmospheric circulation indices as indicators of modes of atmospheric variability (as NAO, among others). Remarkably, the relationship between the NAO and air temperature over the Iberian Peninsula has been the subject of several studies, with non-concluding results. Sáenz *et al*. (2001a, 2001b) and Rodríguez-Puebla *et al*. (2010) did not find any significant relationships, while other authors found the opposite (Fernández-Montes and Rodrigo, 2012; Espírito Santo *et al*., 2014; Ríos-Cornejo *et al*., 2015; Rodrigo, 2016). Generally speaking, it is accepted that the relationship between NAO and air temperature decreases from west to east and is higher in colder months. However, significant associations have also been found in summer for Tmax (Favà *et al*., 2016). It has been suggested that, at the seasonal scale, the influence of NAO is stronger in Tmin than in Tmax in winter (Trigo *et al*., 2002; Rodrigo, 2016), while in Portugal, Espírito Santo *et al*. (2014) found the opposite. To our knowledge, no detailed study has been conducted on a monthly scale.

A second prominent atmospheric pattern that affects the Iberian Peninsula's climate is the Western Mediterranean Oscillation (WEMO; http://www.ub.edu/gc/wemo/), defined by Martin-Vide and Lopez-Bustins (2006). This pattern shows a strong correlation with precipitation, although its relationship with air temperature has not been explored in detail. Until now, we are only aware of the study by Ríos-Cornejo *et al.* (2015) using monthly mean values, which mainly found negative relationships with WEMO in northern and western areas of the Iberian Peninsula and positive ones to the east, although there were differences among months. El Kenawy *et al.* (2012) found positive correlations with WEMO for winter mean air temperature and negative ones in spring, summer and autumn in the northeastern regions. As a general rule, the WEMO strongly influences air temperatures from April to September. No research has been conducted on the relationship between Tmax and Tmin with WEMO on a monthly scale.

In the global frame of the generalized increase of air temperature during the 20th century, four periods are usually identified between circa 1910–1940 (rise), 1941–1975 (pause), 1976–1997 (rise), and 1997–2013 (final pause) (Folland *et al.*, 2018). This study describes the evolution of monthly mean values of Tmax and Tmin over mainland Spain for 100 years (1916–2015). For that, we use the high-resolution air temperature grids from the new MOTEDAS_century dataset (Gonzalez-Hidalgo *et al.*, 2020). Previous studies have indicated that substantial spatial and temporal variability exists in Tmax and Tmin at the annual and seasonal scales (Peña-Angulo *et al.*, 2021; Sandonis *et al.*, 2021), but no detailed monthly analyses have been performed yet. The principal objectives of this study are: (a) to describe the evolution and trends of monthly maximum and minimum mean air temperature over the period 1916–2015 and their spatio-temporal variability; and (b) to analyse the relationship between the evolution of air temperature and other regional factors, and particularly the NAO and WEMO patterns.

2 | DATA AND METHODS

The new MOTEDAS_century dataset combines information retrieved from two sources: the national climate database (*Banco Nacional de Datos del Clima*, BNDC) maintained by the Spanish national weather agency (AEMET), and data digitized from the Annual Summaries Books (*Libros Resúmenes Anuales*, LRA), published until 1950 by the former meteorological services. The information available varies from a minimum of 228 observatories in 1939, and a maximum of 2,030 in 1994. Figure 1 shows the database's main characteristics: the spatial distribution of the observatories at different years, the frequency distribution of observatories according to the number of years with data, and the number of observatories per year. Detailed information on the MOTEDAS_century dataset is presented in Gonzalez-Hidalgo *et al.* (2020).

The MOTEDAS_century grid was developed with the following objectives: (a) maximizing the available information (avoiding the need to discard short-length series, especially from the LRA books); and (b) avoiding statistical gambling and data redundancy by not needing to perform data reconstruction to have continuous time series. Therefore, the grid was interpolated independently for each month, using all the available information without series reconstruction after checking anomalous data, similar to that described in the Reanalyses project (Slivinski *et al.*, 2019). The grid resolution was 10 × 10 km. Detailed information can be found in Gonzalez-Hidalgo *et al.* (2020).

Monthly mean maximum and minimum air temperatures were taken from the MOTEDAS_century dataset (Gonzalez-Hidalgo *et al.*, 2020). Month by month, and for each grid cell, the trend's sign (positive/negative), and significance were analysed by the Mann-Kendal test with a correction for temporal autocorrelation. Spatial and temporal variations of trends were analysed using 30-year moving windows. Also, we analysed the data set with rolling windows of increasing and decreasing temporal span. Under increasing temporal windows, the analysis informs about up-to-date effects, while under decreasing temporal windows the analysis informs about the most recent behaviour of trends. The results of trend analyses using periods of different lengths must be taken with care, as the test's power or sensitivity (i.e. the likelihood to detect a trend when there is actually one) varies according to the sample size. In particular, testing in shorter time series has a lower sensitivity than testing in longer time series, so the test is less prone to yield significant results. In other terms, a trend needs to be stronger to be labelled as significant in shorter series. The minimum time span used was 20 years, as different authors suggested, to avoid an excessive noise over signal ratio (Loehle, 2009; Liebmann *et al.*, 2010; Santer *et al.*, 2011; McKitrick, 2014).

The spatial analyses of change in trends were done calculating, for each temporal window, the percentage of land according to the trend's sign and significance. Their spatial projection was made using sequential maps. The resulting grid is available at the CLICES Project website (https://clices.unizar.es) as anomalies.

Finally, the relationship between monthly Tmax and Tmin and monthly NAO and WEMO indices was analysed at the grid-cell level using correlation analyses over 30-year moving windows and increasing and decreasing temporal windows.

3 | RESULTS

3.1 | Trends of monthly mean maximum and minimum air temperatures

The evolution of the percentage of monthly mean Tmax and Tmin trends classified according to their sign and

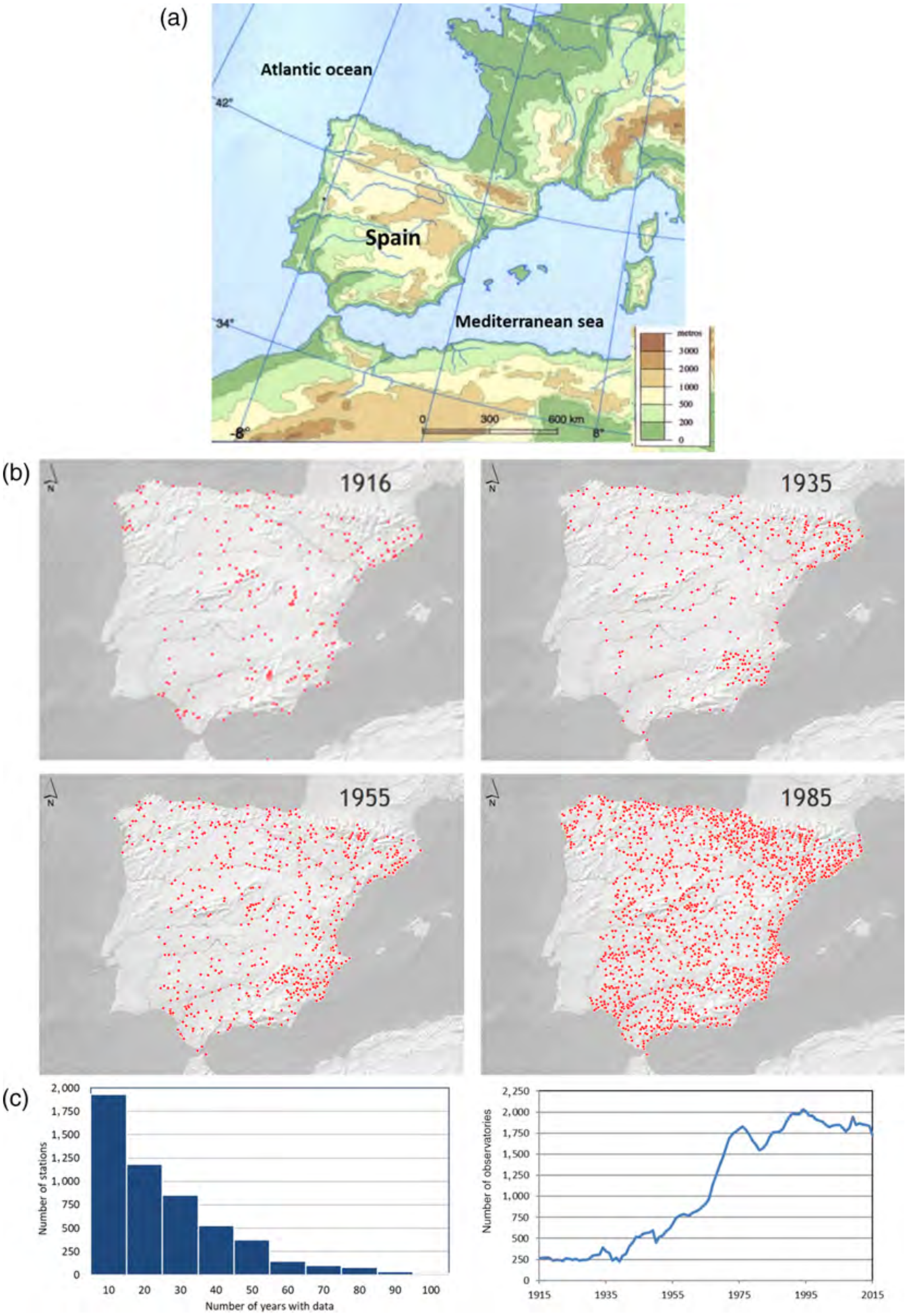

FIGURE 1 From top to bottom: (a) study area; (b) spatial distribution of meteorological stations (different years); (c) frequency distribution of stations according to years of records; (d) number of stations available per year [Colour figure can be viewed at wileyonlinelibrary.com]

significance along the 30-year moving windows is shown in Figure 2. The percentage of land classified by trend sign (positive/negative) in Tmax and Tmin shows the well-known global sequence of rise, then pause, then rise and final pause. The last rising period since circa 1970 is produced later in Tmin than Tmax, and more consistent

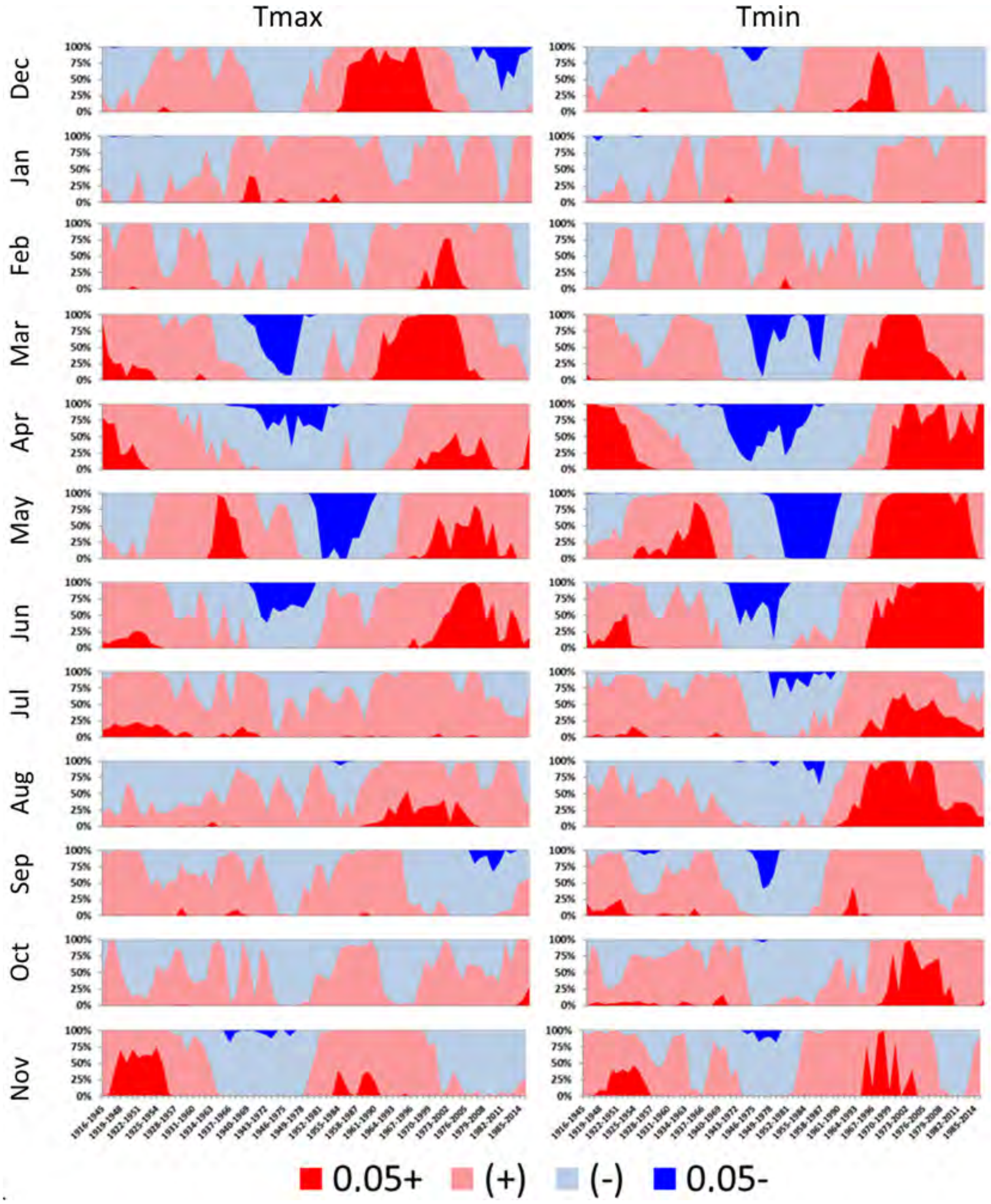

FIGURE 2 Temporal evolution of the percentage of land affected by trends using 30-year temporal windows between 1916 and 2015. The dark shades indicate significance. Data from MOTEDAS_century grid [Colour figure can be viewed at wileyonlinelibrary.com]

behaviour is found in Tmin than Tmax. In short, warming has not been constant, it has not been homogeneous in all months, and it has not been synchronous between Tmax and Tmin.

The first rising period is absent in the winter months (December, January and February). During the second rising period, the areas affected by significant positive trends are more extended in Tmax than Tmin, and more so in December than in January (when they are practically inexistent) and February. During these 3 months, trends are not significant in the last decades of the study period in Tmax and Tmin, and December even shows significant Tmax cooling.

In the spring months (March, April and May), the first rising period appears in Tmax in March and April and later in May. The second rising period affected an extended area in March, while it seemed later and had a lesser extent in April and May. On the contrary, in Tmin, the first rising period is detected over the whole territory in April, later affecting a smaller area in May and practically absent in March. The second rising period is more homogeneous and extended in the 3 months in Tmin than Tmax. The first

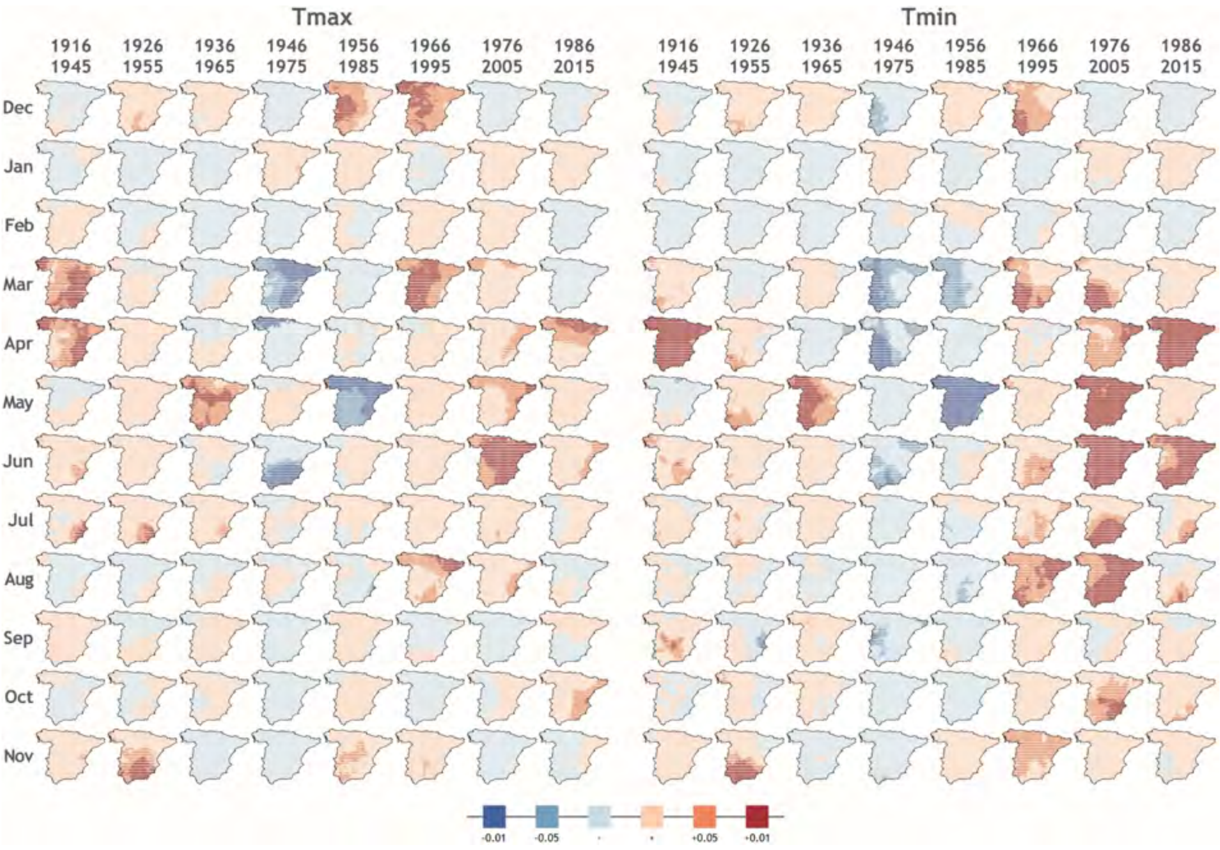

FIGURE 3 Selected sequences of 30-year time windows showing the spatial distribution of trends [Colour figure can be viewed at wileyonlinelibrary.com]

pause is detected clearly in the spring months, most notably in Tmin, with significant negative trends over a high percentage of land. Finally, air temperature trends are not significant in the spring months in the last decades in Tmax, and more recently in Tmin in March and May.

Trends of Tmax and Tmin differ during the summer months (June, July and August). The first rising period is detected only in a small fraction of the study area in Tmax during June and July, in a larger area during the second rising period in June, and to a lesser extent in August. In Tmin, the first rising period is practically absent except in June, while the second rising period is generalized in June, July and August. In general, the surface with significant positive trends is higher in Tmin than Tmax. Also, the first pause is detected in Tmin and in June Tmax, while the surface affected by significant negative trends is smaller than in the spring months. Trends are not significant in the last decades practically in the whole land except in Tmin in June.

Spatial and temporal variability of trends can be observed again in autumn months (September, October and November). Tmin increased in October and November during the second rising, although the surface affected did not reach 90% of the land. During the first rising period, except November, significant positive trends did not reach 25% of the land. The evolution of Tmax trend is different, and only November shows a rise during the first pulse. A non-significant trend in recent decades characterizes the autumn months in recent decades.

According to trend sign and significance in 30-year moving windows, the spatial evolution of areas is presented in Figure 3 in selected 10-year intervals (complete sequence in Figure S1). In general, variations in time reflect expansion and contraction of areas along a longitudinal gradient both in Tmax and Tmin (see as example December 1956–1985/1966–1995), although some latitudinal patterns also exist as is the case of Tmin (July and August in between 1966 and 2015 time span). The sequence of maps shows that no significant trend dominates in the most recent decades, except for some months and areas to the east along the Mediterranean coast. Interestingly, the first pause around the middle of the 20th century (ca. 1946–1975/1956–1985) shows an opposite spatial gradient between Tmax (West–East) and Tmin (East–West) during March, April and May, which are the most affected months.

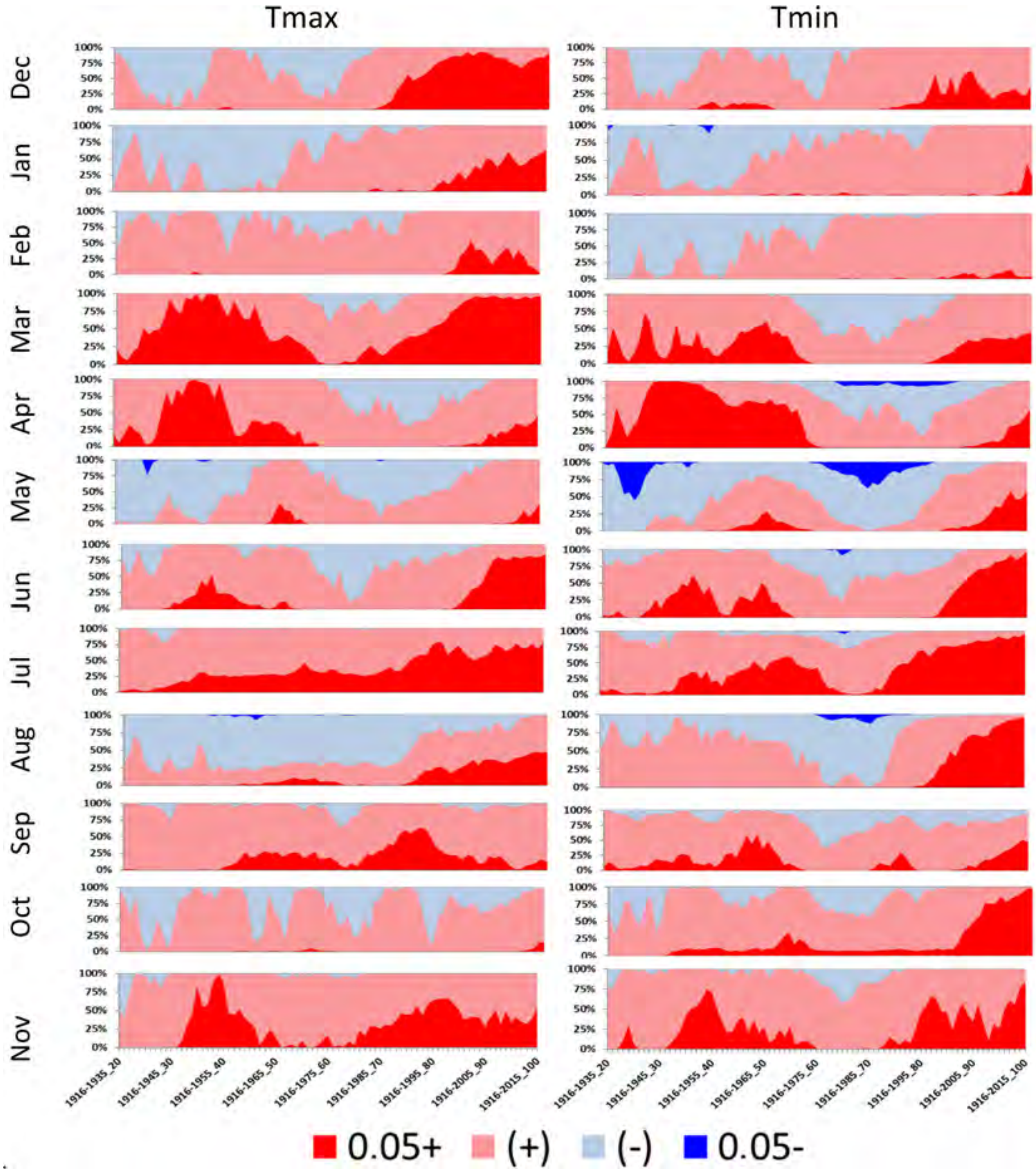

FIGURE 4 Temporal evolution of the percentage of land affected by trends using temporal windows of increasing length. The dark shades fulfil the confidence of significance. Data from MOTEDAS_century grid [Colour figure can be viewed at wileyonlinelibrary.com]

3.2 | The up-to-date effects on trends (increasing temporal windows)

The time evolution of the percentage of land according to the trend sign and significance using temporal windows of increasing length is presented in Figure 4. Figure 5 shows the sequence of maps for selected time windows (complete sequence in Figure S2). As mentioned previously, this analysis mimics the process of progressive updating of the dataset. It must be considered that each time window includes a different number of years, and this could affect the trend's significance. In particular, significant trends are more difficult to discriminate in shorter series. In Figure 4, the cumulative effect of the updating processes is evident and shows the two positive pulses and the pause in the middle of the 20th century. This figure demonstrates: (a) that monthly mean air temperature, both Tmax and Tmin, had a general increase in the whole territory (significantly or not); (b) that the total land affected by air temperature rise differs between Tmax and Tmin; and (c) that there has not been synchronicity between Tmax and Tmin rise at the monthly scale.

The percentage of land affected by a significant increase in Tmax and Tmin during 1916–2015 is shown in Table 1. These results suggest that, in the whole area, the evolution of Tmax and Tmin has not been homogeneous in space, neither synchronous between Tmax and Tmin.

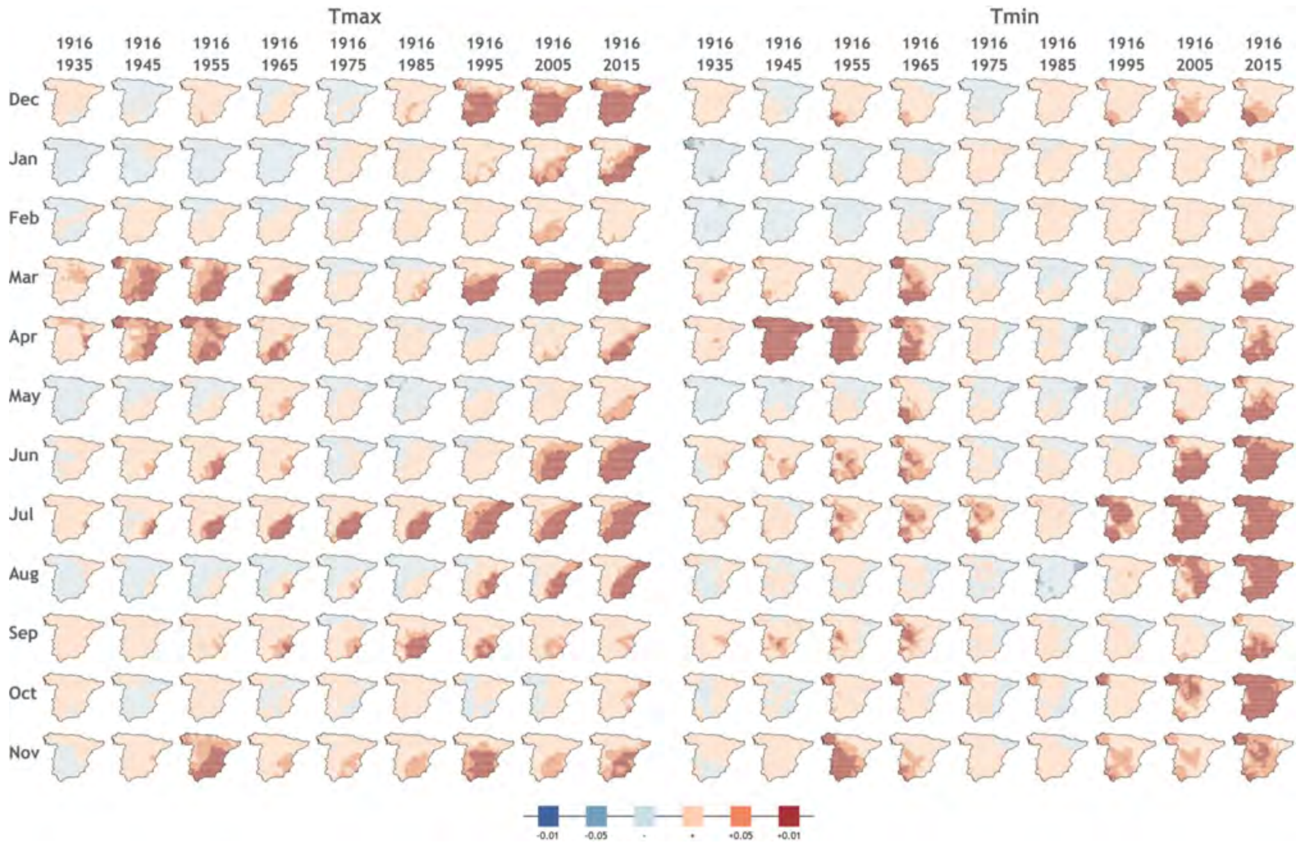

FIGURE 5 A selection of map sequences showing the spatial distribution of trends using time windows of increasing length [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 1 Per cent surface with a significant and positive trend during the period 1916–2015

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Tmax	62.4	2.2	**96.5**	44.6	32.5	84.7	78.2	47.6	10.9	14.2	54.2	**90.5**
Tmin	27.6	2.6	45.4	57.5	57.8	**97.7**	**96.3**	**95.3**	47.3	**98.0**	84.1	35.8

Note: Bold font indicates values higher than 90%.

Generalized Tmax increase (more than 90% of the land affected) is restricted to March and December. June and July also have a large fraction of the territory with significant trends (>75%) and, to a lesser extent, January and November (>50%). Generalized Tmin increase (>90% of total land), on the other hand, is restricted to the summer months (June, July and August) and October, and to a lesser extent April, May and November (>50%). Consequently, we can assume that the increase of air temperature in the Spanish conterminous land has been originated by a combination of Tmax rise in the coldest and warmest months, combined with Tmin rise in the warmest months. There are months in which almost no significant trends are found (February); in which the percentage of land with a significant trend is small (<50%) in both Tmax and Tmin (May and September); and months in which Tmax and Tmin differ noticeably as March and December (percentage of land under significant positive trend in Tmax is two times Tmin), or August and October (opposite effect).

The maps' sequences in Figure 5 show that two spatial gradients exist of expansion–contraction of areas under significant positive trends. In Tmax, significant positive trend areas expand and contract from the Mediterranean coast to the inland area (East–West–East). This gradient is identified in the first and second positive pulses of Tmax rise; during the first one in March, April, June, July and November; and during the second in January, March, April, June, July, August, September, November and December. In Tmin, the spatial gradient is the opposite, with expansion and contraction of the positive significant

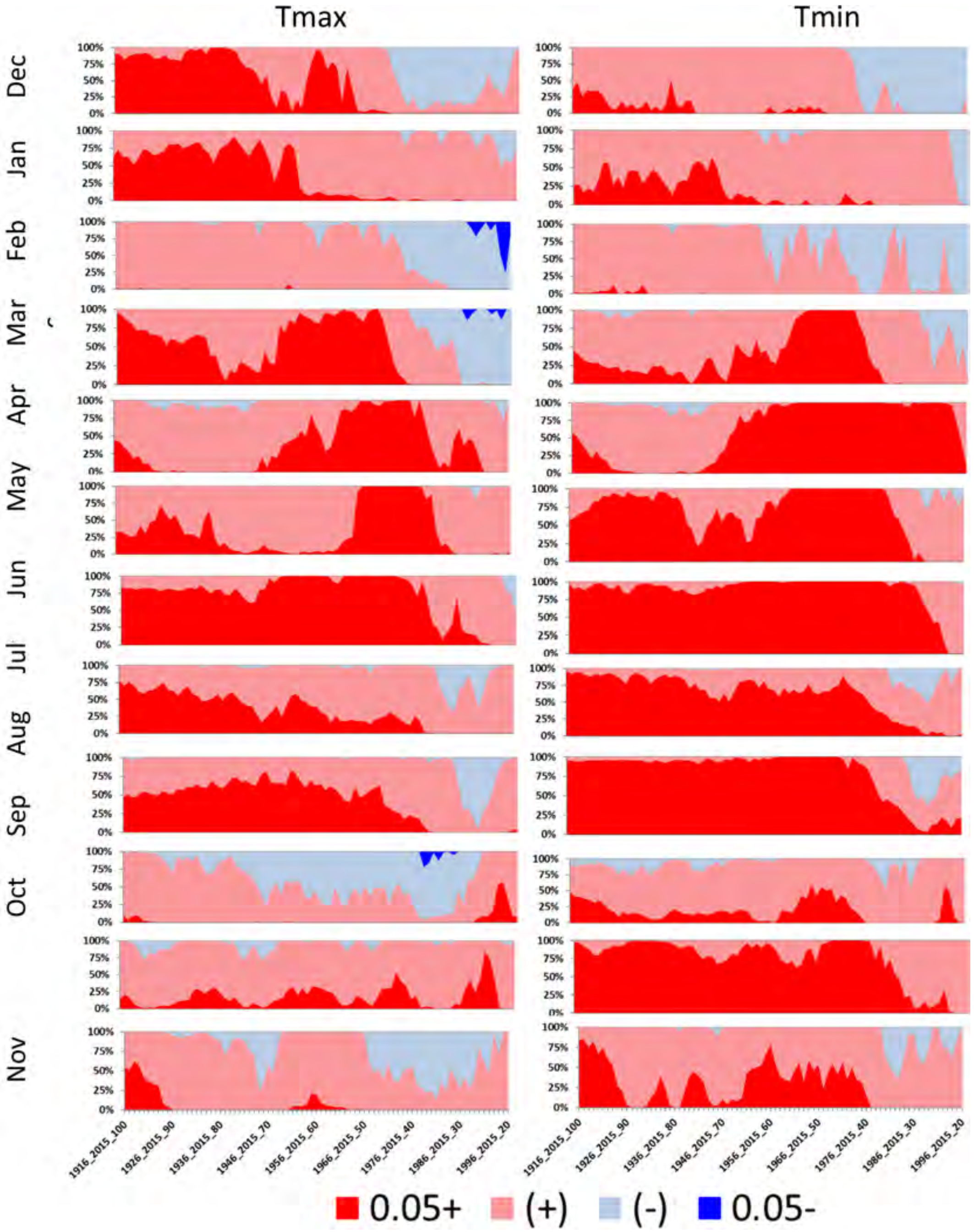

FIGURE 6 Temporal evolution of the percentage of land affected by trends using temporal windows of decreasing length. The dark shades fulfil the confidence of significance. Data from MOTEDAS_century grid [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 2 Detection of final stagnation by using rolling decreasing temporal windows

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Tmax	1954		1973	1990*	1982*	1986	1976*	1975	1998*	1992*	1956*	1963
Tmin	1947		1978*	1996*	1986	1992	1983		1994*	1992*	1976*	1937*

Note: The year indicates the beginning of the temporal windows (e.g. Tmax January: 1954–2015, March 1973–2015, etc.) in which the trend is not significant. The asterisk (*) indicates that there are other previous temporal windows with no significant trends.

trend areas from the West to the inland in March, April, June, July, September and November during the first rising period, and from the South to the inland and the North in December, March, June and September during the second pulse. Spatially the contiguity of areas is higher in Tmax than Tmin during the first period.

3.3 | The effect of the start of the records (decreasing temporal windows)

The time evolution of the percentage of land according to the trend sign and significance using temporal windows of decreasing length is presented in Figure 6. The area affected by positive significant trends decreases in all months in the recent decades for both Tmax and Tmin, except for April's Tmin. The decrease of land affected by significant positive trends could be monotonic from the beginning and influence the entire period (July or August); had been started after an abrupt change (December, March, May and June); or occur at different pulses (April). In Tmin, the decrease of the percentage of land under a significant positive trend is usually preceded by an abrupt change in the most recent decades, especially March, April, May and June, and to a lesser extent in July, August and October.

Table 2 shows the first year of the decreasing time windows in which less than 20% of the territory has significant trends. As can be seen, Tmax trends are not significant from more than 30 years in most of the months. For Tmin, the results are similar. In January, March, May, July, November and December, trends are not significant for more than 30 years.

Spatial evolution of trend under decreasing temporal Windows is presented in Figure 7 at decadal intervals; the sequence includes the entire period windows 1916–2015 (left), until the most recent 1996–2015 considered (right). Complete analyses are included in Figure S3.

As expected, the figure shows a progressive reduction of the areas affected by significant positive trends. This reduction is towards the Mediterranean coast and the southern region. Also, the figure shows that trends of Tmax and Tmin are not significant during at least the last 30 years in most of the study areas. In February, even a negative significant Tmax trend is detected over a large part of the area.

This analysis indicates that the monthly mean values of Tmax and Tmin have not increased significantly

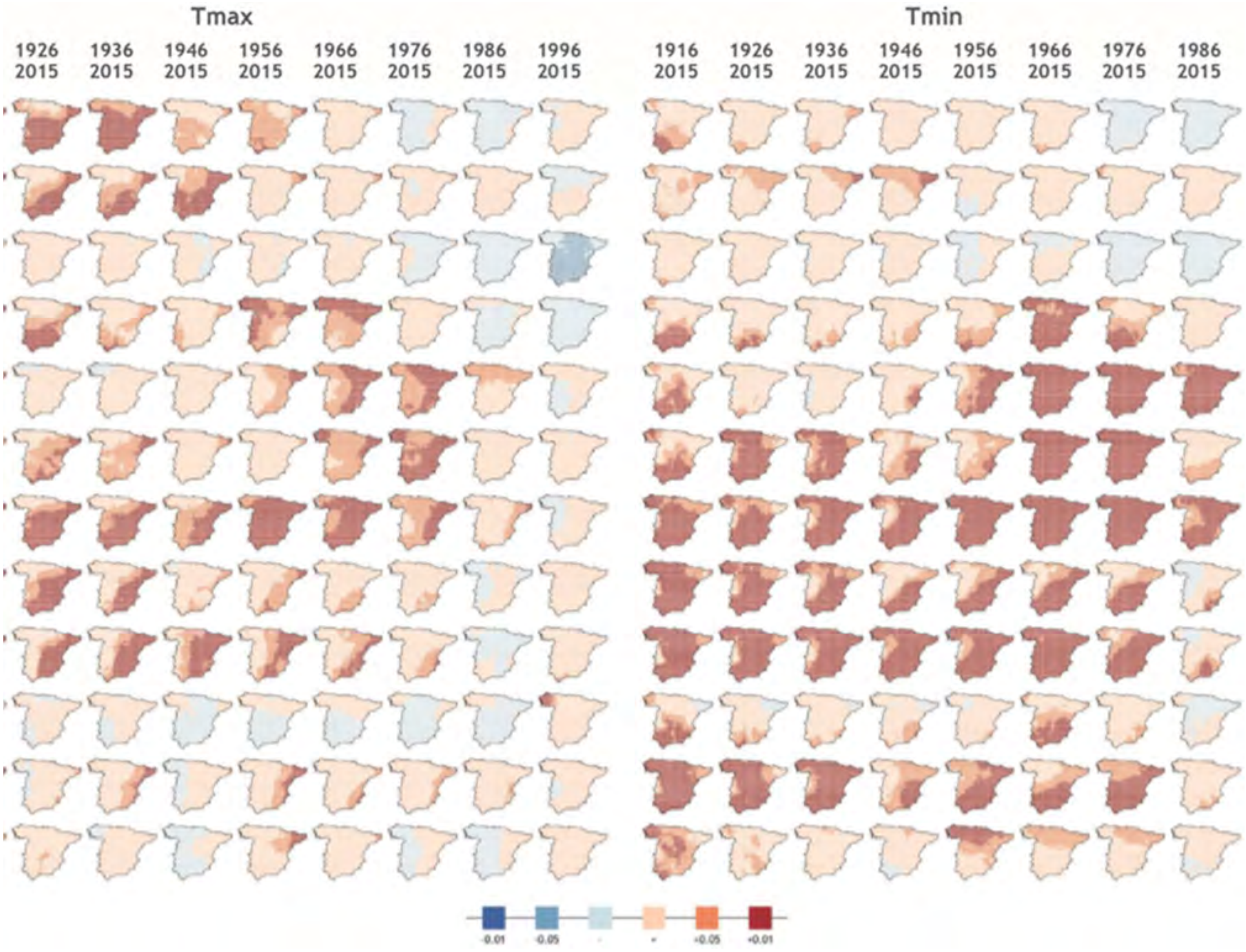

FIGURE 7 A selection of map sequences showing the spatial distribution of trends using time windows of decreasing length [Colour figure can be viewed at wileyonlinelibrary.com]

during the last three decades until 2015 and, in many cases, since the middle of the 20th century. The exception is found in the eastern areas in Tmin in April and June and the extreme south-east in July and August. We notice that in cold months (December, January and February) negative non-significant trend is detected in Tmin in the last 20 years, and in February and March in Tmax, in the whole area. To conclude, this analysis suggests again the extreme dependence of trend analyses of the period selected.

3.4 | Relationship of air temperature with atmospheric low variability patterns

3.4.1 | Relationship with the NAO

The spatial distribution of the correlation between NAO and air temperature according to 30-year moving windows is presented in Figure 8 (complete sequence in Figure S4). The correlation is mostly positive with Tmax and shows a generalized West-to-East spatial gradient. The summer months show the lowest correlation and sometimes even negative relations (not significant) in some areas.

Interestingly, the relationship between NAO and Tmax experienced some changes in time, and significant correlation areas expand and contract along a west-to-east gradient. The most persistent and spatially significant associations are found in February and May. In March, April and October, the area with significant correlation shrink to the west, while in January, September and November, the area grows from the west to the east. No clear relationship between NAO and Tmax was found in December. In the summer months, practically no significant relationship exists since the 1960s. The sequence of windows suggests that the relationship between NAO and Tmax has declined along the study period in the cold months (December–January), in April and the summer months. However, it has been reinforced in February–May (except April) and September–November.

The relationship between NAO and Tmin is a little bit more complicated. Three spatial patterns can be identified: west-to-east from March to August; north-to-south from September to February except October, when a south-to-north pattern emerges during 1951–

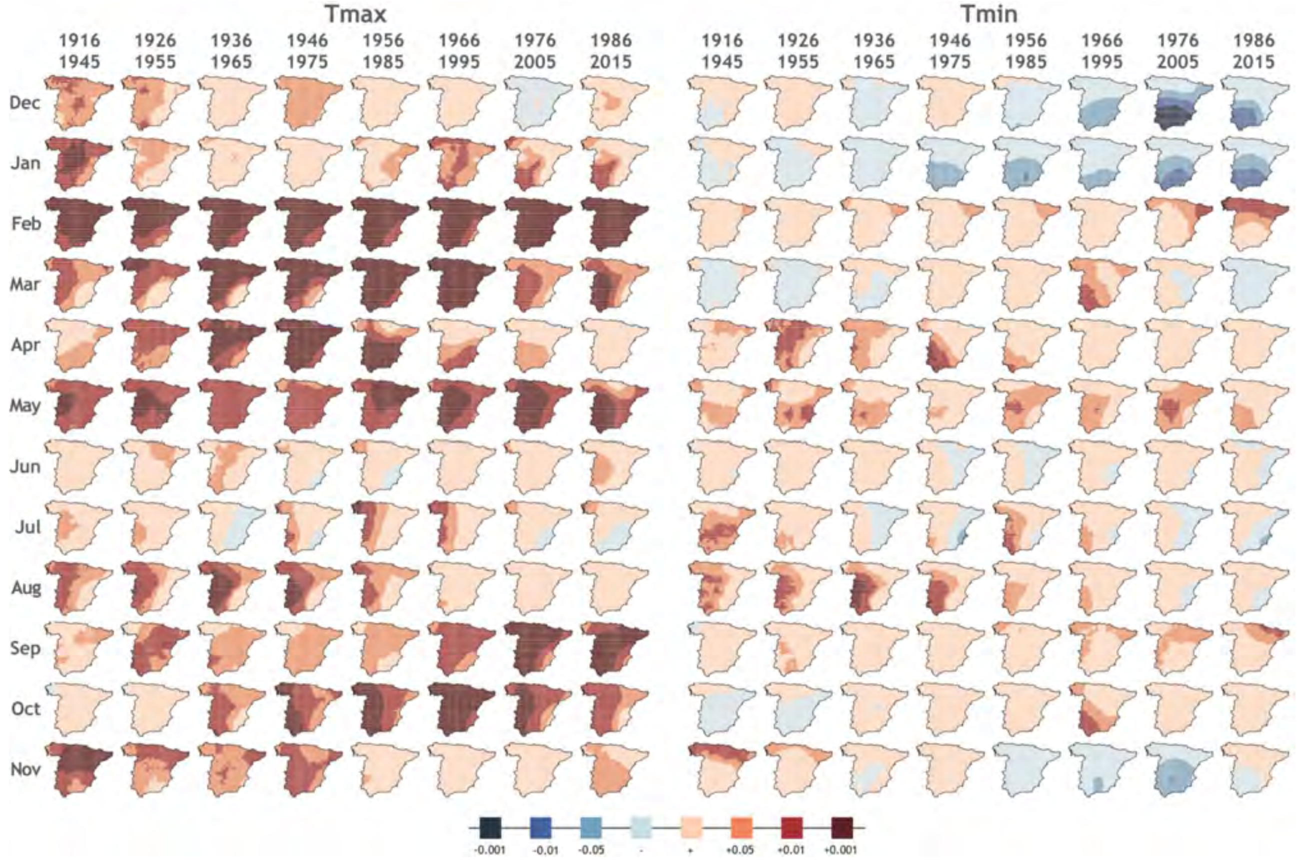

FIGURE 8 Spatial distribution of the correlation between the NAO and maximum (Tmax) and minimum (Tmin) air temperatures, according to 30-year time windows [Colour figure can be viewed at wileyonlinelibrary.com]

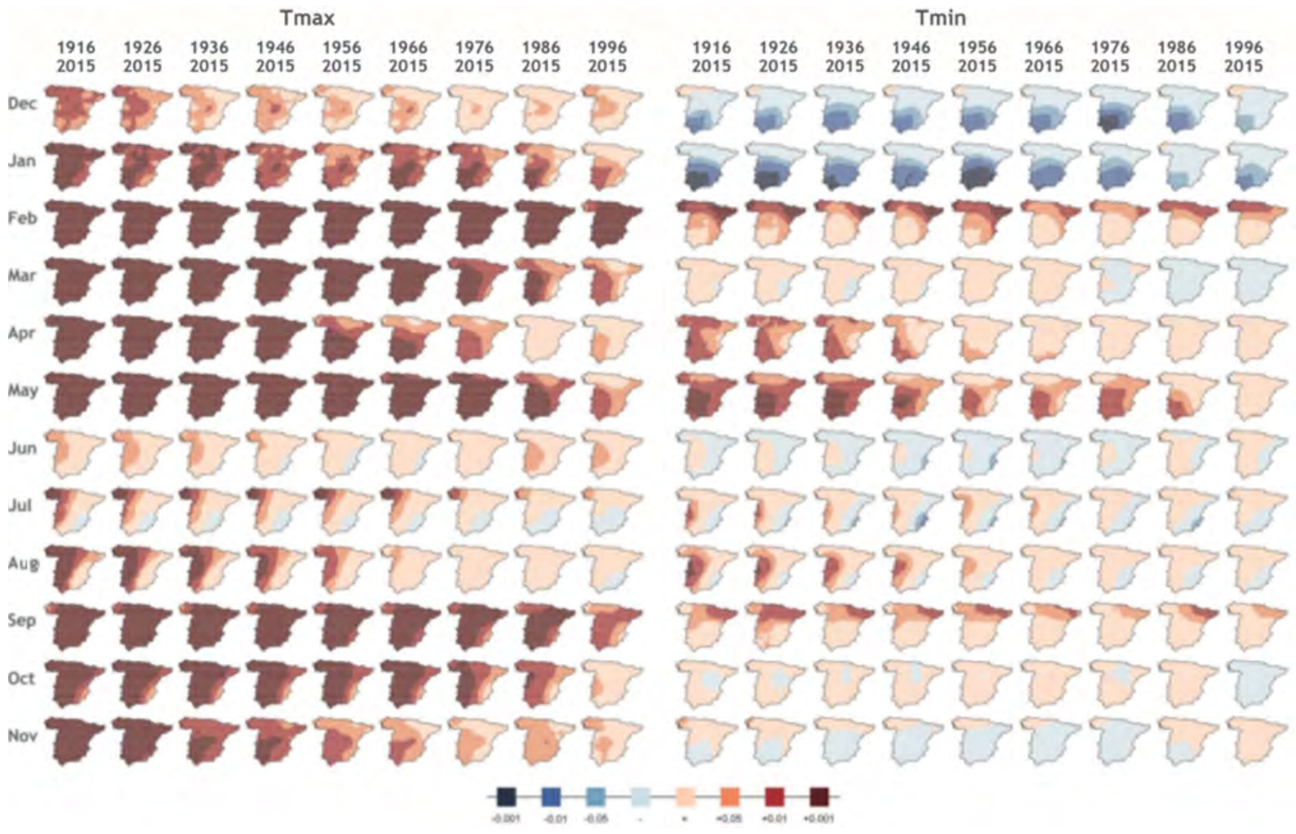

FIGURE 9 Spatial distribution of the correlation NAO and Tmax, Tmin, according to decreasing selected temporal windows [Colour figure can be viewed at wileyonlinelibrary.com]

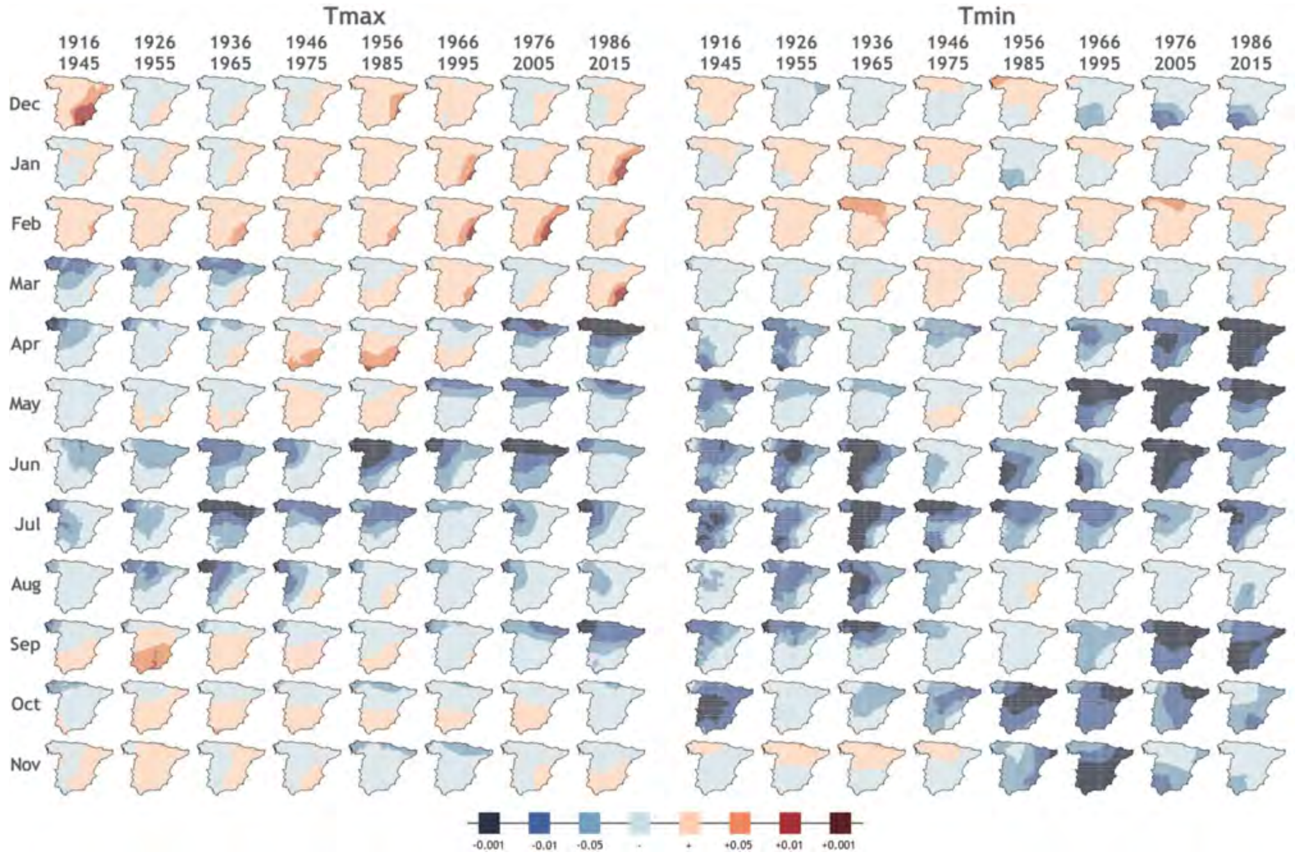

FIGURE 10 Spatial distribution of the correlation between the WEMO and maximum (Tmax) and minimum (Tmin) air temperatures, according to 30-year time windows [Colour figure can be viewed at wileyonlinelibrary.com]

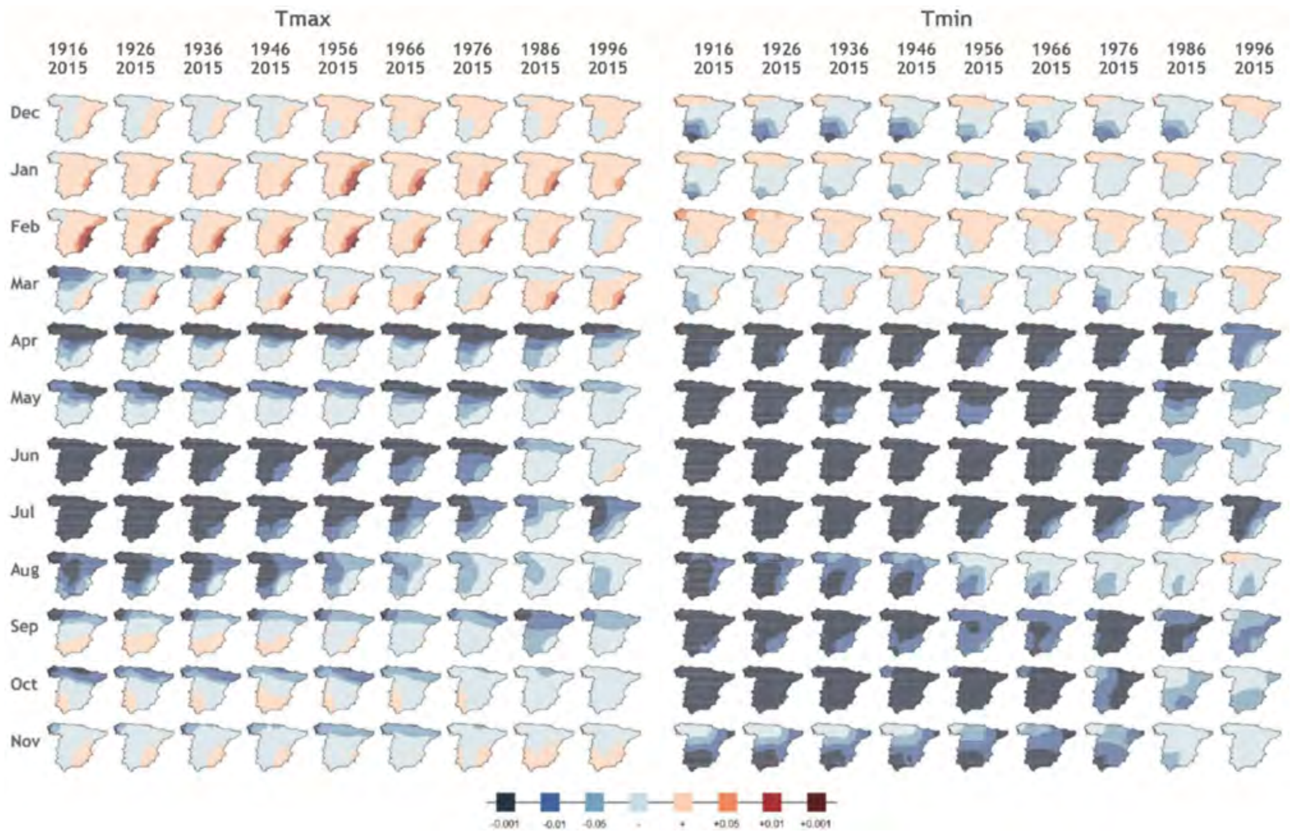

FIGURE 11 Spatial distribution of the correlation WEMO and Tmax, Tmin, according to decreasing selected temporal windows [Colour figure can be viewed at wileyonlinelibrary.com]

1980/1966–1995 time spam. Generally, the area with significant correlation in Tmin is less extended than in Tmax, and negative significant relationships are detected to the south in cold months and to the east in summer (significant in July). The area significantly correlated changed in time. In April, May and August, positive significant correlations occupied extended areas to the west that mostly disappeared during recent decades. Interestingly, a positive relationship is detected along the northern coast in February and September along the whole study period and in the initial decades in November. A negative correlation seems to advance from the south to the inland in recent decades in the cold months (November–January).

Additional information related to the stability of the relationship can be explored by using decreasing temporal windows. Figure 9 shows at decadal intervals the evolution of the spatial correlation (complete sequence in Figure S5). Generally, the area with significant correlations decreases in the most recent decades, except in February. In the last 30 years (1986–2015), the significant correlations are located in the central-western area, particularly in January, February, March, May and September. During October and November in the last 20 years, these areas were reduced. In summer, July and August show a progressive reduction of the areas significantly correlated.

The results for Tmin are contrasting. The monthly mean air temperature evolution shows the west–east gradient that changes to north–south in the cold months. No months reveals a significant relationship over 50% of the land in the last 30 years. The areas significant positive correlated in recent decades are February (northern coastland), September (northeastern region), May (south-western) and the south-western areas with negative relation in December and January. Significant correlated areas also are reduced in the most recent 20 years.

3.4.2 | Relationship with the WEMO

The spatial distribution of the correlation between WEMO and air temperature along 30-year windows is presented in Figure 10 (complete sequence in Figure S6). A general south-east-to-north-west spatial gradient can be detected. Significant positive correlations in the south-east appear at different temporal windows: in February from the 1930s, in the most recent decades in January and March, and in

December, April and September in different decades. The area with positive correlations is reduced, changed to non-significant, or disappeared in the rest of the months. In these months, the correlation is mostly negative (and significant) in the mid-northern areas, from where it extends to cover the whole area in specific months and temporal windows. During the last 30 years, the relationship between WEMO and Tmax seems to be stronger from April to September in the mid-northern area and to the west. There are spatial variations between consecutive temporal windows, April and September being the months with the more substantial variation.

The correlation between WEMO and Tmin shows different characteristics, which differ among cold and warm months. During the warmest months, the same southeast-to-north-west spatial gradient found for Tmax can be seen. Occasionally, the area with significant correlation covered the whole study area between April and September. On the other hand, from November to March, the spatial gradient of correlation changes to north-west-to-south-east or even north-to-south, albeit the area with significant correlations is smaller than in the warmest months. This change of the correlation sign suggests that the results of similar advection on temperature could vary along the year. Generally, the correlation between WEMO and Tmin shows smaller spatial variation found with Tmax and a larger area with significant correlations. This suggests that WEMO has a higher effect on night-time temperatures (Tmin is representative) than diurnal ones (Tmax). During the last 30 years (1986–2015), the relationship between WEMO and Tmin has been generalized and significant in April, May, June, July and September, with more than 50% of the area showing significant correlations.

The temporal evolution of the correlation between WEMO and Tmax and Tmin using decreasing temporal windows is shown in Figure 11 (complete sequence in Figure S7). The series of maps shows the two spatial gradients and particularly in the winter months.

4 | DISCUSSION

4.1 | One hundred years of temperature over the Spanish mainland (1916–2015)

In the Iberian Peninsula, particularly in the Spanish mainland, the analysis of monthly means of maximum and minimum temperatures over 1916–2015 shows that warming has been neither generalized among months nor monotonic in time. It has been different between diurnal (Tmax) and night-time (Tmin) temperature and has noticeable spatial variation. In time, two main periods of temperature rise can be identified in the first and the second half of the 20th century. Still, there are essential differences in the timing and even significance between months and between variables (Tmax and Tmin). Our analysis shows two main gradients of expansion and contraction of areas affected by significant trends. These results confirm previous results based on annual and seasonal mean data (Peña-Angulo *et al*., 2021; Sandonis *et al*., 2021) but also show that these temporal scales hide the great heterogeneity of results found at the monthly scale.

This spatial variability of temperatures has been described previously at the seasonal and annual scales. Brunet *et al*. (2007) identified three spatial patterns of temperature evolution over 1905–2005 at the seasonal scale: north-to-south, south-east-to-south, and south-west-to-south. These patterns persisted in the different subperiods considered in their analysis: 1905–1949, 1950–1972 and 1973–2005, and roughly coincided with the regionalisation of monthly mean temperatures according to different teleconnection patterns presented by Rios *et al*. (2012). In those spatial patterns, the correlation with atmospheric modes of variability was clear: NAO with south-west-to-south, while WEMO with south-east-to-south and north-to-south.

The spatial gradients of expansion and contraction of the areas with significant trends were already detected over 1951–2010 in the first version of the MOTEDAS data set. They were related to warm and cold months (Gonzalez-Hidalgo *et al*., 2016). They were also identified at the seasonal scale in the MOTEDAS_century dataset, although it was suggested that the strongest relationship was with Tmax or Tmin instead of with warm or cold months (Peña-Angulo et al., 2021). These findings are corroborated at the monthly scale in the present research, confirming that they are highly variable throughout the year. In brief, the east-to-west gradient is characteristic of Tmax trends, while the opposite (and, for some months, north-to-south) works for Tmin. The Tmin gradient shows lower spatial continuity than the Tmax one, perhaps due to a stronger effect of local factors such as relief configuration or land use on Tmin than Tmax.

Climate warming is a complex phenomenon in which global and local factors interact in ways that are not always straightforward. A well-known quote attributed to Albert Einstein says, "everything should be made as simple as possible, but not simpler" (Calaprice, 2000). In the case of temperature variability, the generalized warming trend detected in the mean annual temperature record results from a complex combination of processes that act at finer scales and differently for Tmax and Tmin. Our results suggest that the analysis of seasonal or annual mean temperature data is not enough for capturing the rich spatial and temporal variability of temperature trends that is only revealed once the analysis is done at the monthly level and considering Tmax and Tmin separately. Consequently, high spatial and temporal resolution data sets are of paramount importance to understand climate warming. Here, we have shown the value of such a dataset, which included rescuing ancillary data of the first half of the 20th century.

In the Iberian Peninsula (Spanish conterminous land), the spatial and temporal differences (between months) found between Tmax and Tmin trends are not justified by global factors such as human emissions, solar activity, volcanic eruptions and so on. Therefore, to understand warming processes in the study area, we should consider other elements capable of acting at regional or local scales. An attempt to understand the pause during the recent decades suggests that it could be related to a decrease in atmospheric moisture transport from the Atlantic Ocean added to massive land-use change, mainly affecting Tmax and Tmin, respectively (Gonzalez-Hidalgo *et al.*, 2016). These factors, however, do not seem to explain temperature trends during the first decades of the 20th century, when Tmax and Tmin increased in some months. No massive land-use change occurred during this period, as the most extensive changes happened after the Spanish Civil War (see Gonzalez-Hidalgo *et al.*, 2015). Also, an increase in cloud cover has been documented in the pre-war period (Sanchez-Lorenzo *et al.*, 2012). In summary, no single factor explains the sequence of rise-pause periods in temperature trends or the spatial differences observed in the study area.

4.2 | A general overview

In the Iberian Peninsula, the leading mountain chains adopt a west-to-east and a north-to-south alignment to the east (Figure 1). Considering this general distribution of relief, Peña-Angulo et al. (2021) suggested that the spatial distribution of seasonal temperature trends should be understood as the consequence of the relationship between the main atmospheric flows and relief. This hypothesis has been explored in greater detail and at the monthly scale in the present research, focusing on two of the most prominent low-variability atmospheric patterns affecting the climate of the Iberian Peninsula: the NAO and the WEMO, representing the Atlantic and Mediterranean influences, respectively, the primary sources of variation of temperature over the Spanish mainland as suggested by Gámiz-Fortis *et al.* (2011). Furthermore, the spatial changes along time of the areas with significant trends would show that this would be a dynamic relationship. Other factors such as cloudiness, land-use change or soil moisture could produce additional local effects (Fernández-Montes and Rodrigo, 2015).

The positive correlation between NAO and Tmax in the central and western areas is found mainly in the cold months. It can be understood under the classical interpretation of positive NAO conditions related to high pressures over the Iberian Peninsula, clear-sky conditions, and increasing incoming solar radiation. Under negative NAO, the opposite conditions prevail, with increasing cloudiness. The low significance between NAO and Tmax during the coldest months could result from generalized fogs that are frequent under anticyclonic conditions in a large part of the study area except in the coastland (Peña-Angulo et al., 2015). The same relationship between NAO and Tmax has been noticed in different seasons (Fernández-Montes *et al.*, 2012, 2013).

On the other hand, cloudiness and relief have been suggested as the main factors explaining the significant correlation between NAO and Tmax in summer along a north-west-to-south-east gradient over which the sign of the correlation even changes (Favà et al., 2016). Nevertheless, the exact relationship between NAO and Tmax is far from being wholly understood. During the first decades of the study period, we found no coherence between the increase of the area with significant correlation NAO-Tmax and the increase in cloudiness, as shown by Sanchez-Lorenzo *et al.* (2012).

According to Fernández-Montes *et al.* (2012), the configuration of negative NAO conditions can be diverse. This could explain the non-stationary character of the relationships between NAO and temperature found in our analysis, as the spatial location of the pressure dipoles has also changed (Esteban-Parra *et al.*, 2003). Two spatial gradients are found in the correlation between NAO and Tmin. From September to February, NAO and Tmin correlate along a north-to-south gradient. Particularly noticeable are the extended negative correlations to the south, that have been associated with the effect of increased water vapour and cloudiness caused by maritime advection under negative NAO from the south-west on the infrared night-time energy balance (Trigo *et al.*, 2002; Esteban-Parra *et al.*, 2003; Rodrigo, 2016). From April to August, the predominant gradient is west-to-south with negative and significant correlations in the extreme south-east, suggesting that clear sky during positive NAO conditions supports a negative radiative balance of Tmin during the night.

Finally, another interesting result refers to the positive significant correlation in the northern area along the coast in February, September and November. This could imply that southerly flows adiabatically affect Tmin under negative NAO in these areas, in agreement with some of the seasonal atmospheric circulation types described by Fernández-Montes *et al.* (2012, 2013). In short, the results suggest that the effect of NAO is higher in Tmax than Tmin, in apparent discrepancy with the results of Rodrigo (2016) for Spain and Trigo *et al*. (2002) for Europe.

The spatial correlation between WEMO and temperature follows a general south-east-to-north-west spatial gradient in Tmax that changes to north-to-south in Winter Tmin. Again, this pattern suggests a close relationship between advection of northerly maritime air masses and relief, with slightly changing effects among months. Similar results were shown by Ríos-Cornejo *et al*. (2015), analysing monthly mean temperatures.

The spatial correlation gradient changed in the winter months, with positive values to the north and negative to the south, notably extending the area with significant correlations in the south. It means that south and south-easterly flows under negative WEMO are characterized by high vapour content and high cloudiness, producing an increase of Tmin, similar to negative NAO effects. On the contrary, during the warmest months under positive WEMO, the north-west (Atlantic Ocean) advection would be able to reduce Tmin values following a north-west-to-south-east gradient.

These results suggest that the effects of Mediterranean and southerly flows during the coldest months under negative WEMO can smooth the night-time temperatures, while the same is true under Atlantic advection effects during the positive WEMO, mainly during the warmest months, but with a cooling effect.

The relationship between NAO and WEMO correlations (Figures 8 and 10) and the observed temperature trends of Tmax and Tmin (Figure 3) is far from direct, and it cannot be understood as a simple cause–effect relationship. Also, it must be considered that temperature evolution is not affected by a single atmospheric pattern. For example, the expansion–contraction gradients of positive significant Tmax trends from the Mediterranean coast in the east to the west-inland area are opposed to the area where we found a significant correlation with NAO. That is, in areas where NAO correlates positively with Tmax, the trend is not significant. On the other hand, the same areas are usually affected by significant positive trends in Tmin, although the correlation with NAO and WEMO is less intense.

In brief, the areas where we detected a higher increase of temperatures over the 1916–2015 period are located to the east and the central-southern regions. In time, we found that spatial variations seem to be controlled by the relief. All these arguments suggest that temperature evolution over the Spanish mainland during the last century does not reflect a single cause and seems to be related to a dynamic combination of local, regional and global factors. These results suggest the need for detailed spatial analyses of warming processes to identify at the greatest detail the triggering factors and, consequently, the areas affected. Annual and seasonal values do not seem to be the most relevant information to analyse, independently of the underlying causes.

5 | CONCLUSIONS

The analysis of monthly mean Tmax and Tmin over mainland Spain during 1916–2015 using the new high-resolution MOTEDAS_century grid shows that warming in this region is a complex phenomenon characterized by:

1. not being homogeneous across months, but specific to certain months: March, December and to a lesser extent June and July in Tmax, and June, July, August and October in Tmin;
2. not being a monotonic process, but showing two main rising periods that affected specific months;
3. showing a stagnation period with almost no significant rise in both Tmax and Tmin and all months during the last decades;
4. being asynchronous between Tmax and Tmin, which show an independent behaviour from each other;
5. having a large spatial variability and differences between months, with two predominating gradients of expansion–contraction: east–west for Tmax and west–east for Tmin.

We found relationships between low-variability atmospheric modes (NAO and WEMO), combined with relief, and temperature trends on the monthly scale. Nevertheless, caution must be taken regarding this result as this relationship proved to be dynamic in time.

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José Carlos González-Hidalgo: Conceptualization; data curation; formal analysis; funding acquisition; writing - original draft; writing-review & editing. **Santiago Beguería:** Conceptualization; data curation; formal analysis; funding acquisition; writing - original draft; writing-review & editing. **Dhais Peña-Angulo:** Conceptualization; data curation; formal analysis; software; writing-review & editing. **Leire Sandonis:** Conceptualization; data curation; formal analysis; software; writing-review & editing.

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REFERENCES

Arguez, A., O'Brien, J.J. and Simith, S.R. (2009) Air temperature impacts over Eastern North America and Europe associated with low-frequency North Atlantic SST variability. *International Journal of Climatology*, 29, 1–10.

Beranová, R. and Huth, R. (2008) Time variations of the effects of circulation variability modes on European temperature and precipitation in winter. *International Journal of Climatology*, 28, 139–158.

Begueria, S., Vicente-Serrano, S., Tomas-Burguera, M. and Maneta, M. (2016) Bias in the variance of gridded data sets leads to misleading conclusions about changes in climate variability. *International Journal of Climatology*, 36, 3413–3422.

Brunet, M., Jones, P., Sigro, J., Saladie, O., Aguilar, E., Moberg, A., Della-Marta, P.M., Lister, D., Walther, A. and Lopez, D. (2007) Temporal and spatial temperature variability and change over Spain during 1850–2005. *Journal of Geophysical Research*, 112, D12117.

Calaprice, A. (Ed.). (2000) *The Expanded Quotable Einstein*. Princeton: Princeton University Press, p. 314.

Castro-Díaz, Y., Pozo-Vázquez, D., Rodrigo, F.S. and Esteban-Parra, M.J. (2002) NAO and Winter temperature variability in southern Europe. *Geophysical Research Letters*, 29(8), 1160.

del Río, S., Cano-Ortiz, A., Herrero, L. and Penas, A. (2012) Recent trends in mean maximum and minimum air temperatures over Spain (1961–2006). *Theoretical and Applied Climatology*, 109, 605–626.

del Río, S., Herrero, L., Pinto-Gomes, C. and Penas, A. (2011) Spatial analyses of mean temperature trends in Spain over the period 1961-2006. *Global Planetary Change*, 78, 65–75.

Duveiller, G., Hooker, J. and Cescatti, A. (2018) The mark of vegetation change on Earth's surface energy balance. *Nature Comunication*, 9, 679.

El Kenawy, A., López-Moreno, J.I. and Vicente-Serrano, S.M. (2012) Trend and variability of surface air temperature in north eastern Spain (1920–2006): linkage to atmospheric circulation. *Atmospheric Research*, 106, 159–180.

Espírito Santo, F., de Lima, M.I.P., Ramos, A.M. and Trigo, R.M. (2014) Trends in seasonal surface air temperature in mainland Portugal, since 1941. *International Journal of Climatology*, 34, 1814–1837.

Esteban-Parra, M.J., Pozo-Vázquez, D., Rodrigo, F.S. and Castro-Díez, Y. (2003) Temperature and precipitation variability and trends in Northern Spain in the context of the Iberian Peninsula climate. In: Bolle, H.J. (Ed.) *Mediterranean Climate. Regional Climate Studies*. Berlin, Heidelberg: Springer, pp. 259–276.

Favà, V., Curto, J.J. and Llasat, M.C. (2016) Relationship between the summer NAO and maximum and minimum temperatures for the Iberian Peninsula. *Theoretical and Applied Climatology*, 126, 77–91.

Fernández-Montes, S. and Rodrigo, F.S. (2012) Trends in seasonal indices of daily temperature extremes in the Iberian Peninsula, 1929–2005. *International Journal of Climatology*, 32, 2320–2332.

Fernández-Montes, S. and Rodrigo, F.S. (2015) Trends in surface air temperatures, precipitation and combined indices in the southeastern Iberian Peninsula (1970-2007). *Climate Research*, 63, 43–60.

Fernández-Montes, S., Seubert, S., Rodrigo, F.S. and Hertig, E. (2012) Wintertime circulation types over the Iberian Peninsula: long-term variability and relationships with weather extremes. *Climate Research*, 53, 205–227.

Fernández-Montes, S., Rodrigo, F.S., Seubert, S. and Sousa, P.M. (2013) Spring and summer extreme temperatures in Iberia during last century in relation to circulation types. *Atmospheric Research*, 127, 154–177.

Folland, C.K., Boucher, O., Colman, A. and Parker, D.E. (2018) Causes of irregularities in trends of global mean surface temperature since the late 19th century. *Science Advances*, 4, eaaao5297.

Gámiz-Fortis, S.R., Esteban-Parra, M.J., Pozo-Vázquez, D. and Castro-iez, Y. (2011) Variability of the monthly European temperature and its association with the Atlantic sea-surface temperature from interannual to multidecadal scales. *International Journal of Climatology*, 31, 2115–2140.

Gonzalez-Hidalgo, J.C., Peña-Angulo, D., Beguería, S. and Brunetti, M. (2020) MOTEDAS century: a new high resolution secular monthly maximum and minimum temperature grid for the Spanish mainland (1916-2015). *International Journal of Climatology*, 40, 5308–5328.

Gonzalez-Hidalgo, J.C., Peña-Angulo, D., Brunetti, M. and Cortesi, N. (2015) MOTEDAS: a new monthly temperature database of Spanish continental land and the temperature trend between 1951-2010. *International Journal of Climatology*, 35, 4444–4463.

Gonzalez-Hidalgo, J.C., Peña-Angulo, D., Brunetti, M. and Cortesi, N. (2016) Recent trend temperature evolution in Spanish mainland (1951-2010): from warming to hiatus. *International Journal of Climatology*, 36, 2405–2416.

Guijarro, J.A. (2013) Tendencias de la temperatura. In: García-Lega, C. and Valero, F. (Eds.) *Fenómenos Meteorológicos Adversos en España*. Madrid: WCRP, AMV ediciones, pp. 313–323.

Hansen, J., Ruedy, R., Sato, M. and Lo, K. (2010) Global surface temperature change. *Reviews of Geophysics*, 48, RG4004.

Hartmann, D.L., Klein-Tank, A.M.G., Rusticucci, M., Alexander, L. V., Brönnimann, S., Charabi, Y., Dentener, F.J., Dlugokencky, E.

J., Easterling, D.R., Kaplan, A., Soden, B.J., Thorne, P.W., Wild, M. and Zhai, P.M. (2013) Observations: atmosphere and surface. In: Stocker, T.F., et al. (Eds.) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, UK: Cambridge University Press, pp. 159–254.

Janis, M.J., Hubbard, K.G. and Redmond, K.T. (2004) Station density strategy for monitoring long-term climatic changes in the contiguous United States. *International Journal of Climatology*, 17, 151–162.

Jones, P., Lister, D.H., Osborn, T.J., Harpham, C., Salmon, M. and Morice, C. (2012) Hemispheric and large-scale land-surface air temperature variations: an extensive revision and an update to 2010. *Journal of Geophysical Research*, 117, D05127.

Jones, P.D. (2016) The reliability of global and hemispheric surface temperature records. *Advances in Atmospheric Science*, 33, 269–282.

Liebmann, B., Dole, R.M., Jones, C., Bladé, I. and Allured, D. (2010) Influence of choice of time on global surface temperature trend estimated. *Bulletin of the American Meteorological Society*, 91, 1485–1149.

Loehle, C. (2009) Trend analysis of satellite global temperature data. *Energy and Environment*, 20, 1087–1098.

Lüdecke, H.J., Cina, R., Dammschneider, H.J. and Lüning, S. (2020) Decadal and multidecadal natural variability in European temperature. *Journal of Atmospheric and Solar Terrestrial Physics*, 205, 105294.

Martin-Vide, J. and Lopez-Bustins, J.A. (2006) The western Mediterranean oscillation and rainfall in the Iberian Peninsula. *International Journal of Climatology*, 26, 1455–1475.

McKitrick, R.R. (2014) HAC-robust measurement of the duration of a trendless subsample in a global climate time series. *Open Journal of Statistics*, 4, 527–535.

Menne, M.J. and Williams, C.N. (2009) Homogenisation of temperature series via pairwise comparisons. *Journal of Climate*, 22, 1700–1717.

Menne, M.J., Williams, C.N. and Palecki, M.A. (2010) On the reliability of the U.S. surface temperature record. *Journal of Geophysical Research*, 115, D11108.

Montandon, L.O.M., Fal, S., Pielke, R.A., Sr. and Nigoyi, D. (2011) Distribution of landscape types in the Global Historical Climatology Network. *Earth*, 15, 1–24.

Peña-Angulo, D., González-Hidalgo, J.C., Sandonis, L., Beguería, S., Burguera, T., López-Bustins, J.A., Lemús-Canovas, M. and Martín-Vide, J. (2021) Seasonal temperature trends on the Spanish mainland: a secular study (1916-2015). *International Journal of Climatology*, 41, 3071–3054.

PeñaAngulo, D., Cortesi, N, Brunetti, M. and Gonzalez-Hidalgo, J.C. (2015) Spatial variability of maximum and minimum monthly temperature in Spain during 1981–2010 evaluated by correlation decay distance (CDD). *Theoretical and Applied Climatology*, 122, 35–45.

Peña-Angulo, D., Trigo, T., Cortesi, N. and González-Hidalgo, J.C. (2016) The influence of weather types on the monthly average maximum and minimum temperatures in the Iberian Peninsula. *Atmospheric Research*, 178–179, 217–230.

Peterson, T.C. and Voose, R.S. (1997) An overview of the Global Historical Climate Network temperature database. *Bulletin of the American Meteorological Society*, 78, 2837–2849.

Rao, Y., Liang, S. and Yu, Y. (2018) Land surface air temperature data are considerably different among BEST-LAND, CRU-TEM4v, NASA-GISS, and NOAA-NCEI. *Journal of Geophysical Research, Atmospheres*, 123, 5881–5900.

Rios, D., Penas, D. and del Rio, S. (2012) Comparative analysis of mean temperature trends in continental Spain over the period 1961-2010. *International Journal of Geobotanical Research*, 2, 41–55.

Ríos-Cornejo, D., Penas, A., Alvarez-Esteban, R. and del Río, S. (2015) Links between teleconnection patterns and mean temperature in Spain. *Theoretical and Applied Climatology*, 122, 1–18.

Rodrigo, F. (2016). Influencia de la nao en la covariabilidad de Temperaturas y precipitaciones de invierno en España, 1946-2005. X Congreso Internacional AEC: Clima, sociedad, riesgos y ordenación del territorio. https://doi.org/10.14198/XCongresoAECAlicante2016-35

Rodríguez-Puebla, C., Encinas, A.H., García-Casado, L.A. and Nieto, S. (2010) Trends in warm days and cold nights over the Iberian Peninsula: relationships to large-scale variables. *Climate Change*, 100, 667–684. https://doi.org/10.1007/s10584-009-9721-0.

Sáenz, J., Rodríguez-Puebla, C., Fernández, J. and Zubillaga, J. (2001a) Interpretation of interannual winter temperature variations over southwestern Europe. *Journal of Geophysical Research*, 106, 20641–20651. https://doi.org/10.1029/2001JD900247.

Sáenz, J., Zubillaga, J. and Rodríguez-Puebla, C. (2001b) Interannual winter temperature variability in the north of the Iberian Peninsula. *Climate Research*, 6, 169–179. https://doi.org/10.1002/joc.699.

Sanchez-Lorenzo, A., Calbó, J. and Wild, M. (2012) Increasing cloud cover in the 20th century: review and new findings in Spain. *Climate of the Past*, 8, 1199–1212.

Sandonis, L., González-Hidalgo, J.C., Peña-Angulo, D. and Beguería, S. (2021) Mean temperature evolution on the Spanish mainland 1916-2015. *Climate Research*, 82, 177–189.

Santer, B.D., Mears, C., Doutriaux, C., Caldwell, P., Gleckler, P.J., Wigley, T.M.L., Solomon, S., Gillett, N.P., Ivanova, D., Karl, T.R., Lanzante, J.R., Meehl, G.A., Stott, P.A., Taylor, K.E., Thorne, P.W., Wehner, M.F. and Wentz, F.J. (2011) Separating signal and noise in atmospheric temperature changes: the importance of timescales. *Journal of Geophysical Research*, 116, D22105. https://doi.org/10.1029/2011JDO16263.

Slivinski, L.C., Compo, G.P., Whitaker, J.S., Sardeshmukh, P.D., Giese, B.S., McColl, C., Allan, R., Yin, X., Vose, R., Titchner, H., Kennedy, J., Spencer, L.J., Ashcroft, L., Brönnimann, S., Brunet, M., Camuffo, D., Cornes, R., Cram, T. A., Crouthamel, R., Domínguez-Castro, F., Freeman, J.E., Gergis, J., Hawkins, E., Jones, P.D., Jourdain, S., Kaplan, A., Kubota, H., Le Blancq, F., Lee, T.-C., Lorrey, A., Luterbacher, J., Maugeri, M., Mock, C.J., Moore, G.W.K., Przybylak, R., Pudmenzky, C., Reason, C., Slonosky, V.C., Smith, C.A., Tinz, B., Trewin, B., Valente, M.A., Wang, X.L., Wilkinson, C., Wood, K. and Wyszyński, P. (2019) Towards a more reliable historical reanalysis: improvements for version 3 of the Twentieth Century Reanalysis system. *Quarterly Journal of the Royal Meteorological Society*, 145, 2876–2908.

Sun, X., Ren, G., You, Q., Ren, Y., Xu, W., Xue, X., Zhan, Y., Zhang, S. and Zhang, P. (2018) Global diurnal temperature range (DTR) changes since 1901. *Climate Dynamics*, 5–6, 3343–3356.

Thorne, P.W., Allan, R.J., Ashcroft, L., Brohan, P., Dunn, R.J.H., Menne, M.J., Pearce, P.R., Picas, J., Willett, K.M., Benoy, M., Bronnimann, S., Canziani, P.O., Coll, J., Crouthamel, R., Compo, G.P., Cuppett, D., Curley, M., Duffy, C., Gillespie, I., Guijarro, J., Jourdain, S., Kent, E.C., Kubota, H., Legg, T.P., Li, Q., Matsumoto, J., Murphy, C., Rayner, N.A., Rennie, J.J., Rustemeier, E., Slivinski, L.C., Slonosky, V., Squintu, A., Tinz, B., Valente, M.A., Walsh, S., Wang, X.L., Westcott, N., Wood, K., Woodruff, S.D. and Worley, S.J. (2017a) Towards an integrated set of surface meteorological observations for climate science and applications. *Bulletin of the American Meteorological Society*, 98, 2689–2702. https://doi.org/10.1175/BAMS-D-16-0165.1.

Thorne, P.W., Donat, M.G., Dunn, R.J.H., Williams, C.N., Alexander, L.V., Caesar, J., Durre, I., Harris, I., Hausfather, Z., Jones, P.D., Menne, M.J., Rohde, R., Vose, R.S., Davy, R., Klein-Tank, A.M.G., Lawrimore, J.H., Peterson, T.C. and Rennie, J.J. (2016) Reassessing changes in diurnal temperature range: intercomparison and evaluation of existing global data set estimates. *Journal of Geophysical Research: Atmospheres*, 121, 5138–5158. https://doi.org/10.1002/2015JD024584.

Thorne, P.W., Madonna, F., Schulz, J., Oakley, T., Ingleby, B., Rosoldi, M., Tramutola, E., Arola, A., Buschmann, M., Mikalsen, A.C., Davy, R., Voces, C., Kreher, K., de Maziere, M. and Pappalardo, G. (2017b) Making better sense of the mosaic of environmental measurement networks: a system-of-systems approach and quantitative assessment. *Geoscientific Instrumentation, Methods and Data Systems*, 6(2), 453–472.

Thorne, P.W., Parker, D.E., Christy, J.R. and Mears, C.A. (2005) Uncertainties in climate trends: lessons from upper-air temperature records. *Bulletin of the American Meteorological Society*, 86, 1437–1442.

Trigo, R.M., Osborn, T.J. and Corte-Real, J.M. (2002) The North Atlantic Oscillation influence on Europe: climate impacts and associated physical mechanisms. *Climate Research*, 20, 9–17.

Vose, R.S., Wuertz, D., Peterson, T.C. and Jones, P.D. (2005) An intercomparison of trends in surface air temperature analyses at the global, hemispheric, and grid-box scale. *Geophysical Research Letters*, 32, L18718.

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