

RESEARCH ARTICLE

MOTEDAS century: A new high-resolution secular monthly maximum and minimum temperature grid for the Spanish mainland (1916–2015)

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Abstract

Information was retrieved from the Annual Climate Summaries (ACS) on average monthly temperatures in Spain for the period 1916–1949, and combined with the digitalized data from the National Climate Data Bank of the Spanish meteorological service (AEMET) to create the new MOTEDAS_century (MOnthly Temperature Dataset of Spain) database of mean monthly maximums (T_{\max}) and minimums (T_{\min}). This database was used to calculate a high-resolution (10×10 km) grid that allowed to make a detailed analysis of the temporal evolution of temperature in Spain during the period 1916–2015. Over the period, mean T_{\max} increased by 1.2°C , while T_{\min} increased by 1.0°C (this ratio is reversed in the second half of the century). In the last 30 years, however, mean annual T_{\max} and T_{\min} trends have not been significant. There are some differences between the new mean annual maximum and minimum temperature series and previous versions, which seem to arise from the much higher number of weather stations analysed, their location and the processing used. There is a discussion on the improved spatial representativeness of the new MOTEDAS_century that provides a more detailed representation of the spatial variability of temperatures in continental Spain.

KEYWORDS

database, MOTEDA_century, Spain, temperature-trend, XX-century

1 | INTRODUCTION

Meteorological records are essential information required in the study of the recent evolution of the climate in the

period between the appearance of observation networks in the mid-19th century and remote satellite observations in the 1970s. Thus temperature, precipitation, humidity, sunshine, pressure, etcetera, data from ground weather stations continue to be the best source of information for analysing the evolution of the climate over the last

Annual mean value of T_{\max} and T_{\min} and metadata information of original series can be download at www.Clices.Unizar.es

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150 years, place the current period in its temporal context, and create databases to evaluate results from the models. This type of data have been compiled by several research centres and resulted in databases covering the world (see the review by Strangeways, 2010), and are well-known by their acronyms: GHCN (Lawrimore *et al.*, 2011), GISS (Hansen *et al.*, 2010), HadCRUTEM4 (Jones *et al.*, 2012), BEST (Rohde *et al.*, 2013), which, with some recent contributions (Xu *et al.*, 2018) are complemented by others created at continental, national and regional scales.

The original information from these datasets is very variable in time and space due to the irregular development of meteorological observation networks. The number of weather stations in the 20th century follows global patterns, with a gradual increase up to the Second World War, after which they multiply exponentially only to stagnate, or even decrease, in the 1980s and 90s as satellite observations became more widespread. The weather stations that have disappeared were preferentially the rural ones, those in high places and at high latitudes (see Peterson and Vose, 1997). Consequently, the spatial distribution of weather stations is not uniform in time and there are gaps and concentrations at certain times, whose effects may affect the results of climate analyses. Thus, for example the distribution of weather stations across the planet is strongly biased according to the different types of land use, with some (such as urban environments) being over-represented, while others are clearly under-represented (Montandon *et al.*, 2010). Also, changes in land use at or around the stations had notable effects on the temperature records (Duveiller *et al.*, 2018).

The result from the foregoing is that research into climate always leads to a compromise between the temporal duration of the analysis and the spatial density of the information. If long periods are to be studied (e.g., over 50 years) the number of observations will always be low; however, if spatial details are required, the periods of record will be shorter and always restricted to the most recent decades. The situation described is fairly general worldwide, with variations among regions. As it can be expected, the case of Spain is no exception.

There is a massive amount of climate information recorded in Spain since the mid-19th century and comes especially from the observations network organized by the successive meteorological services. This information was partially digitalized during the 1980s and formed the National Climate Data Bank (Banco Nacional de Datos del Clima, BNDC in Spanish), which is managed by the Spanish meteorological service (AEMET). The BNDC has been the main source of data for many studies of climate

change in Spain, under the conditions described: analysis of prolonged periods usually included only a small selection of weather stations (Brunet *et al.*, 2006; 2007; Staudt *et al.*, 2007; Sigro *et al.*, 2015); and, vice-versa, there is a great deal of information when analysing recent periods, especially since the mid-20th century (del Río *et al.*, 2011, 2012; Herrera *et al.*, 2012, 2015; Guijarro, 2013). In González-Hidalgo *et al.* (2010); González-Hidalgo *et al.* (2015) there are two reviews on studies made on precipitation and temperatures in Spain and the databases used; for the remaining variables in the BNDC, Vicente-Serrano *et al.* (2017) have recently published a general status report on the issue.

Despite the above, the digitalized information of the BNDC does not include all the historical records from the observatory network, since a large amount of data is kept on paper in the Annual Climate Summaries (ACS) books, published by the meteorological services since the network started in 1860 up to 1950, and preserved in the AEMET libraries. AEMET has worked partially to put these documents into digital form (within the ARCIMIS project), without applying any kind of processing, so they can be consulted and analysed. So far, retrieval of non-digitalized data has not been completed.

Since 2008, we have worked to retrieve the information on the ACS books by digitalising part of the data, particularly the monthly means of maximum (T_{\max}) and minimum (T_{\min}) temperatures and monthly precipitation amounts, and to convert them into a digital format suitable for later processing.

This paper describes the progress of data retrieval for monthly mean T_{\max} and T_{\min} temperatures from the ACS books for the period 1916–1949; the combination of these data with the digital archives of the BNDC covering the 1916–2015 period; the development of grids for both variables; and the analysis of temporal trends of annual averages over the study area. Studies currently under way will, in future, show more detailed analysis of the spatial variations in the trends, their monthly and seasonal behaviour, as well as the analysis of monthly precipitation.

2 | DATA AND METHODS

2.1 | Retrieval of information from the ACS

The retrieval process for information from the ACS books took place in a series of three steps: (a) digitalisation; (b) conversion to an alphanumeric format; and (c) pairing with the data series from the BNDC.

Pairing both sources was the most laborious task because sometimes the names of the weather stations in the ACS books change over the years or do not match with names on the BNDC. This led to two methods being combined: direct assignation for series of observations taken in consecutive years from weather stations whose names remained the same in all the summaries and between these and the BNDC; and the search for data series matching in the ACS books and in the BNDC. The procedure enabled about 70% of the total data retrieved from the ACS books to be paired with the BNDC series, with the remaining 30% being observations from weather stations with no direct matching to those in the BNDC, that is, new ones. The results from this task were threefold: (a) gaps were filled in the intermediate periods in the BNDC weather stations that had been digitalized; (b) the length of many series in the BNDC was extended for the first years; and, lastly, and (c) information was retrieved from the ACS books for weather stations not included in the BNDC.

Once the data from the ACS books were digitalized and combined with the data from the BNDC, a general check was carried out by verifying that each weather station lied within the administrative limits of the municipality it was assigned to; the elevation of each station was compared with a DEM with a spatial resolution of ~ 1 km (GTOPO30, USGS1996), before correcting errors in entries of altitudes for stations in the ACS.

Figure 1 shows the number of weather stations with records of monthly maximum and minimum temperature means for at least 1 month-year⁻¹. The figure is limited to the period with data in the ACS books (1916–1949) and shows that, between 1916 and 1949, the total number of weather stations in the ACS is much larger than those in the BNDC archives of AEMET, except for the 1930s which included the Spanish Civil War and the immediate post-war period.

The absolute numbers command attention. Data has been preserved from over 200 weather stations from 1916 to 1949, and can be split into three periods:

- An initial one from 1916 to the end of the 1920s, with total information varying from 200 to 250 weather stations and clearly much more from the ACS books, which have data from about 250 stations, compared with the BNDC with just over 100 weather stations per year.
- A second period covering the 1930s and extending to immediately after the war up to approximately 1942. Initially, the total number of weather stations was higher than 300, although in this case the BNDC contains a higher number of stations than the ACS books, which decreased. The end of this period includes the collapse of the network due to the Spanish Civil War, a period in which there is a sharp rise in monthly and spatial gaps, although information is maintained from over 200 weather stations.
- A third period starting at around 1945, which saw the network being rebuilt and a steady rise in the number of weather stations to more than 500. Once again, the information from the ACS books exceeds that in the BNDC (see below). Publication of the ACS books ended before 1950.

The differences between the two documentary sources suggest that many records from the meteorological network were not digitalized, either deliberately or because the original information (observation files) were not available or lost. Figure 2 shows the annual evolution of the number of weather stations with temperature information retrieved from the ACS books that are not present in the BNDC, and the stations present in the BNDC that do not appear in the ACS books.

It should be emphasized that the group of weather stations completely absent from the BNDC hold a large

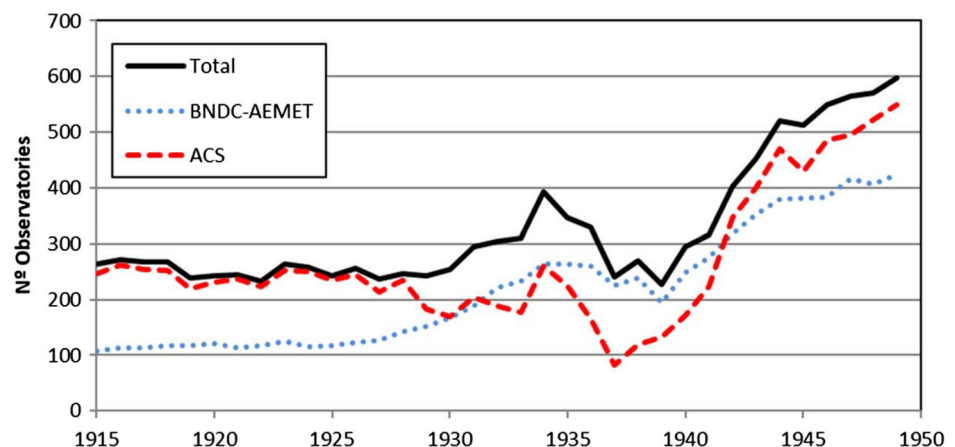


FIGURE 1 Number of weather stations with monthly temperature information per year for 1916–1949. The values indicate whether there is at least one T_{\max} or T_{\min} monthly record

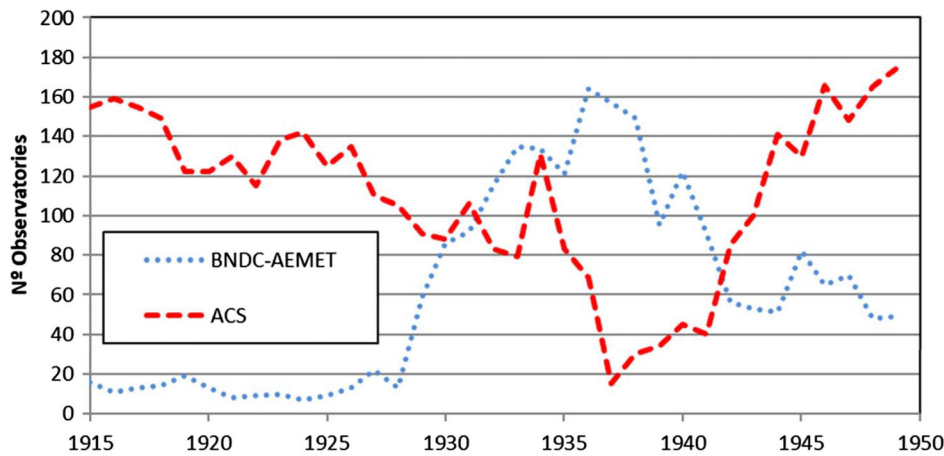


FIGURE 2 Evolution of the number of weather stations from the ACS not included in the BNDC of AEMET and present in the BNDC but not in the ACS

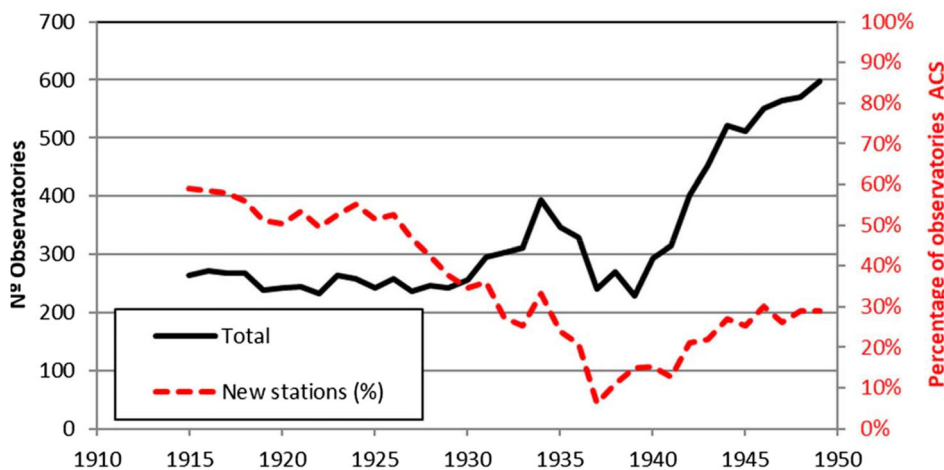


FIGURE 3 Evolution of all weather stations with temperature information (black curve and left y-axis) and the percentage representing those from the ACS not included in the BNDC (red curve and right y-axis)

quantity of information from before the 1930s and immediately after the Spanish Civil War, with over 100 observations annually retrieved in each year and not included in the BNDC. Similarly, there are many more weather stations only present in the BNDC in the 1930–1940 period, suggesting that perhaps at the time of compiling and publishing the ACS books this information was not available but that this information was found during the digitalisation done by AEMET decades later. The data series in the ACS books are generally short, with a few notable exceptions such as the collection of observations from lighthouses.

Figure 3 shows the evolution of the percentage of the number of weather stations from the ACS books not included in the BNDC. Except for the war years, the ACS provided at least about 20% of the total data, and before 1930 the proportion was over 50% of the total. To sum up, digitalisation of the ACS books significantly increased the information on monthly temperature available for the 1916–1949 period, by extending series already contained in the BNDC, filling-in the missing data and

retrieving from oblivion hundreds of observations made at a time for which there is no other information.

In brief, the combination of documentary sources in the BNDC of AEMET and the ACS books is the most detailed dataset of temperature available to analyse temperatures in the first half of the 20th century in Spain, a period that is especially scarce in data. Figure 4 shows the evolution of the number of weather stations for the whole period. There are 5,259 weather stations in total, and the maximum number of observations taken simultaneously occurred in 1994 with 2030, while the minimum was in 1939 with 228. Figure 4 repeats the general pattern described in previous papers and from other places, with an increase during the 1950s and 60s, stagnation around 1980, followed by a decrease. The number of weather stations has been maintained at over 500 since the end of the 1940s, and above 1,500 since 1975, with more than 200 observations annually from the start of the century.

This information is the starting point for the new MOTEDAS_century database (MOTEDAS is the acronym

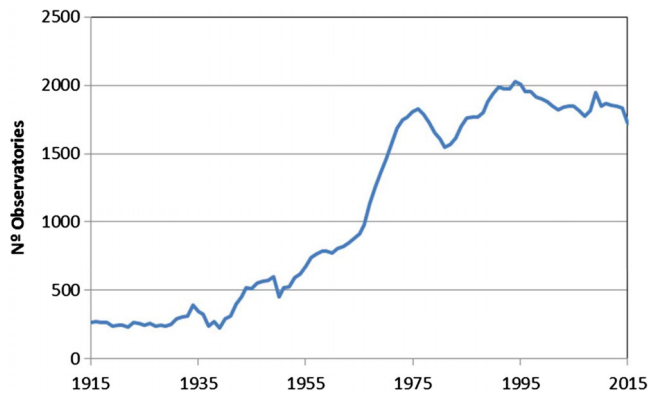


FIGURE 4 MOTEDAS_century database: Evolution of the number of weather stations per year with T_{\max} or T_{\min} temperature information in a certain month from 1916 to 2015 in mainland Spain

for MONTHly TEMperature DATaset of Spain from Gonzalez-Hidalgo *et al.*, 2015).

2.2 | Recording periods

Table 1 shows the distribution of the number of weather stations in the MOTEDAS_century database according to the number of years with information available for the whole period analysed (1916–2015). It can be seen that there is a very high number of stations with short recording periods. From the 5,259 weather stations that have at some time recorded temperature information, 36.6% have time series of less than 10 years, and 3,969 stations (75.5%) have time series shorter than the 30 years recommended as the normal WMO period.

This situation is accentuated in series prior to 1950 (Table 2). In this case, out of the total of 1,178 stations, 475 (40% of the series) have less than 5 years of data, and 63% less than 10 years; observations of just one, 2 or 3 years account for 25% of the number of weather stations.

In general, the information retrieved from the ACS books comes from series of short or very short duration. From a total of 1,107 weather stations, almost one third have data covering less than 3 years, which may also be incomplete, and more than 72% include observations less than 10 years long. The interesting fact is that, in turn, there are 96 weather stations with series longer than 20 years, and 29 contributing information spanning 35 years or more, meaning that almost the whole ACS period is included.

The importance of data retrieval from the ACS books is summarized in the following facts: for the 1916–1949

period, the BNDC records include information from 679 weather stations, while the ACS books contain data from 1,107, of which 135 are new.

2.3 | Distribution by altitude

Figure 5 shows the location of the temperature stations in the MOTEDAS_century dataset, showing an apparently fairly uniform cover.

However, the distribution of these weather stations in a space with such a highly contrasting orography as mainland Spain must also consider the spread of altitudes, as apart from coastal areas the average altitude is of around 500 m.a.s.l.

Figure 6 offers a comparison of the dataset split by altitudes. Observatories at less than 250 m above sea level are evidently over-represented, and coincide with the denser population on the coast. On the other hand, above 750 m the percentage of land and the weather stations indicate that observations are under-represented in these areas. The differences become sharper especially above 750 m, which is the altitude mainly covering the northern plateau and mountain and foothill areas.

The temporal evolution of the stations altitude is not uniform. Figure 7 shows the percentage of weather stations over five-year periods, grouped into altitude intervals; the data are expressed in proportion to the total number of stations in each 5-year interval.

The very small percentage of observations taken at high elevation is noticeable, especially over 1,000 m, as well as at altitudes above 750 m following the Spanish Civil War (1936–1939), when the proportion of weather stations fell for 80 years, although the ground above this height accounts for 42% of the whole country. The proportion in the <250 m interval also decreased, while it increased between 250 and 750 m. These data seem to suggest some effects in the observation network of the rural exodus from 1940, and show the difficulty encountered for making stable climate observations in rural areas; therefore, care is required in applying any interpolations to high altitudes simply because there is very few data.

The network has evolved over time in a way that suggests that there was some kind of pattern to its development, gradually covering the adjoining territory from the main cities (provincial capitals). The proliferation of observations from places close together gave rise to a dense grid in which the abandonments and closures of observation points in recent years has not lessened the average distance between neighbouring stations. This is seen in Figure 8, which shows the temporal evolution of the number of weather stations and the average distance

TABLE 1 Number of weather stations (*N*), combination of BNDC and ACS for 1916–2015, according to length in years of records (years)

Years	1–5	6–10	11–15	16–20	21–25	26–30	34–35	36–40	41–45	46–50	51–55	56–60	64–65	66–70	71–75	76–80	84–85	86–90	91–95	95–100
<i>N</i>	935	991	677	513	482	371	320	214	225	148	87	63	54	45	45	36	23	11	8	11
%	17.8	18.8	12.9	9.8	9.2	7.1	6.1	4.1	4.3	2.8	1.7	1.2	1.0	0.9	0.9	0.7	0.4	0.2	0.2	0.2

to their nearest neighbour. The figure shows as an example the case of January because the amount of stations slightly differs among months.

Figure 8 shows that the distance between neighbours has been stable at approximately 7 km for decades, despite an increase in the number of weather stations in the same period. This number is significantly lower than those previously obtained from former databases such as MOTEDAS (Gonzalez-Hidalgo *et al.*, 2015) at about 14 km, since we have included all weather stations in MOTEDAS_century, without leaving aside any that had few records, as it was done in MOTEDAS. In general, neighbouring weather stations stood 20 km apart between 1916 and 1935; after the Spanish Civil War, there was a gradual fall in mean distance, due to the new development of the meteorological network and more observations throughout the country, which stabilized from the mid-1970s, regardless of the fluctuations in opening and closing weather stations.

2.4 | Points prior to developing the grids

Analysing the information from the BNDC and ACS showed that many of the series contained data from a very few years, which probably explains why they were left out of the digitalisation carried out by AEMET. On the other hand, the spatial distribution of available stations changes from month to month. Faced with this situation, two options were suggested for creating the grids:

- perform a reconstruction of the time series merging data from several neighbouring stations and filling the existing gaps before making the interpolation and calculation of the grid; or
- consider each monthly time unit in isolation and calculate each monthly field independently with the information available, in order to obtain a continuous time series in every cell.

The first approach combines neighbouring weather stations and basically follows the proposal of Hansen and Lebedeff's (1987) to obtain longer series than the initial ones. There are several methods for selecting neighbours, but they are mainly based on criteria of closeness and similarity of behaviour in the common periods among series. With these series, a "reference series" is calculated and either used to reconstruct each weather station, or to be used as the series representing an area, which was Hansen and Lebedeff's (1987) original idea. There is no single procedure or universal algorithm to create the reference series, nor has one of the variables proved to be better than the others, and there is a good amount of

TABLE 2 Number of weather stations (N), combination of BNDC and ACS for 1916–2015, and percentage they represent of the total prior to 1950, depending on the number of years of observation (years)

Years	1	2	3	4	5	6–10	11–15	16–20	21–25	26–30	31–35
N	156	103	82	51	83	273	158	147	45	32	48
%	13.2	8.7	7.0	4.3	7.0	23.2	13.4	12.5	3.8	2.7	4.1

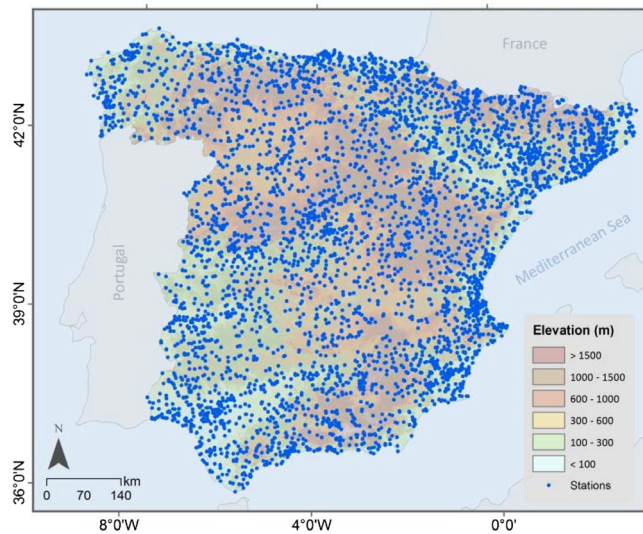


FIGURE 5 Location of the temperature weather stations in the 1916–2015 period

discussion on the number of neighbours, distances between them and other aspects, since by varying the number of weather stations in time, the reference series tends to reflect the average of them all, but not their variability, and so the reconstructed periods become biased as the number of weather stations changes, usually decreasing when going back in time (Beguería *et al.*, 2016; 2019).

In our opinion, this method could be suitable for creating a grid when there is abundant information, as it is the case of the second half of the 20th century, with the advantage that the number of weather stations used in each time unit (day, month or year) is the same and enables uncertainty intervals to be calculated very easily, as has been applied in some previous studies on temperatures in Spain (Gonzalez-Hidalgo *et al.*, 2015). As commonly used, this procedure lacks propagation of uncertainty from the creation of the reference series to the creation of the grid, as also pointed out by Beguería *et al.* (2019).

This approach, however, does not seem to be the best option in this case, since not only there is a huge difference in the number of weather stations among years (see Figure 4), but the length of the records also varies (see

Tables 1–3). Therefore, the procedure would lead to an overstated and forced reconstruction from several weather stations for long periods of time, with the worst case scenario being possibly having to reconstruct 99 years and 11 months, which not only produces redundant information as it comes from neighbouring stations, but would also be just a game of statistics. Alternatively, information from short series ought to be discarded, but then the benefits of retrieving digitalized data would be lost to a great extent.

The second option enables use of all the information available in each time unit, without forcing cases, such as the one mentioned, to be reconstructed. This procedure, however, is not exempt from problems since each time unit (x -month of x -year) is calculated from a different number of weather stations.

In our case, the procedure chosen to develop MOTEDAS_century was to reconstruct the T_{\max} and T_{\min} values for every month and year in each grid cell (monthly fields), a common procedure in grids on a world scale (Jones *et al.*, 1986; 2012; Jones and Wigley, 2010), and using the anomalies method. The process was carried out in three steps.

In order to validate the adequacy of the selected gridding method, the MOTEDAS grid of Gonzalez-Hidalgo *et al.* (2015) was recalculated for the period 1951–2010 using the two methodologies: (a) using only a selected set of series reconstructed in their missing values, as done in Gonzalez-Hidalgo *et al.* (2015); and (b) using all (unreconstructed) series available at any moment, with a changing number of stations from month to month, simulating the conditions used to develop MOTEDAS_century. The interpolation method applied in this step to reconstruct the monthly fields in the new grid was the same as that used in the MOTEDAS grid.

In the second step, the objective was to identify which interpolation method returned the best results. T_{\max} and T_{\min} grids were calculated for the period with least information (1916–1949), using four interpolation models: multiple linear regression (MLR), Universal Kriging or Kriging with external drift (UK), Inverse Distance Weight (IDW), and the method proposed by Brunetti *et al.* (2006) (adding an angular weighting factor taking into account anisotropies in spatial distribution).

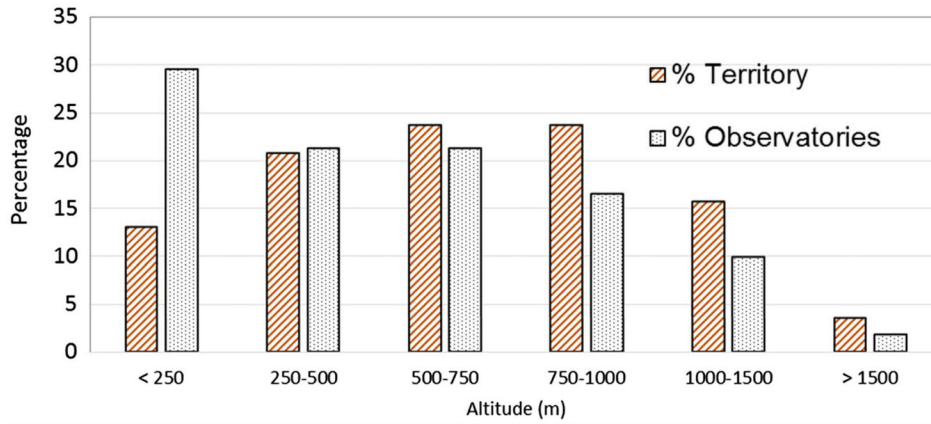


FIGURE 6 Distribution by altitudes of the percentage of weather stations and territory

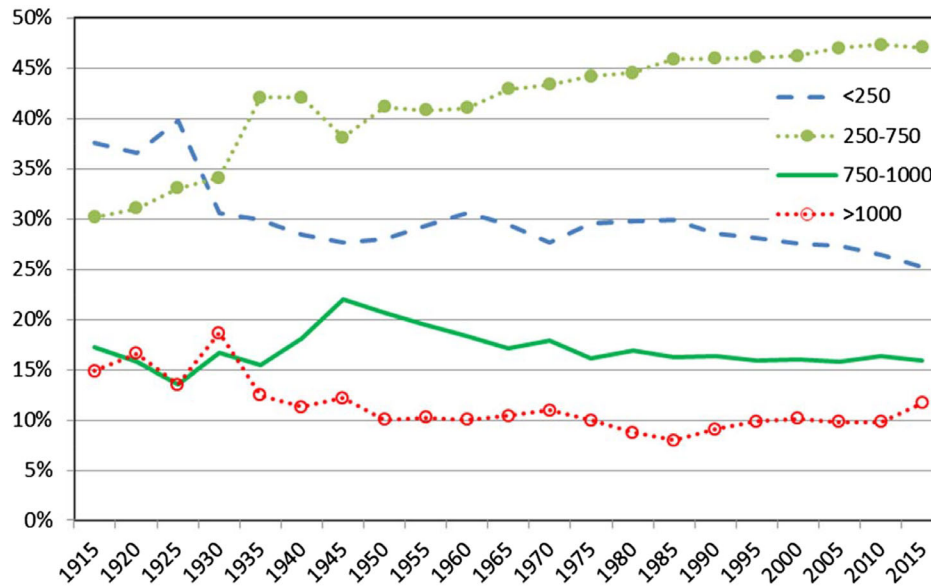


FIGURE 7 Evolution of the percentage of weather stations by altitude intervals (m.a.s.l.)

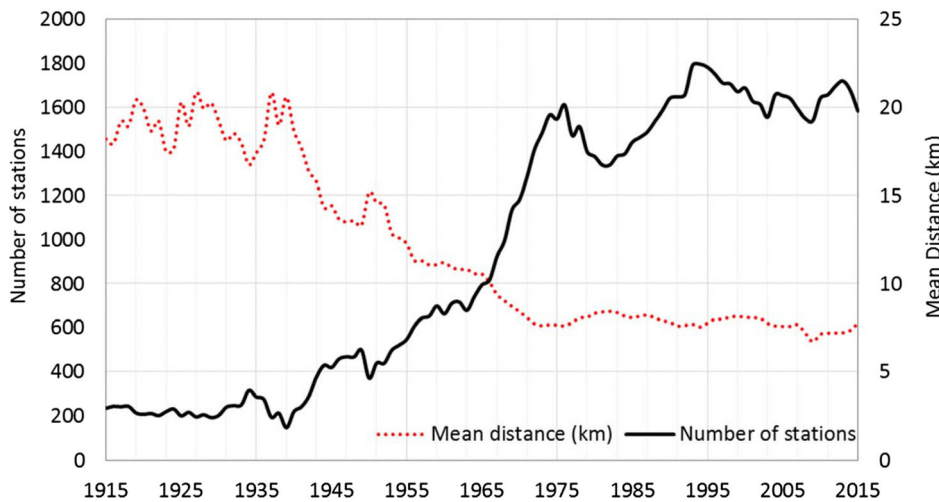


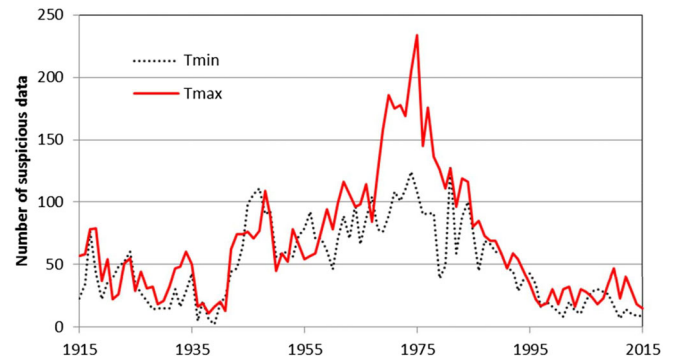
FIGURE 8 Number of observations per year (T_{max} , January) and average distance between neighbouring weather stations

of stations around the grid point as was done in González-Hidalgo et al. (2011)) that we will call Angular Distance Weighting (henceforth AD). Evaluation of the

models were carried out by comparing time series estimated by interpolation methods with the observed ones. Models validation were done using a leave-one-out

TABLE 3 Anomalous data detected and discarded out of the total

	January	February	March	April	May	June	July	August	September	October	November	December
T_{\max} anomalies	388	444	455	546	680	700	738	667	673	612	516	438
T_{\min} anomalies	355	328	330	350	412	492	677	609	550	417	331	341
T_{\max} (%)	0.07	0.08	0.09	0.10	0.13	0.13	0.14	0.13	0.13	0.12	0.10	0.08
T_{\min} (%)	0.07	0.06	0.06	0.07	0.08	0.09	0.13	0.11	0.10	0.08	0.06	0.06

**FIGURE 9** Evolution of the total annual anomalous data detected and discarded

procedure: each month and year value for x-station was excluded from the dataset, and reconstructed by the model using all the other stations. Finally, the estimated value was compared with the observed data by using five statistics (see Peña-Angulo *et al.*, 2016 for details). The selected statistics were the following: MAE (mean absolute error) and r (correlation), measuring goodness of fit; MBE (mean bias error) and the ratio of means (ratioMean), measuring bias in the first moment; and also the standard deviation ratio (ratioSD), measuring bias in the second standardized moment. In the end, the AD model was chosen because of its better results. Lastly, the mean monthly grids were calculated for maximum and minimum temperatures for 1916–2015, which formed the base for the mean monthly and temperature variation grids.

2.5 | Creating the grid: Quality control, interpolation, and uncertainty analysis

Having selected the interpolation method and in order to remove any errors in the original sources, in their transcription or in subsequent data processing, a quality control process was carried out as a preliminary step to interpolation, using the following criteria to detect and eliminate suspicious data:

- $T_{\max} < T_{\min}$;
- monthly mean $> 50^{\circ}\text{C}$ and $< -50^{\circ}\text{C}$;
- monthly temperature variation (range) $> 50^{\circ}\text{C}$;

Lastly, data were also discarded when: (a) the difference with the nearest neighbours (less than 75 km away) were $> 5^{\circ}$; and (b) the temperature difference with at least two of them was higher than three times the mean lapse rate.

Figure 9 shows the time evolution of the annual totals of data considered suspect and removed from the dataset before interpolation. In general, the greatest amount of

TABLE 4 Monthly means for the validation criteria of the AD model

Tmax	January	February	March	April	May	June	July	August	September	October	November	December	Mean
MAE	0.981	0.983	0.979	0.986	1.004	1.041	1.072	1.061	1.033	0.986	0.947	0.970	1.004
MBE	0.002	0.001	-0.002	0.004	0.004	0.001	-0.001	0.002	0.000	0.005	0.000	0.000	0.001
Ratiomean	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
RatioSD	0.925	0.925	0.909	0.923	0.915	0.922	0.935	0.930	0.911	0.913	0.924	0.928	0.922
r	0.908	0.901	0.893	0.897	0.901	0.910	0.924	0.920	0.897	0.896	0.911	0.914	0.906
Tmin	January	February	March	April	May	June	July	August	September	October	November	December	Mean
MAE	0.965	0.942	0.920	0.891	0.902	0.938	0.981	0.993	0.969	0.931	0.928	0.960	0.940
MBE	-0.001	0.000	0.002	0.002	0.003	0.001	0.001	0.001	-0.001	0.000	0.002	0.002	0.002
Ratiomean	1.001	1.000	0.999	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.049	1.000
RatioSD	0.934	0.938	0.939	0.941	0.930	0.926	0.932	0.939	0.937	0.941	0.942	0.937	0.937
r	0.918	0.920	0.914	0.913	0.903	0.904	0.912	0.916	0.920	0.925	0.925	0.918	0.918

anomalous data coincides with the increase in the number of weather stations between the 1950s and the 1960s, and it is larger for T_{\max} than for T_{\min} , so it does not affect the period of data retrieved from the ACS books. There are also monthly differences, with a higher number of suspects detected in summer than in winter.

However, the relative amount of data discarded due to anomalies is very low. Table 3 shows the total monthly data for T_{\max} and T_{\min} , the total number of anomalous in both, and their percentages. In T_{\max} , 6,857 months were discarded and 5,192 in T_{\min} , which accounts for less than 1% of the total, respectively.

Interpolation with the quality-checked data was carried out combining weights balanced by longitudinal and angular distances (Brunetti *et al.*, 2006). Interpolation was not performed on the raw temperature data but on anomalies series, which were calculated by the differences method with respect to the 1951–2010 mean climatology obtained from the high resolution climatology of Peña-Angulo *et al.* (2016).

Uncertainty in the annual values of T_{\max} and T_{\min} series was estimated by calculating, in the monthly T_{\max} and T_{\min} series, the standard error in the values observed and estimated by the interpolation method using the leave-one-out method. The standard error in the mean annual T_{\max} and T_{\min} series was estimated as the median of monthly errors calculated by the normal process ($\frac{\sigma}{\sqrt{n-1}}$), being sigma the standard deviation of observed and calculated stations data by month, and lastly the confidence interval CI ($p < 0.05$) were calculated by:

$$CI = \text{Annual Mean} \pm (\text{average standard error} * 1.96).$$

2.6 | Trend analysis

The sign and significance of the trends of average annual maxima and minima series were analysed using the Mann–Kendall nonparametric test (Mann, 1945), after validating and eliminating the autocorrelation by pre-whitening the series (see Gonzalez-Hidalgo *et al.*, 2015). The significance level was set at $p < .05$. The trends were calculated in moving windows of length ranging from 20 to 100 years to find how they had changed over time. The trend rate was evaluated by the Theil-Sen slope estimator (Sen, 1968).

3 | RESULTS

3.1 | Model and grid validation

Table 4 shows leave-one-out mean monthly error statistics for the interpolation method used to reconstruct the monthly fields for 1916–2015.

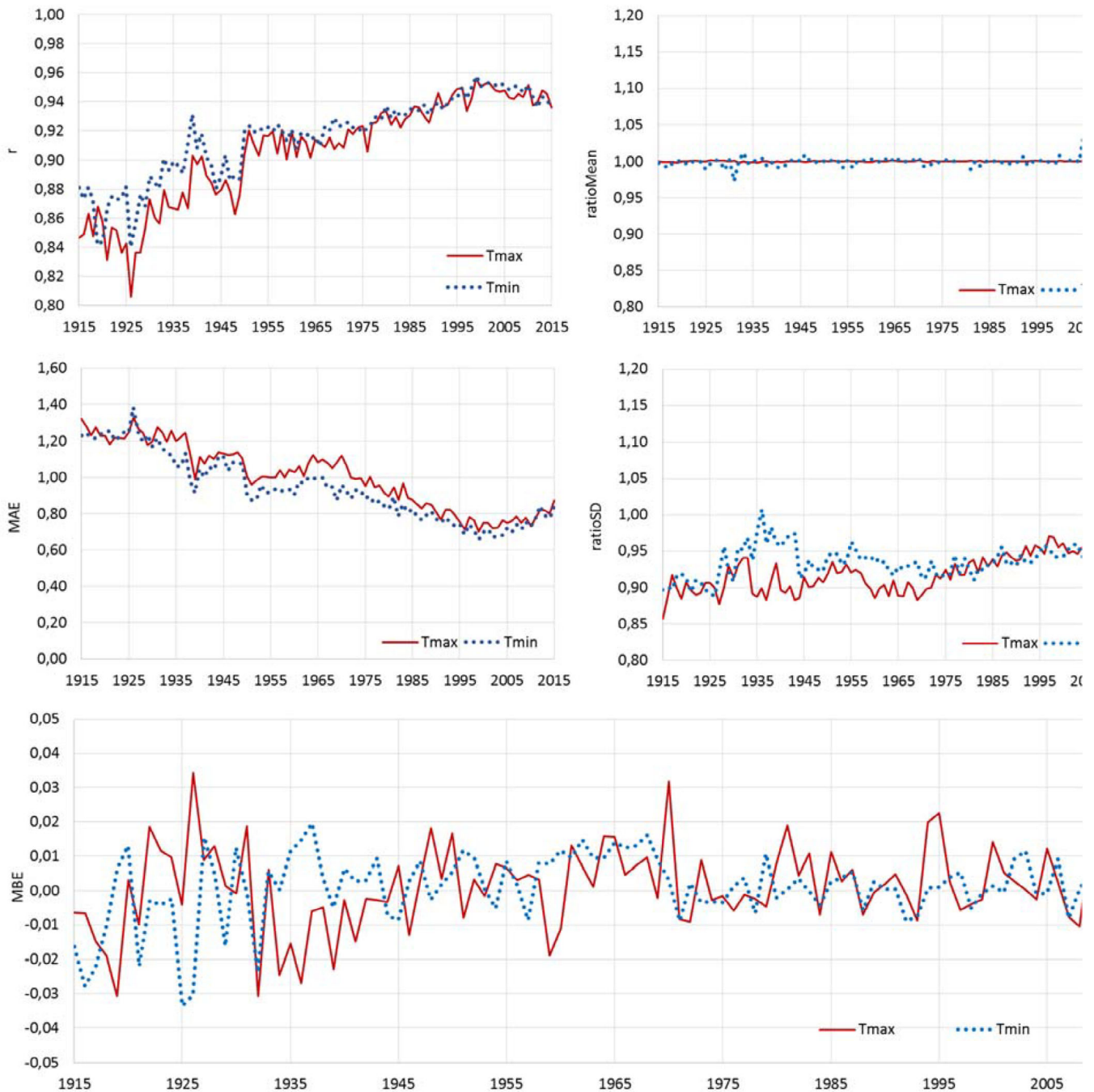


FIGURE 10 Evaluation of the annual mean of error statistics in the AD interpolation method

In general, the five statistics suggest that the method provided good results for monthly means, although differences are found between T_{\max} and T_{\min} in the various indicators and variations in these among months. The grid estimations are unbiased, as shown by the MBE values close to zero, and those of ratioMean close to one. The fit with the observed series is also very good, with r values higher than 0.9 in most cases. The absolute error (MAE) is around 1°C for T_{\max} , and slightly lower in T_{\min} ,

with no significant differences between months. The ratioSD is between 0.90 and 0.94 in almost all cases, indicating an underestimation in the standard deviation of 6–10%, which can be considered a normal and acceptable value.

The five indicators display variations over time (Figure 10). The value of r increased from approximately 0.85 at the start of the study period to around 0.95 at the end. The differences between T_{\max} and T_{\min} are only

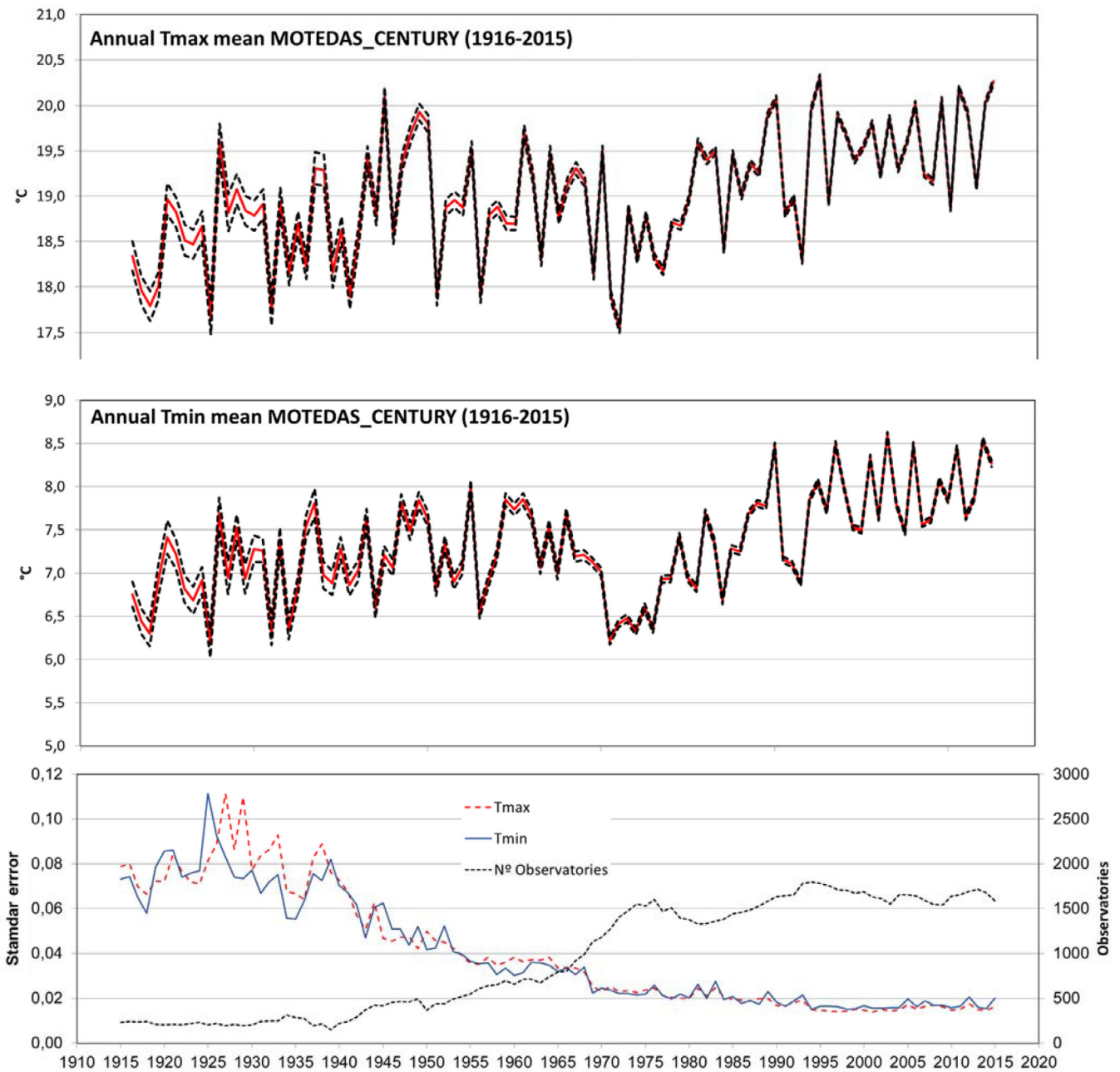


FIGURE 11 Evolution of the annual mean of T_{\max} , T_{\min} , and their confidence intervals (broken line). Bottom, annual standard error (T_{\max} and T_{\min}), and number of weather stations per year 1916–2015

noticeable in the early years of the century, with better values in T_{\min} than T_{\max} . In agreement with this behaviour, the absolute error (MAE) decreased during the same period from 1.2 to less than 0.8°C. The error was generally higher in T_{\max} than T_{\min} . The MBE and the ratio of means oscillated randomly around their mean values (0 and 1, respectively), indicating no trends or major changes in bias. The standard deviation ratio, on the other hand, had an increasing trend from approximately 0.90 to around 0.95, with better behaviour (values closer to one) in T_{\min} until about 1975, when the two variables

become almost equal. The presence of a trend in the temporal evolution of this statistic, albeit small in magnitude, could potentially affect any study of the temporal evolution of the variability of temperatures in the study area. The same could occur with studies based on standardized anomalies.

The time evolution of the mean bias error (MBE) deserves closer inspection, since the presence of temporal trends in this statistic would translate to biases in the regional averages that would affect the estimation of temporal trends in the mean temperature. As it was

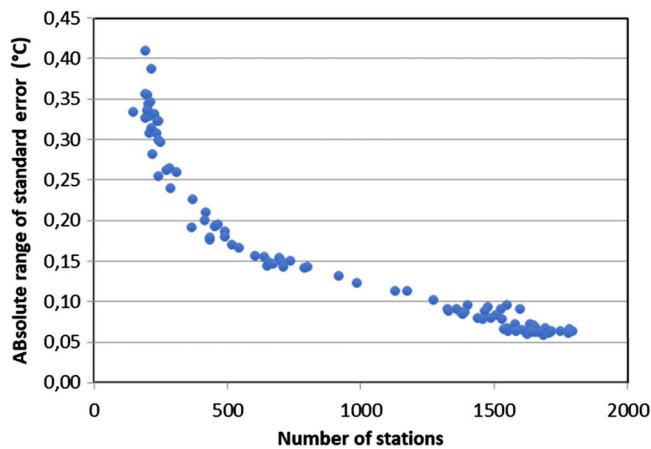


FIGURE 12 Variations in the absolute 95% standard error interval (upper-lower limits) according to the number of weather stations. T_{\max} with observations from January

mentioned, the values oscillated around 0 during the whole period, and there were no signs of trends. The variability of the MBE was notably higher during the first decades, and especially prior to 1940, in agreement with the evolution observed in the goodness of fit (r). During the first decades the MBE of T_{\max} tended to be higher than that of T_{\min} , while the opposite occurred in the 1930s. From 1950 the variability in both indicators decreases and they become much more similar to each other.

3.2 | The evolution of annual means of T_{\max} and T_{\min} , 1916–2015

T_{\max} and T_{\min} mean annual series for 1916–2015 are shown in Figure 11, together with their uncertainty intervals ($p < .05$). Mean annual temperatures have risen on the Spanish mainland between 1916 and 2015, an increase whose values are very similar to those described for the whole of the planet: 1.2°C in T_{\max} and 1.0°C in T_{\min} .

The evolution of temperatures has not followed a monotonic trend. Broadly speaking, both T_{\max} and T_{\min} follow the well-known phases of the evolution of temperatures in the 20th century shown in previous analyses: (a) a gradual increase until the 1940s; (b) the first hiatus, with falls between approximately 1940 and 1970; (c) another, faster increase since 1970; and (d) a stagnation from the end of the 1980s until the present day in the second hiatus.

For both variables the estimated uncertainty is, as expected, higher during the first decades of the study period, although the range of the uncertainty is not very

wide and, as already seen, it is not associated to a systematic bias that would distort the trend calculation. The figure also shows that the standard error is related negatively to the number of observations. The relationship between both variables is shown in Figure 12.

The standard error interval increases when a small number of observations are analysed, which is to be expected, and therefore decreases as the observations increase. In the case shown, values of less than 0.2 are achieved with 500 or more observations, and less than 0.1 with over 1,000. These values correspond in time to years 1945 and 1975, respectively. Similar behaviour was found in the remaining months and in T_{\min} .

3.3 | Variations in the trend of T_{\max} and T_{\min} annual mean series

The evolution of the annual means for T_{\max} and T_{\min} in the study period confirms the absence of a stable trend, as already suggested. Figure 13 enables a detailed analysis of the sign and significance of the trends for possible time periods spanning between 100 and 20 years within the period 1916–2015. Colours refer to the positive and negative sign and two significance levels according to the Mann–Kendall test.

The horizontal axis represents the starting year of the time window, and the vertical axis its length in years. In the lower part of both figures the lowest horizontal line represents the minimum value of the length of the time windows studied (20 years). It shows that, except in periods starting around 1965 and up to 1975, the 20-year trends were not significant in T_{\max} . In 30- and 45-year windows, significant trends were found in those starting from the beginning of the century and those starting from 1950 to 1965, respectively. These results are very similar for the two variables (T_{\max} and T_{\min}). However, between these two periods a band of windows between 20 and 50 years in length appears with a negative trend, more pronounced in T_{\min} than T_{\max} , with starting year ranging between the 1940s (for the 40-year windows) and the 1960s (for the 20-year windows). The significance of these trends is generally low, and only significant for some cases of T_{\min} . This negative trend is known as the first hiatus of the 20th century, and has been identified previously (see Easterling and Wehner, 2009, among others). In general, time windows longer than 60 years have all positive trends and mostly significant, especially in T_{\max} , and from 80 years they are all significant in both variables. It is interesting to note that trends are not significant from 1975 in T_{\max} , and from 1985 in T_{\min} , as will be discussed below.

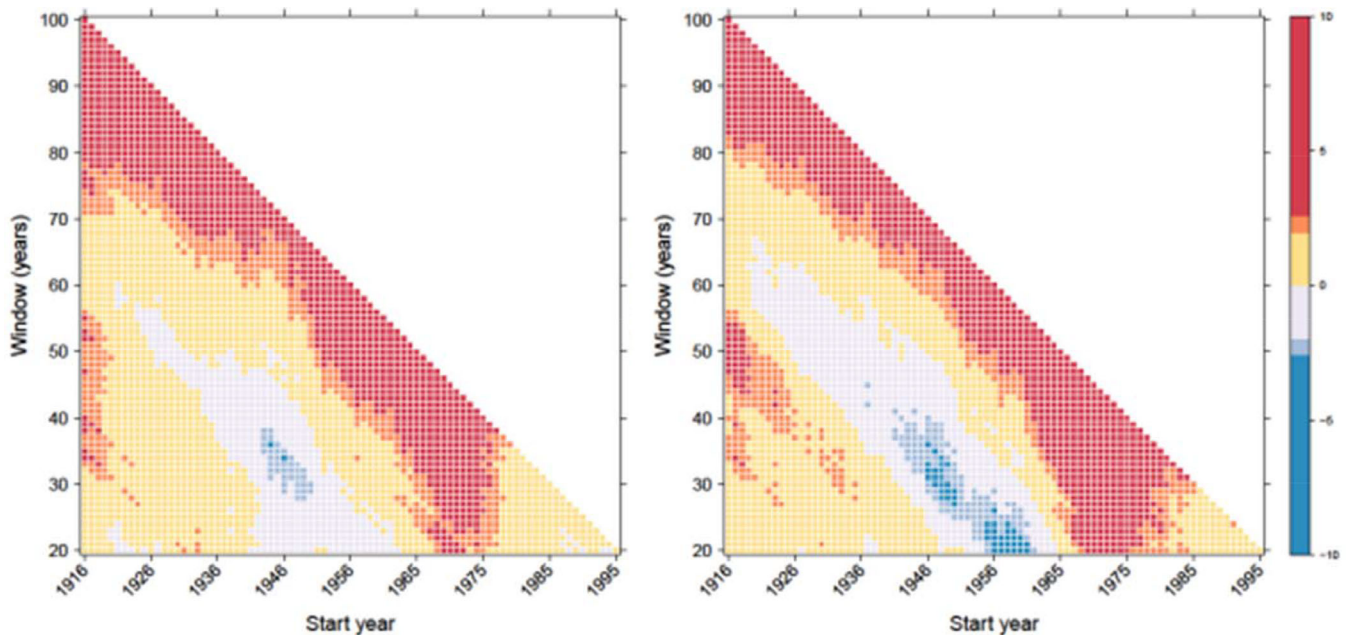


FIGURE 13 Trend analysis using moving windows, T_{\max} (left) and T_{\min} (right), during the period 1916–2015. The figure shows the significance and the trend sign according to the Mann–Kendall test. The darkest shades of red/orange and blue indicate significant trends (positive and negative, respectively) at the $\alpha=0.01$ level, while intermediate shades indicate significance at the $\alpha=0.05$ level. The two middle bands (yellow and pale blue) indicate nonsignificant (positive and negative) trends

The detailed study of the sequence of time windows provides complementary information on the evolution of temperatures. In particular, the hypotenuse of the triangle corresponds to the trends of all those windows ending in 2015. They correspond to the diagonal between the 100-year window in the top left, and the 20-year window in the bottom right. The evolution of the rate of change and its confidence interval along this diagonal is shown in Figure 14, together with the absolute amplitude of the interval (its range). Both T_{\max} and T_{\min} display a similar pattern, and it is noticeable that the confidence intervals increase when the time period is short. Thus, for example, in windows shorter than 50 years the range of the confidence interval exceeds $0.2^{\circ}\text{C}\cdot\text{decade}^{-1}$, a value that is almost double than the estimated rate during the 20th century.

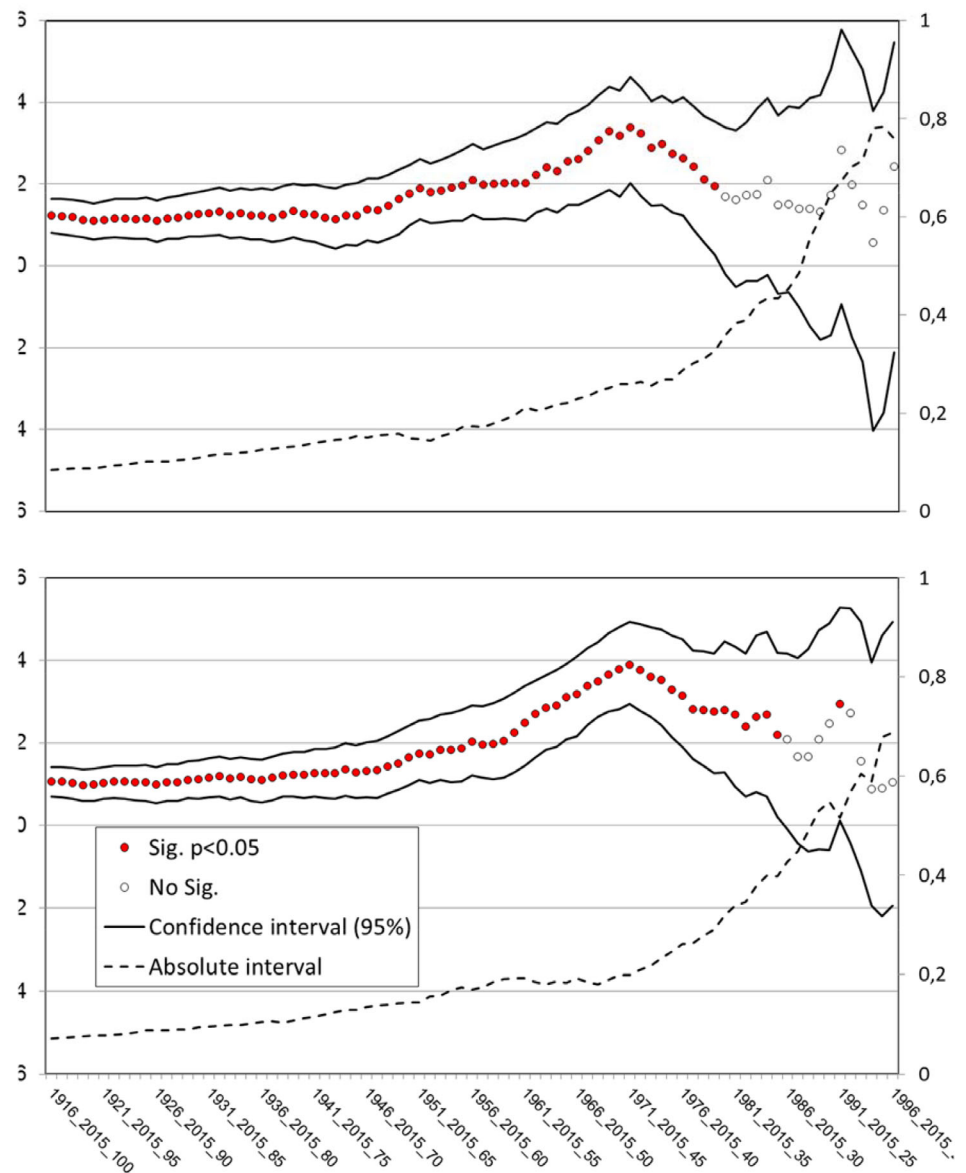
The rate of T_{\max} mostly exceeds that of T_{\min} in the 1916–2015/1950–2015 windows, then they are equivalent until 1956–2015. Since then, the T_{\min} rates of change in all windows exceed those of T_{\max} , with a maximum difference in the 1971–2015 period, following which there is a continuous decreasing of the trend, with significant rates in T_{\max} up to the 1979–2015 window, and in T_{\min} until 1985–2015. This means that during the last 41 and 34 years, respectively, no significant trends in the annual means of T_{\max} and T_{\min} are detected in the Spanish mainland, which is related at the same time to the decreasing rates of change and the very high uncertainty in the calculation of these trend rates.

These trends are calculated as mean values from the gridded data, and therefore hide spatial differences. In Figure 15 we show the spatial distribution of the sign (positive/negative) of trends in monthly T_{\max} and T_{\min} distinguishing between two significance levels: not significant and $p < .05$. The first one embraces the complete period 1916–2015 (100 years), the second one the period 1951–2015, which is fairly similar to the previous version of the dataset (MOTEDAS, spanning the period 1951–2010), and the third one represents the most recent 25 years (1991–2015). Generally speaking, the trends have varied among the months, T_{\max} and T_{\min} and time, conforming a complex scenario that demands specific and detailed analyses.

4 | THE DIFFERENT VERSIONS OF TEMPERATURE EVOLUTION IN SPAIN: MOTEDAS_CENTURY, MOTEDAS, SDAT, AEMET, BEST, NCEP-NCAR

In this project, an exhaustive process of data retrieval was carried out to combine information on the temperature from the ACS books with that of the BNDC to create a gridded dataset that maximizes the use of all the information available in each time unit and would allow assessing the evolution of the temperature over the

FIGURE 14 Evolution of the trend in falling periods 1916–2015 of annual mean T_{\max} (top), and T_{\min} (bottom). The number after the periods gives their length in years



Spanish mainland. In addition, the comparison of the global series created in the present work with previous versions from other sources is of great importance.

The comparison was made with: (a) the MOTEDAS version calculated with 1,358 reconstructed series, for the 1951–2010 period (Gonzalez-Hidalgo *et al.*, 2015); (b) the national series calculated by AEMET for the 1951–2014 period (J.A. Guijarro, personal communication); (c) the version from the SDAT database, for 1916–2014 (Brunet *et al.*, 2006; Sigro *et al.*, 2015); (d) the series calculated for Spain from the BEST database, for 1916–2012 (Rohde *et al.*, 2013); and (e) the mean series calculated from the NCEP-NCAR reanalysis (Kalnay *et al.*, 1996) for the study area (45° – 35° N, 10° W– 5° E), for 1951–2015.

Figure 16 shows the annual means for T_{\max} and T_{\min} expressed as anomalies with respect to the common reference period 1961–1990; anomalies were

recalculated when needed (as for MOTEDAS_century). All the series follow a similar time pattern in the shared periods.

The overall impression is that the three versions of the secular evolution (MOTEDAS_century, BEST and SDAT, although BEST ended in 2012 and SDAT in 2014) share a very similar time pattern. The three series display the usual phases of rising, stagnation and falling, re-ascendant and final stagnation previously described and stressed in several papers (see Easterling and Wehner, 2009; Foster and Rahmstorf, 2011; Kaufmann *et al.*, 2011; Karl *et al.*, 2015). Despite these similarities, however, the trends magnitude and significance change noticeably among datasets. The greatest differences were observed in T_{\max} in the early years when BEST gave higher values than SDAT and MOTEDAS_century. Also, from 1990 onwards, SDAT gave the highest values with

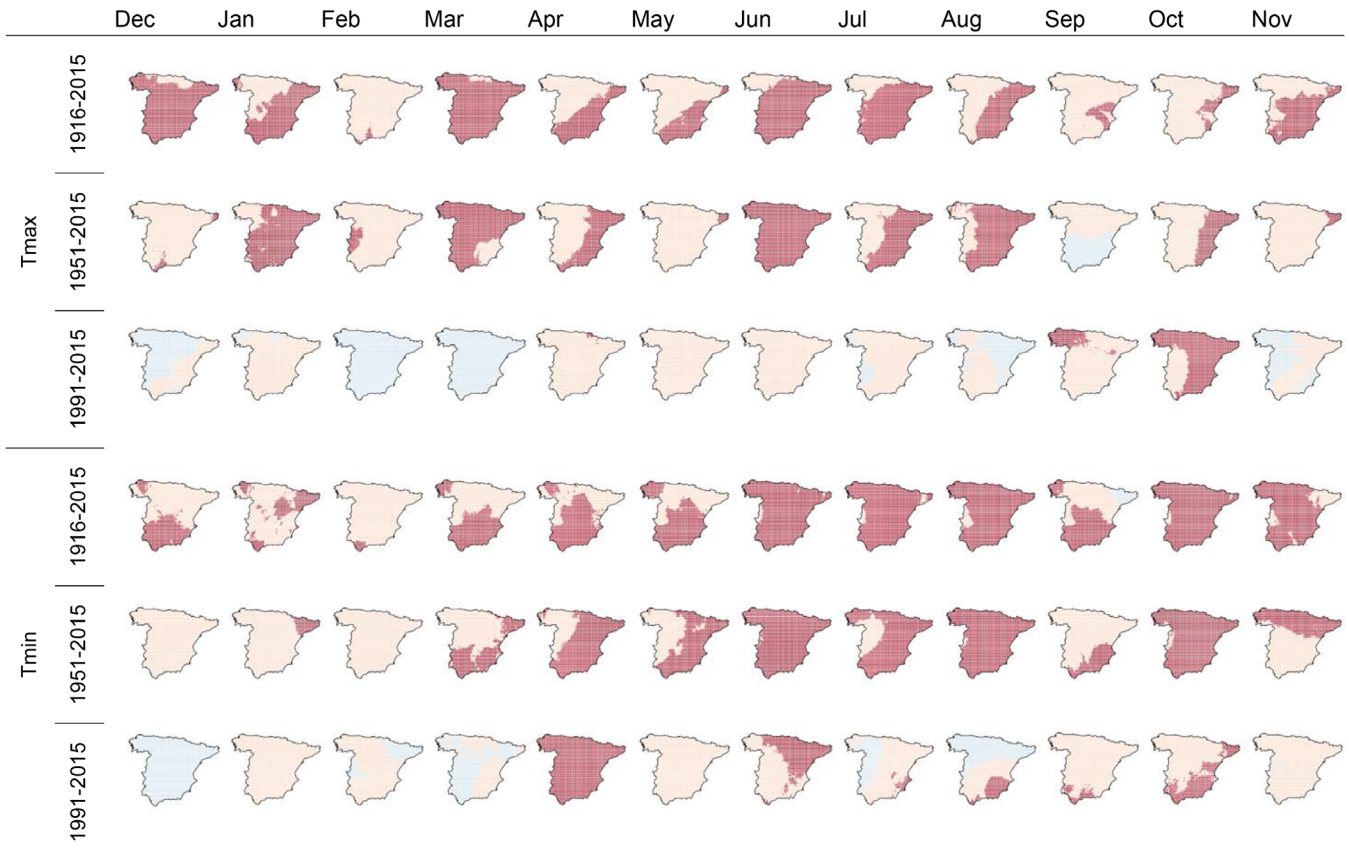


FIGURE 15 Spatial distribution trends of monthly T_{max} and T_{min} . Positive/negative (red/blue), significant $p < .05$ /no significant (strong/light colour)

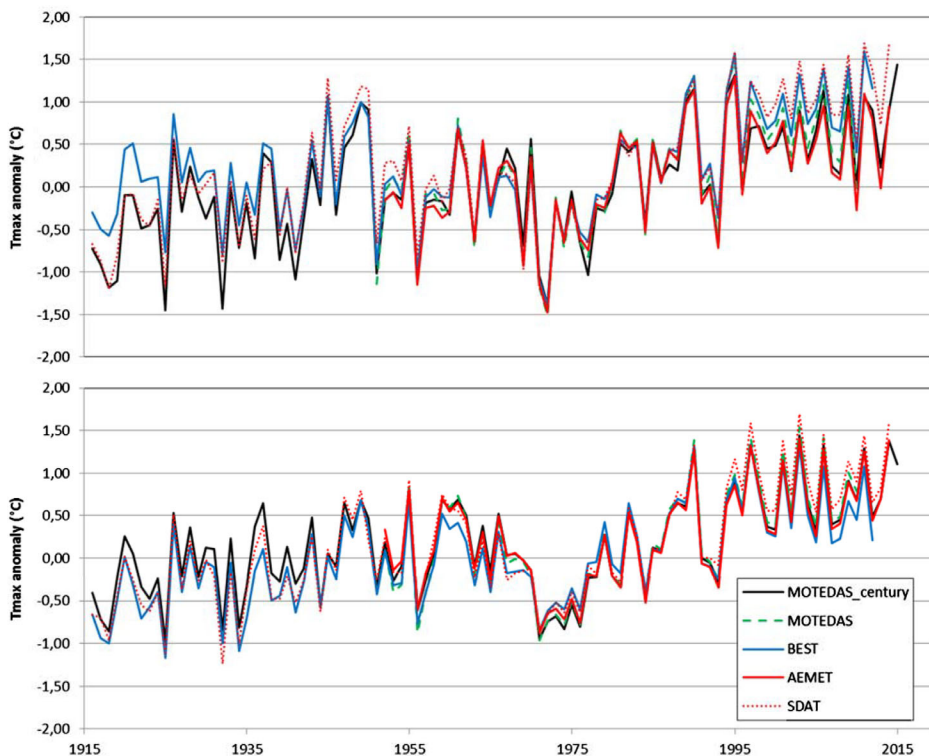
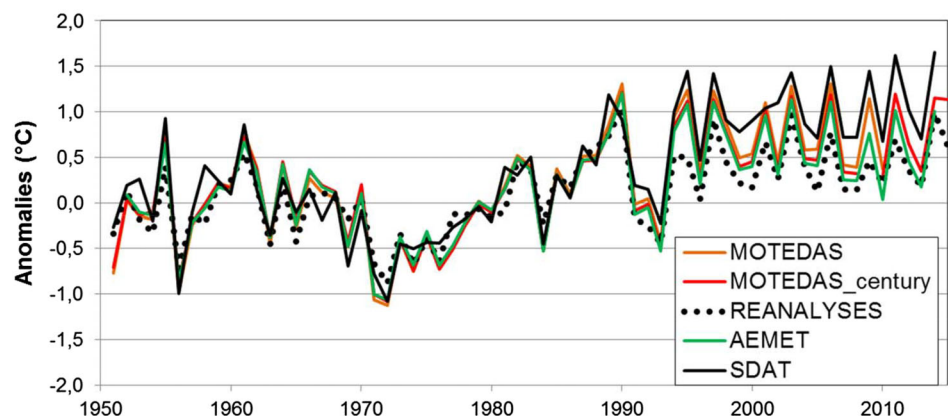


FIGURE 16 Annual means in the T_{max} (upper) and T_{min} (bottom) series for mainland Spain in the MOTEDAS_century, MOTEDAS, BEST, AEMET, and SDAT databases

TABLE 5 Trend rate °C·decade⁻¹ (Sen estimator) in the mean annual T_{\max} and T_{\min} series of the BEST, SDAT, and MOTEDAS_century databases in various periods

		BEST		MOTEDAS century		SDAT	
		T_{\max}	T_{\min}	T_{\max}	T_{\min}	T_{\max}	T_{\min}
1916_2012 (97 years)	Rate	0.105	0.119	0.118	0.097	0.150	0.146
	Interval (\pm)	0.043	0.031	0.045	0.039	0.040	0.035
	Sig	0.001	0.001	0.001	0.001	0.001	0.001
1938_2012 (75 years)	Rate	0.157	0.119	0.118	0.111	0.163	0.167
	Interval (\pm)	0.061	0.044	0.066	0.059	0.061	0.057
	Sig	0.001	0.001	0.001	0.001	0.001	0.001
1963_2012 (50 years)	Rate	0.356	0.220	0.242	0.279	0.372	0.339
	Interval (\pm)	0.105	0.074	0.114	0.115	0.084	0.086
	Sig	0.001	0.001	0.001	0.001	0.001	0.001
1973_2012 (40 years)	Rate	0.393	0.244	0.299	0.376	0.44	0.424
	Interval (\pm)	0.135	0.108	0.161	0.124	0.111	0.116
	Sig	0.001	0.001	0.001	0.001	0.001	0.001
1978_2012 (35 years)	Rate	0.321	0.157	0.209	0.272	0.369	0.356
	Interval (\pm)	0.173	0.167	0.190	0.160	0.153	0.152
	Sig	0.001	-	0.050	0.010	0.001	0.001
1983_2012 (30 years)	Rate	0.295	0.137	0.166	0.244	0.319	0.300
	Interval (\pm)	0.211	0.242	0.241	0.219	0.197	0.221
	Sig	0.010	-	-	0.050	0.010	0.050
1988_2012 (25 years)	Rate	0.184	-0.039	0.105	0.099	0.202	0.193
	Interval (\pm)	0.334	0.257	0.340	0.235	0.275	0.282
	Sig	-	-	-	-	-	-
1993_2012 (20 years)	Rate	0.163	-0.065	0.089	0.089	0.094	0.023
	Interval (\pm)	0.473	0.366	0.580	0.355	0.294	0.250
	Sig	-	-	-	-	-	-

Note: The confidence interval (95%) and significance are included. The bold style indicates the highest rate.

FIGURE 17 Annual averages of the mean monthly temperature. Comparison among MOTEDAS, MOTEDAS_Century, AEMET, SDAT, and Reanalyses

annual differences of over $0.05^{\circ}\text{C}\cdot\text{decade}^{-1}$ with respect to the other two.

Table 5 shows the T_{\max} and T_{\min} trends at various periods in the three-secular series, ending in 2012 as that

was the last time BEST was updated. The first covers 1916–2012 and the remaining periods are a sequence of pre-determined lengths of 75, 50, 40, 35, 30, 25, and 20 years. The analysis shows that, in the 1916–2012

period, T_{\max} and T_{\min} rose significantly ($p < .05$) in all three datasets. The increase was higher in T_{\min} than T_{\max} in the BEST database, but not in MOTEDAS_century or SDAT. In periods of less than 75 years but more than 30 the rate of T_{\min} is higher than T_{\max} in MOTEDAS_century, while in SDAT generally the rate of T_{\max} is higher than T_{\min} in the periods studied. The highest rates were reached in the 1973–2012 period and falling off afterwards, and no significant trend has been found in the last 25 years in the three datasets, or even in longer periods. Except in the most recent period, the highest rates of change were found in the SDAT database.

The results in the Table show the frame of secular evolution of temperatures in Spain, defined by: (a) global increase, at a rate of approximately $0.1^{\circ}\text{C}\cdot\text{decade}^{-1}$; (b) a period of maximum increase starting in the 1970s and lasting for two decades, at rates over $0.3^{\circ}\text{C}\cdot\text{decade}^{-1}$; and (c) absence of significance in most cases in the final three decades. The result suggests that the hiatus in the Iberian Peninsula lasted for much longer than two decades, whichever source is analysed, and requires a convincing explanation that has not been forthcoming so far (Medhaug *et al.*, 2017; Tung and Chen, 2018). In fact, the trends found have not only decreased, but also lack significance for periods of more than 25 years.

The main differences among the various databases are seen in the values of rates in the most recent periods; in the different behaviour of T_{\max} and T_{\min} ; and in the length of periods with or without significant trends. If the full period in SDAT (1916–2014) is considered, the trends have not been significant in T_{\max} and T_{\min} respectively since 1989 and 1987, dates that are similar to, but slightly behind, the MOTEDAS_century ones; if the AEMET (1952–2014) version is examined the trends have not been significant since 1977 and 1987 in T_{\max} and T_{\min} , respectively, with these dates being much closer to those in MOTEDAS_century (1980 and 1986), which has a similar time span.

Finally, Figure 17 shows the comparison of the mean annual series. The time-related pattern is again very similar among the various databases, and once more the SDAT version returns the highest values in recent decades, while the re-analysed series contains the lowest, especially for the last two decades.

5 | DISCUSSION

The comparison of annual mean T_{\max} and T_{\min} series from the new MOTEDAS_century dataset with their counterparts in the BEST, AEMET, and SDAT databases suggests that processing the newly retrieved information

does not modify substantially the temporal patterns of temperature in the Spanish mainland. The difference observed among the various sources can be attributed to a combination of effects from the different number of weather stations examined, which is very much higher in MOTEDAS_century, to their characteristics and the processing.

The original sources indicate that SDAT consists of 22 secular series (Brunet *et al.*, 2006; Sigro *et al.*, 2015) subject to an exhaustive process of quality control and reconstruction. Consulting the BEST website shows that in the period analysed, the series representing Spain was calculated from fewer than 20 weather stations located at less than 500 km apart, with station 1,000 km apart used if necessary, without stating exactly which ones. The series from MOTEDAS (1951–2010) comes from a grid created with 1,358 weather stations homogenized and reconstructed in their missing values, while the AEMET series combines 2,886 high quality-checked stations with over 10 years of data, with the number varying in time (Guijarro, 2013), as with MOTEDAS_century, whose series was calculated with a minimum of 228 stations and, since 1950, always with more than 1,000 observations per month.

Since the most noticeable differences among the datasets occur in the recent period, and these differences increase progressively, especially in T_{\max} , as well as the number, type and characteristics of weather stations, these, together with the processing of the information, seem to be factors causing the discrepancies among the databases. The comparative study of the rates obtained from the databases suggests that, the higher the number of weather stations used in calculating the global series, the lower the value of the mean temperature in recent decades and, therefore, the trend.

It has been suggested that the temperature in an area can be evaluated precisely if there are sufficient weather stations correctly distributed so that they collect the characteristics of the area (Janis *et al.*, 2004). Following this argument, any increase in the number of weather stations for the climate databases would improve the quality of the information in the scales of detail, and especially in the analysis of spatial patterns, but could become redundant for studying the regional temperature because many weather observations are not statistically independent, so that when a certain amount of observations is exceeded, in fact there will be no significant reduction in uncertainty (Jones *et al.*, 2012). The comments are rooted in the basic assumptions of all interpolation techniques (Hewitson and Crane, 2005): the common variance among weather stations expressed by positive correlations remains high, even at distances of over 1,000 km (Mitchell and Jones, 2005), and all these are caused by

the real situation - a permanent lack of climate information in many parts of the world in the time before satellites. For this reason, and particularly in environments of high spatial climatic variability such as the Spanish mainland, we do not believe that the increase in observations analysed produces redundant information, but completely the opposite particularly if original data (not reconstructed) are used, even more so in periods in which there has been a marked scarcity of climate data so far.

In the Iberian Peninsula, Peña-Angulo *et al.* (2015) demonstrated that the spatial variability in temperatures is very high. In general, the shared variance among weather stations of >50% is achieved at distances of less than 200 km; varies over the months and between T_{\max} and T_{\min} ; and very frequently is only achieved at less than 50 km apart. For this reason, the value of retrieving information from the ACS books, as carried out in the CLICES project, becomes important, so that the grids created and the mean series calculated from combining the retrieved data and those already present in the BNDC, seem to reflect more precisely the temperature evolution in a geographically complex region such as the Iberian Peninsula.

6 | CONCLUSIONS

We retrieved all the information on temperature in mainland Spain published in the ACS books for the 1916–1949 period, and combined them with sources from the BNDC, in order to create a 100-year grid (1916–2015) to analyse trends in temperature with the highest spatial resolution possible.

Retrieval, digitalisation and processing of information enabled gaps to be filled for weather stations previously included in the BNDC of the Spanish meteorological services, to extend the period of records for many of these series, and recover unknown weather stations. The global calculation indicates that, since 1916, there is annual information on the monthly means from over 200 weather stations, both for T_{\max} and T_{\min} , until 1950.

Due to the nature of the retrieved data (short time span and fragmentation) and, in order to use all the available information to create a grid, we reconstructed the annual monthly fields with the anomalies method, based on the climatology from 1951 to 2010.

The analysis of the mean annual diurnal temperature series (T_{\max}) and nocturnal (T_{\min}) on the Spanish mainland indicates that, for 1916–2015, the temperatures have risen by about 1°C, with slightly higher values for T_{\max} and lower for T_{\min} , although the opposite is true from the middle of the century. Lastly, for over three decades, the trend for both measurements has not been significant.

The results from the comparison among the different datasets of temperature in mainland Spain suggests that the information processed for the combination of original data to obtain a global series does not affect the main temporal pattern of the resulting series, which is very similar in all versions, but it is a different matter for its behaviour at certain times, especially in recent decades, and the value of the rate of change at various periods. Thus, the visual similarity in the series hides substantial differences, particularly in T_{\max} , and may be caused by the different number of weather stations studied and their characteristics, quality controls applied and the method used to calculate the global series.

The spatial distribution of trends shows that temperature in Spanish mainland has been a highly complex spatial processes that needs specific analyses.

The MOTEDAS_century grid in the anomalies format is available on request from the authors and metadata are available on the website of the CLICES Project.

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