TEMPERATURE TRENDS

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ABSTRACT
Mean maximum and minimum monthly temperatures have been collected for all stations with at least 10 years of observations during the period 1951-2012. 2856 series were compiled in total, which were homogenized with the R package “Climatol”. Trends of the homogenized series were computed by linear regression with time, whose greater positive values were obtained in summer and spring, but with differing patterns in the main hydrological basins. Maximum temperature trends were negative in the Canary Islands only. Geographical distribution of trends and dependence with altitude have been studied, the higher trends corresponding to the eastern third of the Iberian peninsula and Tajo river basin.
Keywords: homogenization, temperature series, trends, DTR.

1. INTRODUCTION

Temperature is the most studied variable in the current concern about the outcomes of the continuous rise of CO_2 in the atmosphere, since a higher concentration of a gas transparent to short wave radiation but absorbing important portions in long wave bands implies an increment of the energy retained by the atmosphere (greenhouse effect) that must end in an increase of the mean temperature of our planet, although this heating can vary significantly depending on the geographical areas.

The Spanish thermometric series have already been studied by different authors, either on the whole country (Brunet et al., 2007; Moratiel et al., 2010; Del Río et al., 2011 y 2012) or focusing on specific areas (Piñol et al., 1998; Serra et al., 2001; Morales et al., 2005; Del Río et al., 2005 y 2007; Martínez et al., 2010; Homar et al., 2010; Moratiel et al., 2011; Martín et al., 2012). But the heterogeneity of these studies is not limited to the application area, since they differ in the density of stations and the period covering the series as well as in the quality control and homogeneity applied to them, making it difficult to compare their results. for this reason, and because in any case the series are getting longer over the years, the approach chosen here is to update the study of Spanish thermometric series, covering a common period and comprising a large number of observing stations. The methodology used and the results obtained will be presented and discussed in the following sections.

2. METHODOLOGY

In order to have a wide spatial representation, the study involved all series of monthly average maximum and minimum temperature that had a minimum of 10 years of observation during the period 1951-2012. 2856 series met this condition, whose distribution by major watersheds can be seen in Table 1, while their locations are displayed on the map in Figure 1. The total number of monthly maximum and minimum mean temperatures amounted to 934,615 and 934,615 respectively, although fewer than 500 data were available each month at the beginning of the studied period (Figure 2), to increase progressively until about 1500 around 1975-78 and, after a slight decrease, continue to climb up to some 1800 monthly observations around 1995. Afterward there is a sharp decline, until around 1,000 observations per month by the end of the period.

The "Climatol" R package V. 2.2 (Guijarro, 2013) has been used for quality control, gap filling and homogenization (correction of abrupt jumps in the average due to changes of instrumentation or observing conditions) of the series, applied independently to each hydrological basin. This program is designed to take advantage of all available climatological information throughout the study area, even that from short series, and that is why series with up to only 10 years of observation have been included. They obviously can not be used directly for representative trend calculation, but they can act as reference for the longer series. Table 1 shows the number of outliers rejected and cuts made in the series to correct the detected jumps in the average, accounted by basins. In relative terms, 0.20% of average maximum and 0.19% of minimum temperatures were rejected, while the average number of jump corrections has been 2.23 and 2.31 per series respectively.

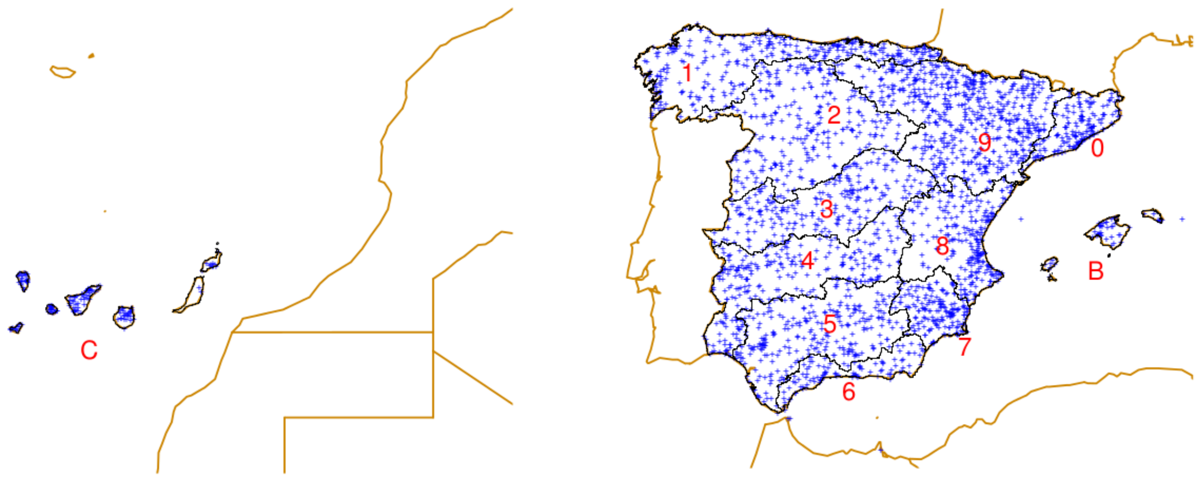

Fig. 1: Location of stations used from Canary Islands (left), and from Balearic Islands and mainland watersheds (right).

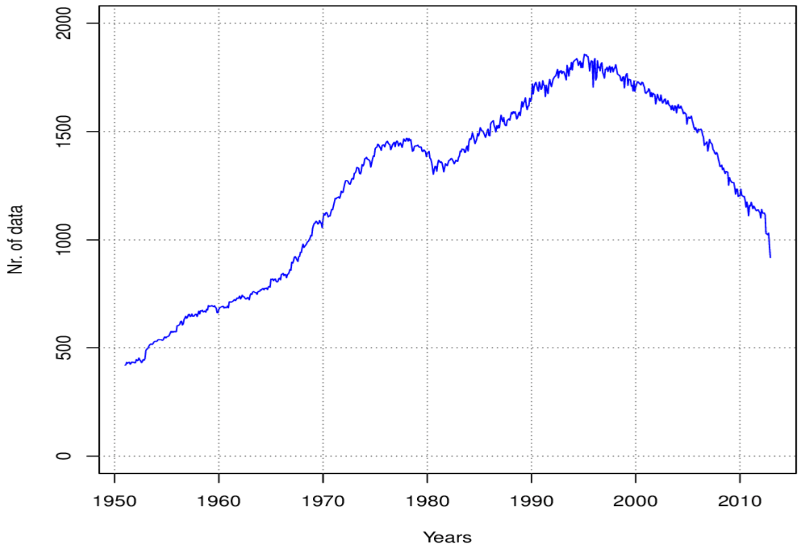

Fig. 2: Number of available monthly data over the study period. (Valid both for maximum and minimum temperatures).

			Maximum temp.		Mínimum temp.	
	Watersheds	Nr. of stations	Rejected outliers	Nr. of jumps	Rejected outliers	Nr. of jumps
1	Norte	323	150	602	145	603
2	Duero	279	250	727	224	667
3	Tajo	232	146	552	131	513
4	Guadiana	271	225	658	184	645
5	Guadalquivir	264	221	548	209	556
6	Sur	104	55	214	82	262
7	Sureste	175	149	504	165	549
8	Levante	255	120	723	119	705
9	Ebro	588	414	1237	328	1323
0	Pirineo Oriental	174	109	284	140	378
B	Baleares	48	13	84	26	100
C	Canarias	143	45	248	62	307
	TOTAL	2856	1897	6381	1815	6608

Table 1: Number of stations, rejected outliers and corrected jumps in the series, by watershed.

3. RESULTS AND DISCUSION

3.1. Variations of the average annual temperature

In the first place we are going to examine the evolution of temperatures over time, averaging by basin the annual mean temperatures computed form the completed and homogenized series, and smoothed by applying a five year moving average. Figure 3a shows that the maximum temperature variability has been quite similar over the different basins, with an increasing trend whose main exception is the cooling period that occurs approximately in the decade 1965-1974. The Canary archipelago, because of its location away from the rest of Spain and subject to a distinct climate, displays the most discrepant behavior, since it has an overall negative trend, and the common decline period is accompanied there by another descent around 1980-90. Minimum temperatures, on the other hand, appear more regular, both over time and space, the Canary Islands now following the general trend (Figure 3b).

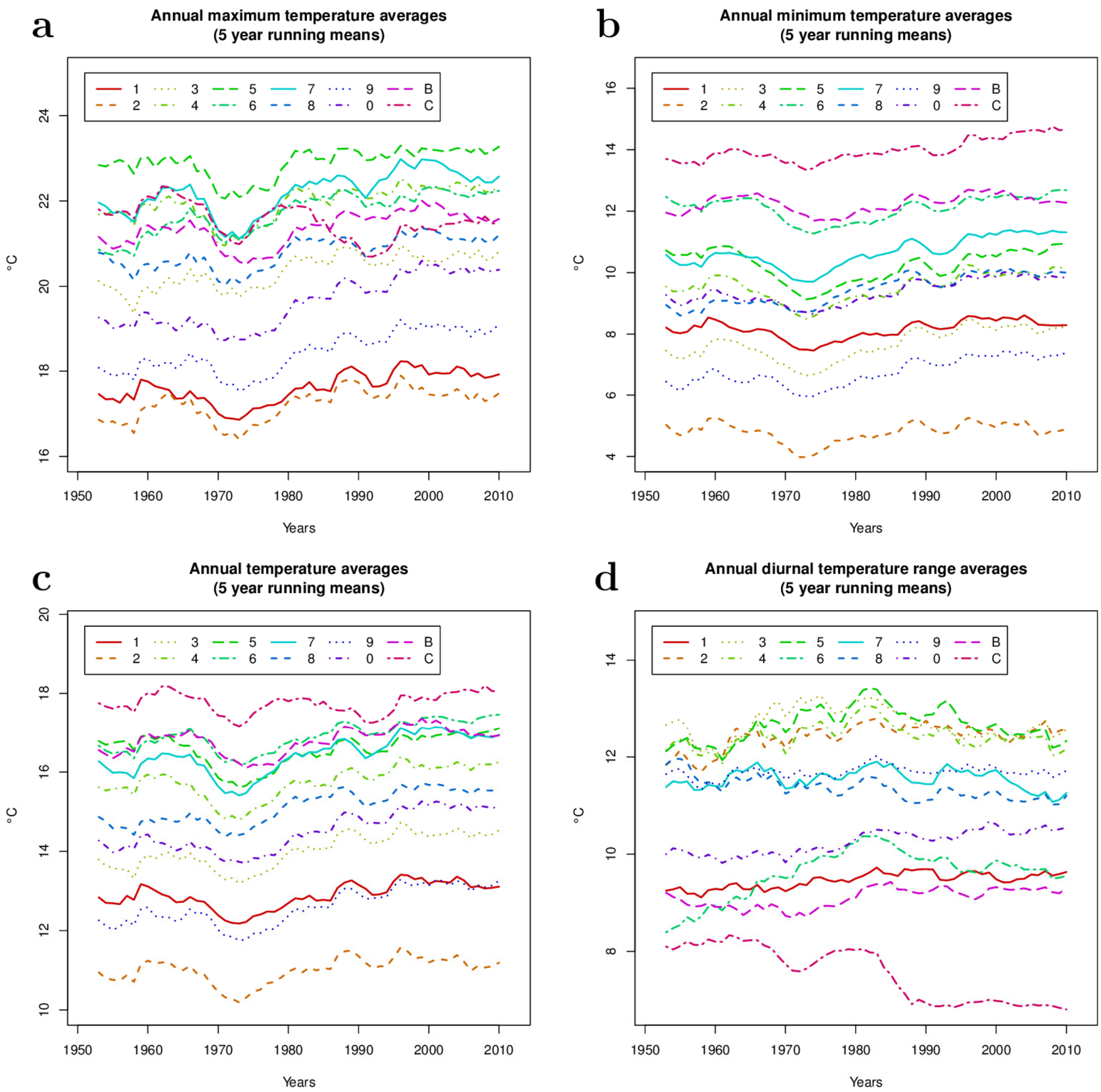

Fig. 3: Time variations of the average annual maximum temperature (a), minimum (b), mean (c) and DTR (d) in each watershed.

Figure 3c shows the variations of the average temperature, which obviously are intermediate between those of maximum and minimum since they are calculated as their half-sum, while their difference yields the average daily temperature range, DTR (Fig. 3d). Its evolution is the most varied between basins, since it shows a sharp decline between 1983 and 1988 in the Canary Islands (basin C) reflected only in some other basins, but much weaker. Moreover, it presents a sustained increase in basin 4 (Guadiana) since the beginning of study period until 1982 that is not in the others, whose behaviors show very different trends, both positive and negative. These DTR spatial variations deserve further studies to evaluate its possible causes, among which you can find variations of cloudiness, relative humidity, wind and urbanization of the station surroundings (Karl et al., 1993) .

The variability of temperature series over time makes trends dependent on the years used for their computation, since they can match ascent or descent phases of long period oscillations that would skew the results. In the 62 years studied here we may find both the descent thermometric phase and the subsequent increase that may be associated with the dimming and brightening observed in the series of incident solar radiation (Sanchez-Lorenzo et al., 2007), although the temperature series have a delay lag of around a decade. In any case, as both phases of descent and ascent are included in the period 1951-2012, this 62 years seem suitable for the computation of trends, that presumably will be less biased than if any other sub-period were taken for their calculation.

3.2. Temperature trends over the last 62 years

Monthly and annual temperature trends have been obtained through ordinary least squares linear regression with time from the homogenized series, using a post-processing function included in the Climatol package. Figure 4 shows the monthly trends for the period 1951-2012 averaged by watershed and expressed in °C per 100 years. The most outstanding feature in mean maximum temperatures (Figure 4a) is the Canary Islands graph, which is the only one displaying negative values in all months except in December. The more negative trends, lower than -2°C/100yr, happen in September and October, followed by May.

The rest of the basins show trends almost always positive, except for some not significant values in September, November and December, while maximum trends occur in summer and spring, especially in the months of June and August (more than 4°C/100yr in some basins), followed by March, February and July. In the Atlantic basins (5-Guadalquivir, 3-Tajo, 2-Duero and 4-Guadiana) trends in April and May are almost as low as those of the months between September and January, while in the other basins they are similar to the February and March trends.

As to the minimum temperature trends (Figure 4b), patterns are somehow similar to those of the maximum, with a majority of positive trends, peaks in June and August, and insignificant values in September, November and December, but these patterns are more different between basins than they were in the case of maximum temperatures. The Canary Islands graph is very similar to that of its maximum counterpart, only shifted around 3°C/100yr higher, and therefore all monthly values have now positive trends. Eastern basins, mainly Levante (8) and Sureste (7), have higher trends in the summer months, while in December and January they drop to insignificant values. In other basins, however, there is much difference between the trends in summer and in the rest of the year.

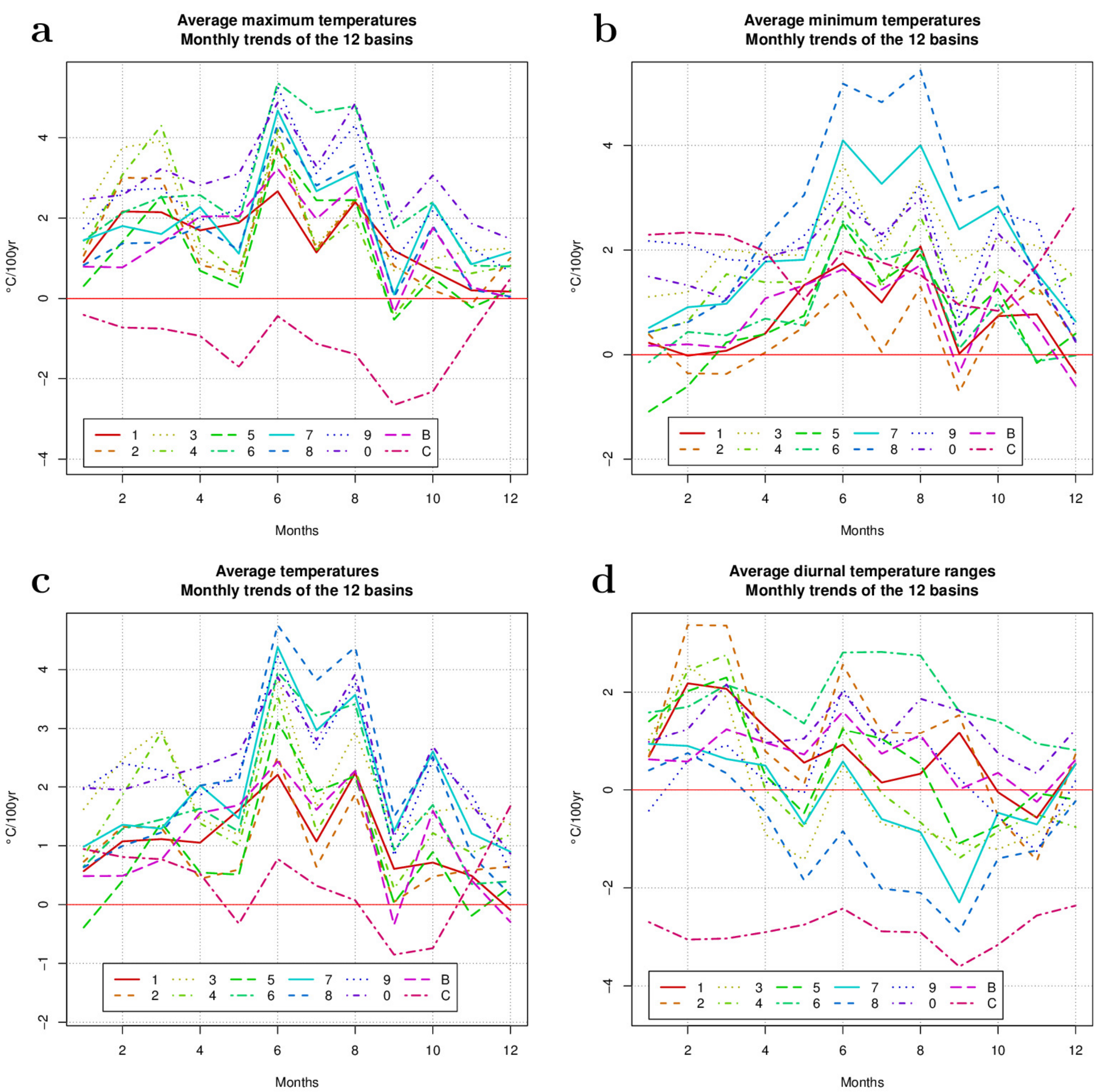

Fig. 4: Monthly trends of maximum temperature (a), minimum (b), mean (c) and DTR (d) in each watershed during 1951-2012.

Being intermediate between those of maximum and minimum, it is unnecessary again to discuss the trends in mean temperatures (Fig. 4c), so we will focus on the DTR trends (Figure 4d), which generally appear positive in February, March and June. In the Canary Islands they are negative all year, by far when compared to other basins, and without showing large variations between months. DTR trends in the other basins are quite similar from November to January, while between June and September they are more diverse, with positive peaks in the Sur (6), Pirineo Oriental (0) and Duero (2) basins, and minimum (mostly negative, especially in September) in the Levante (8), Sureste (7) and Tajo (3) watersheds.

Martin et al. (2012) also found a decreasing DTR trend on the Tenerife Island, calculated over a period of 67 years (1944-2010), while in the higher elevations that trend was not significant. Table 2 shows the trends in annual maximum and minimum temperatures averaged per basin and their dependence with altitude. All annual trends are positive except those of maximum temperatures in the Canary Islands. Moreover, all maximum temperature trends are more significant than α=0.01, while the significance of minimum temperatures trends is more varied, from highly significant in seven watersheds to non-significant in those of Duero and Guadalquivir. It is in the Canary Islands where the correlation of these trends with altitude is higher, and with opposite signs for maximum (which decrease with height) and minimum temperatures (that increase with altitude), resulting in an increase of the DTR trend with height (contrary to what Martin et al., 2012 obtained in the Tenerife Island). However the Canary Islands location away from the Iberian Peninsula is unique, and in most other basins the maximum temperature trends increase with altitude (except in Duero and Ebro), while minimum temperature trends exhibit a varied dependence with altitude, with an equal number of positive and negative correlations.

It is noteworthy that annual trends of all annual maximum and minimum temperature series are positive in the Iberian Peninsula and Balearic Islands, as well as all the annual maximum temperature trends in the Canary Islands, where here annual minimum temperature trends are, on the contrary, negative, also in all Canary observatories. Their spatial distribution is shown in Figure 5, with circles representing positive trends and negative values appearing as inverted triangles, with sizes proportional to the absolute trend values. In the Canaries the maximum temperature trends are more negative in the western islands, where those of the minimum temperatures are also more positive. In both cases it is also evident the effect of altitude on the increase of the absolute value of trends, as discussed above.

Trends in the Iberian Peninsula, both for maximum and minimum temperatures, are higher in the eastern third and the Tajo basin. Maximum temperature trends are also high in the Sur watershed, but in the Balearic islands trend values are small in both cases. However, the strong trend discontinuities in some basin divides (more visible in the minimum temperatures) seem difficult to explain just by the barrier effect of the mountain ridges, and therefore in future work it will be advisable to perform the homogenization and gap filling for the entire Peninsula instead of on a per basin basis.

4. CONCLUSIONS

The temperature evolution of the last 62 years shows an upward trend, although for a period of about 10 years around 1970 there was a cooling phase. Overall maximum temperatures all have positive trends except in the Canary Islands, where they are negative. The minimum temperature trends are all positive, without exception, although in some basins their values are not significant.

Trends in average maximum temperatures are particularly high in summer and spring, exceeding in some basins 4°C/100yr in June and August. But in the Canaries they are negative in most months.

	Altitude (m)			Maximum temperature				Minimum temperature			
Cu	Min.	Max.	Dif.	Trend	Sig.	r	Sig.	Trend	Sig.	r	Sig.
1	1	1500	1499	1,44	***	0,53	***	0,67	*	0,04	-
2	116	1890	1774	1,49	**	-0,17	**	0,37	-	-0,08	-
3	220	1500	1280	1,94	***	0,50	***	2,06	***	-0,14	*
4	2	1020	1018	1,65	***	0,66	***	1,46	***	0,47	***
5	1	1592	1591	1,15	**	0,17	**	0,63	-	0,52	***
6	2	1800	1798	2,59	***	0,69	***	0,77	*	0,45	***
7	0	1350	1350	1,94	***	0,33	***	2,06	***	-0,61	***
8	2	1730	1728	1,60	***	0,64	***	2,56	***	0,14	*
9	4	2263	2259	2,42	***	-0,12	**	2,10	***	-0,55	***
0	0	1967	1967	2,96	***	0,23	**	1,70	***	-0,34	***
B	2	1030	1028	1,39	***	0,34	*	0,71	*	-0,26	+
C	3	2367	2364	-1,07	**	-0,81	***	1,80	***	0,81	***

Table 2: Station altitudes in each basin, trends in maximum and minimum temperatures annual averages (°C/100yr), and correlation coefficients (r) with altitude. Significance levels: 0 '***' 0,001 '**' 0,01 '*' 0,05 '+' 0,1 '-' 1.

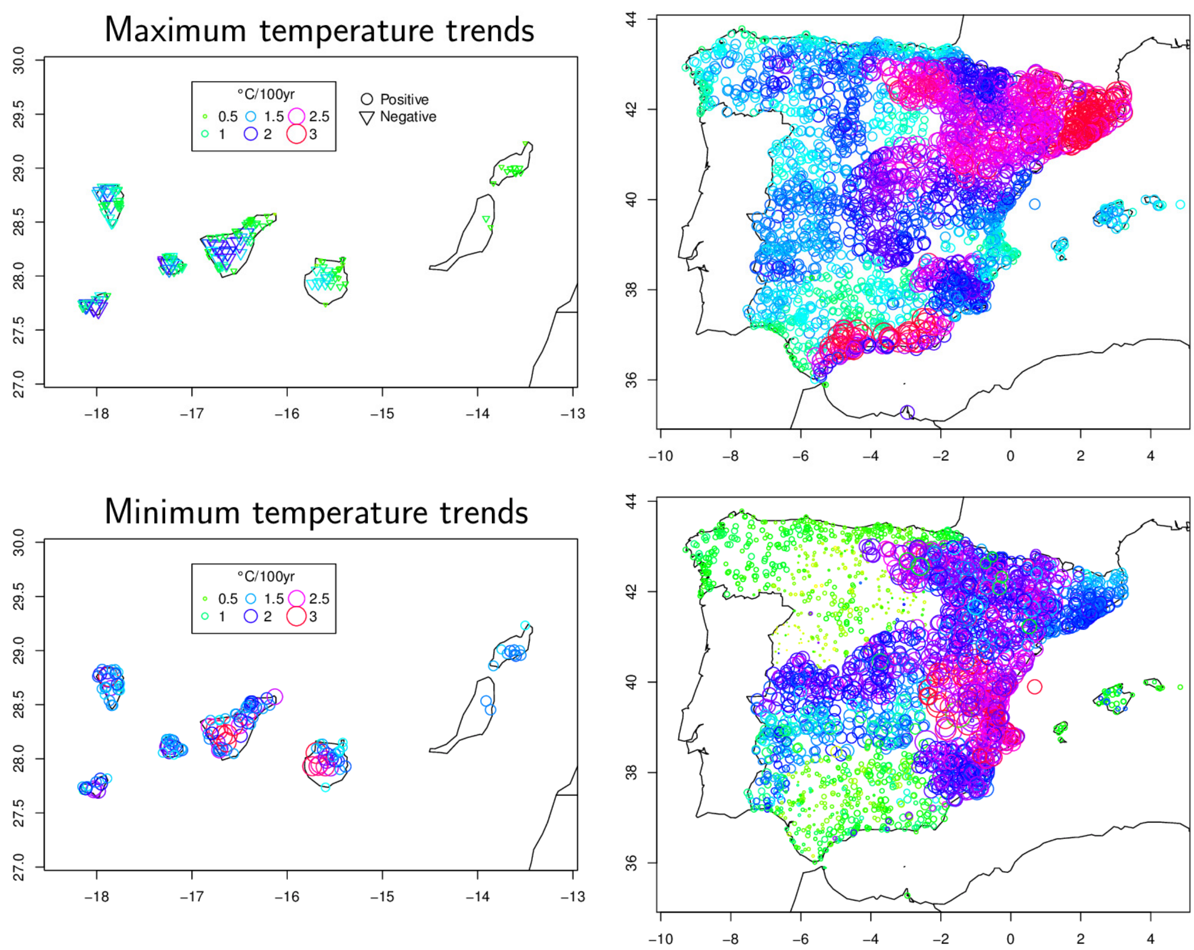

Fig. 5: Annual trends in average maximum (top) and minimum (bottom) temperatures during the period 1951-2012, in °C/100yr.

Minimum temperatures, with notable variations between basins, also have significant positive trends especially in June and August. They are positive throughout the year in the Canary Islands, with the highest values concentrated from December to March.

The seasonal pattern of Daily Temperature Range trends is very diverse in the studied basins, the most outstanding feature being the negative values in the Canaries throughout the year.

Trends in annual mean maximum are positively correlated with altitude in all basins except in Canaries, Duero and Ebro, where the relationship is reversed. The dependence of the minimum trends on altitude is much more varied, with a majority of positive correlations in the Atlantic basins and negative in the Mediterranean watersheds.

In future works it will be advisable to homogenize all series together rather than basin by basin, to smooth the strong discontinuities observed in their divides.

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