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TEMPERATURE AND PRECIPITATION REGIONAL CLIMATE SERIES OVER THE CENTRAL PYRENEES DURING 1910–2013

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ABSTRACT

Quality controlled homogenized regional anomaly series of temperature and precipitation are obtained for the central Pyrenees for the period 1910–2013. A 0.1 ºC/decade positive trend is found for minimum and maximum annual temperature exceeding the significance level of 0.05 for the whole studied period. A significant warming is found in all seasons except boreal spring in minimum temperature and winter in maximum temperature. The annual regional precipitation anomaly series shows a high inter-annual variability and a slightly negative non-significant trend of -0.6 %/decade. Non-significant negative trends of precipitation are found in all seasons for the whole period examined. Considering the recent period 1970–2013, values of temperature trends are generally higher than those obtained for the whole period. For this latest period, all maximum temperature trends are significant while only the minimum temperature trend in winter is non-significant. Spring is the season that presents the greatest warming, with 0.9 ºC/decade for maximum temperature and 0.4 ºC/decade for minimum temperature. Evaluating the same period for precipitation anomalies, trends in the annual, winter and summer series remain negative, while spring and autumn trends are positive although non-significant. This series represents the longest homogenized climate dataset available for the central Pyrenees region, including the newly recovered period 1910–1949, offering new possibilities for climate analysis and paleoclimate proxy calibration.

KEYWORDS: mountain climate; climate change; quality control; homogenization; trend analysis; Pyrenees

1. INTRODUCTION

The Pyrenees range is located in Western Europe and forms a natural boundary between Spain and France (Ariño *et al.*, 2012) with Atlantic and Mediterranean climatic influences (Beguería *et al.*, 2003).

Due to its biological richness and water resources, the Pyrenees are a valuable ecosystem that is important for local and regional development of tourism (Marín-Yaseli and Martínez, 2003), energy production, agriculture (Beguería *et al.*, 2003; López-Moreno *et* *al.*, 2008) and biodiversity (Regato, 2015).

Studying the climate in mountainous regions such as the Pyrenees differs from other environments because they are remote, making it difficult to record data using standard observational methods. Additionally, alpine regions experience large climate variability over short distances, due to local conditions (Barry, 1992). For example, a recent study of the number of precipitation and snow winter days for the period 1981–2010 in the western and central Pyrenees shows a relationship between these variables and the weather types in the mountain range (Buisan *et al.*, 2015). These results highlight the importance of long term observations for reliable climate analysis.

Climate change does not affect all regions equally: the warming rate can be different and even opposite between different areas (Brunet *et al.*, 2007), with mountain ranges being particularly vulnerable to climate change (Beniston, 2003).

Future climate scenarios show a mean decrease in precipitation and increase in temperature for the next century in the Spanish Pyrenees region (López-Moreno *et al.*, 2008), accompanied by a sharp reduction in the thickness and duration of snowpack (López-Moreno *et al.*, 2009). The seasonal projected precipitation analysis indicates an intensification of extremes: an upward trend of drought periods and a rise in the number of days with intense precipitation events (López-Moreno and Beniston, 2008). The number and intensity of warm and very warm days and nights (daily maximum and minimum temperature exceed the percentiles 90th and 99th, respectively) during winter is also projected to increase during the next decades, more in the Pyrenees than the surroundings areas (López-Moreno *et al.*, 2014). Similar results are found (an increase in temperature and a reduction in the number of frost days) were also obtained in the north western Mediterranean Basin, again highlighting importance of observational databases in these vulnerable and topographically complex areas (Barrera-Escoda *et al.*, 2014).

For other purposes, such as paleoclimatic studies, a thermopluviometric knowledge is necessary to calibrate natural records (proxies) against instrumental climate data (Romero-Viana *et al.*, 2008; Abrantes *et al.*, 2009; Peña *et al.*, 2015b), and the results of the calibration can be affected by the quality of the instrumental data (Brönnimann, 2015). Previous reconstructions in the Pyrenees used high-quality instrumental data that were not completely representative of the study area. See for example: Dorado Liñán et al. (2012), in which only six observatories were used, two of them far from the Pyrenees; Büntgen et al. (2008), in which instrumental series from a single close observatory were used, only reconstructing local climate; or in Esper et al. (2015), in which the observational gridded dataset CRU3.1 was used, computing the average temperature over the study area, against the recommendation of the CRU3.1 authors not to use this dataset for trend analysis without comparing with other sources due to the non homogenized conditions of the individual series (Harris *et al.*, 2014).

In addition to the above, it is recommended by GCOS (Global Climate Observing System) Climate Monitoring Principles (Aguilar *et al.*, 2003), that quality control and homogenization procedures have to be applied to any instrumental data being used to examine long-term climate variability and change.

In the Pyrenees, some studies of quality control and homogeneity of temperature have been undertaken for different spatial and temporal scales using diverse analytical approaches.

One high-altitude series was checked for homogeneity using a bivariate test by Bücher and Dessens (1991); Esteban et al. (2012) and Cuadrat et al. (2013) used HOMER (HOMogenization software in R, Mestre et al., 2013), the same multiple break point homogenization method used in the present work, however they only analysed data from three observatories in Andorra and the whole Pyrenees region during the shorter 1950–2010, respectively. On the other hand, precipitation trends have been studied in a quality controlled and homogenized dataset for the north eastern Iberian Peninsula, showing the highest values of precipitation intensity in the Pyrenees with decreasing trends for the period 1955-2006 (López-Moreno *et al.*, 2010), but without any autocorrelation testing or significant level considered. The present work deals with the complete analysis: precipitation and temperature for all series in the central Pyrenees and including the newly recovered period 1910–1949.

In the present study, a high quality and long-term (1910–2013) regional anomaly series for precipitation (PPT) and maximum (Tmax) and minimum temperature (Tmin) is developed for the central Pyrenees. Quality control and homogenization procedures have been applied to obtain reliable regional anomaly series. Daily quality control has been implemented using Extra QC routing from RClimdex Software (user guide and software available in http://www.c3.urv.cat/data.html) while HOMER, a state-of-the-art homogenization method developed during the Action COST-ES0601 (HOME), has been applied, having been previously tested on temperature data in the study area (Pérez-Zanón *et al.*, 2015). Following homogenization, the regional anomaly series have been calculated applying the Osborn correction (Osborn *et al.*, 1997) that avoids the bias introduced due to the varying sample data.

In section 2 the data are presented, before being subjected to a detailed quality control procedure and homogenization in section 3. Using regional anomalies of Tmax, Tmin and PPT, climate variability and change in the central Pyrenees is examined in section 4, focusing on the whole 1910–2013 period as well as the recent 1970–2013 period. The quality of the homogenized regional series is tested in section 5, comparing this series to individual observatory series as well as independent homogenized datasets for the Pyrenees region. Final conclusions are drawn in section 6.

2. DATA

Daily PPT, Tmax and Tmin records have been provided by the Spanish National Meteorology Agency (AEMET) and the Catalonia Meteorological Service (SMC). These records came from 155 observatories having either manual or automatic observations (155 series of PPT and 126 series of Tmax and Tmin). The data series available from these observatories are of various lengths and cover the period 1910–2013. At the beginning of the study period, these series are not as complete as would be desired. For this reason and to support the homogenization procedure, four series were added from the high-quality Spanish Daily Adjusted Temperature Series (SDATSv2, Brunet *et al.*, 2006) quality controlled databank from observatories located in Pamplona, Huesca, Barcelona and Zaragoza. The spatial distribution of observatories is shown in Figure 1 while the covering period and percentage of available data is shown in Table S1 for the 155 series in the Pyrenees. The annual amount of available daily data for PPT is higher than for both Tmax and Tmin for the whole study period, due to the historical interest in precipitation measurement by the hydroelectric power stations in the Pyrenees. Figure 2 shows the amount of available daily data for each variable annually. The impact of the Spanish Civil War (1936–1939) is visible by the decrease in available data during that period.

3. BUILDING A HOMOGENIZED CENTRAL PYRENEES DATASET, 1910–2013

3.1 QUALITY CONTROL

From the recording process until the final analysis of climate time series, some errors may be introduced in the data due to changes in the observation place (relocation), measuring instrument or sheltering structure (which allows good air flow across the thermometers but prevents heating from direct sunlight), time of observation, observer, land use and cover, urbanization or because of manipulating (such as unit conversions), formatting, transmitting and archiving data methods. For this reason, Quality Control (QC) procedures are applied to detect and identify these errors (Aguilar *et al.*, 2003). ExtraQC routines from RClimdex software, developed through the International Expert Team on Climate Change Detection and Indices (http://www.c3.urv.cat/data/soft/rclimdex_extraqc.zip) have been used.

Before running the Extra QC routines, the files containing time series should be formatted as the software requires. This step illustrates the need of QC, since some incorrect dates were detected: six dates were corrected and 12 lines were removed because of date repetition.

Taking into account the recommendations from Aguilar et al. (2003), gross errors, tolerance, internal consistency and temporal coherency have been checked and summarized in the following statistics for cases that were considered suspect, and evaluated for temporal and spatial coherency, after being flagged by the software:

- Outliers: Values exceeding a threshold defined for lower (upper) bound as the percentile 25 (75) less (plus) three times the interquartile.
- Duplicated dates: includes all dates which appear more than once in a data file.
- Toolarge: reported precipitation daily values exceeding 200 mm and temperature daily values exceeding 50 ºC.
- Jumps: those records where the temperature difference with the previous day is greater than or equal to 20 ºC.
- Tmaxmin: includes all those cases where maximum temperature is lower than minimum temperature.

Another check was applied to evaluate long continuous periods of null precipitation (called Zero PPT) that are likely due to observation or instrument error.

For the three variables (see Table 1), a total amount of 3,744,719 values were checked, from which 17,286 values (0.5%) were flagged as errors after applying the previous criteria and their revision. In total, 99.5% of the flagged suspect data were rejected by replacing the original value to missing data and 0.5% (91) corrected following visual inspection. Most of the rejected data (96.2%) were consecutive zero values of precipitation recorded at six observatories: almost a year (334 days) in Barbastro and a total amount of 9281 days for Pobla de Segur.

Apart from these errors, the most useful indicator to detect suspect values was the Outlier filter. For temperature, 271 incoherent values (Tmax < Tmin) were found.

3.2. DEVELOPMENT OF COMPOSITE SERIES

After applying the daily QC, the distances between observatories were evaluated in order to develop long-term series. A total of 63 PPT time series and 37 Tmax and Tmin time series were merged into composite groups, with a maximum of six observatories per group (Table S2). The date of the combination was recorded to be considered in homogenization analysis (see section 3.3). If two merged series had available overlapped data, the most completed was selected. After revising the geographical features, the maximum distance accepted in combinations was 29 km, however the mean distance between the rest of observatories is 2 km. The maximum difference in altitude was 167 m.

Monthly averages of Tmax and Tmin were then calculated with the missing data tolerance of no more than 7 non-consecutive or 5 consecutive missing daily values for a month (Pérez-Zanón *et al.*, 2015). Applying the same criteria to PPT, 138 values of the monthly amount (0.27 % of the total monthly values) were calculated even though those months included missing values (Figure S1).

Time series must satisfy minimum requirements in terms of length and completeness to run the homogenization software HOMER. For that reason, series with less than 270 monthly values were dismissed, except for Bossots observatory which had 254 monthly values for Tmin and Tmax in 22 years. After combining data and considering the minimum length requirements, 48 Tmin and Tmax series were included in the final dataset prepared for homogenization while 60 PPT series were available (Table S3).

Due to the interactive nature of HOMER, the homogenization procedure was applied over monthly Tmin and Tmax in two separate groups of observatories: those which have more than one year of data before 1940 and a period longer than eight years of consecutive data (21 series) were considered long series and the remaining series (27) which were considered short series and include only data from 1940. The 60 monthly PPT series were all examined at the same time.

Monthly quality control was then applied to the previously described group of series to detect additional outliers, using the Fast QC routine included in HOMER, by visual comparison of the monthly and annual differences series within each group. Then, some incoherent monthly values were removed by comparing to neighboring observatories. For example, for the PPT recorded in Agramunt observatory, no complete year of data is available for the period 1928–1934, only 47 monthly values. This makes it impossible to calculate the annual mean or to apply break detection correctly. Figure 3 shows the histogram of the number of monthly values removed by decade, which shows a bias at the beginning of the study period due to the incompleteness and the quality of the series for PPT. For temperature, the maximum number of data removed occurs in the 1940's, when most of the series began. Table 2 summarizes the number of detected monthly outliers by variable.

3.3. HOMOGENIZATION

Most long-term meteorological observations are affected by non-climatic factors such as local environment or instrumental changes (Peterson *et al.*, 1998; Brunet *et al.*, 2006). One of these factors can be observatory relocation, which is affecting our combined dataset. To correct the series for these kinds of errors, it is necessary to check the homogeneity of the series with statistical tools and/or neighborhood comparison and, if required, correct the series. The applied homogenization method is a modern one, developed during the HOME Cost Action (Venema *et al.*, 2012), called HOMER (Mestre *et al.*, 2013). HOMER was selected because it includes the best segments and features of some other state-of-the-art methods such as PRODIGE (Caussinus and Mestre, 2004), ACMANT (Domonkos, 2011) and Joint Detection (Picard *et al.*, 2011) and was tested in a homogenization case of study of temperature in the study area (Pérez-Zanón *et al.*, 2015).

HOMER is an interactive method which allows the user to introduce metadata such as how, where and by whom data was recorded (Brunet *et al.*, 2002; Aguilar *et al.*, 2003), and uses the expertise of the climatologist to evaluate the influence of a statistically detected break point. The features of ACMANT detection included in HOMER also allows the detection of the month of a break point in case metadata aren't available. However, ACMANT detection and the "month assess" procedure are only available for temperature data after the first correction, due to the need for a reference series (previously homogenized series) to be computed. The dates of combination of series, recorded during composite series development (section 3.2) are unfortunately the only metadata available in this study for temperature data. However, for PPT homogenization, the metadata information available in Saladié (2003) was considered, although, it was not introduced in HOMER to avoid overestimating the number of break points detected.

The key steps of applying HOMER to achieve homogenized monthly series are summarized in Figure 4. This procedure is repeated as many times as it is necessary to detect inhomogeneities, taking into account that in the first steps the breaks detected may have a higher amplitude than those detected in next steps, to check them against metadata and accept or discard those breaks which could be highlighted by the detection methods in previous executions. The homogenization procedure is considered completed when the annual plots of pairwise detection (automatic generated by the software after each correction) do not highlight the same break point more than five times in the inspected series, and the visual comparison between the annual QC time series and the homogenized output doesn't show any suspicious signal of inhomogeneity.

A total of 407 inhomogeneities were detected (1.2 for PPT and 3.3 for Tmax and Tmin per observatory on average). Table 3 summarizes the total number of break points, including those supported by metadata and the maximum number of break points in one series by variable. The maximum number of break points is 13 for the three variables in one series. For temperature data, most of the series had to be corrected: for Tmin all series had at least one break point detected, and for Tmax only two series had no breaks points detected. A total 26 PPT series have been considered homogeneous as no break points were detected. The lowest break point amplitude in absolute value with supporting metadata was 0.07 ºC for Tmin and 0.11 for PPT (log-transformed precipitation data). Ten break points with supporting metadata were simultaneously detected in Tmin and Tmax.

Figure 5 shows the annual number of break points detected and the fraction of break points per series, taking into account the number of series with at least the 80% (10 months) of the data available for that year. The maximum number of break points detected were in 1931 with six break points for PPT, 1971 for Tmax with 12 break points and 1976 with seven break points for Tmin. In the case of PPT, this maximum number of breaks detected may coincide with the decrease in the number of available observatories during the 1930's. However in the case of temperature, a change in the signal is detected in the 1970's. For the density of the number of break points per series available, the maximum values are recorded at the beginning of the study period: 1916 for PPT, 1921 for Tmax and 1938 for Tmin. These results are due to the low number of data available, and in the case of Tmin, it coincides with the Spanish Civil War (1936–1939).

Figure 6 shows the distribution of the number of series according to the number of break points detected (left panel) and the number of break points detected by decade (right panel). For PPT, between zero and one break point were detected in two-thirds of the series (40 series). The number of break points in a series then decreases rapidly, with six break points the maximum for one series. For temperature, most of the series were corrected using between two and three break points, and a maximum of eight (seven) break points were necessary for one (two) series for Tmax (Tmin). The number of break points by decade indicates that our dataset is a good station network (as only 6 Tmax and Tmin series have more than 1 break per decade) considering the previously mentioned difficulties associated with obtained observed series in mountainous areas, and the fact that one break point for mean temperature series in the European western region is expected between every 15 and 20 years (Venema *et al.*, 2012).

Another important factor in assessing the impact of homogenization is the amplitude of the break points detected. Figure 7 shows the frequency distribution of the break points amplitude by variables. Most of the break points are not too large (<|2|), which could be considered a good signal of the network quality data. These results are also similar to the break point amplitude showed by Brunet *et al.* (2006) for SDATSv2 and Trewin (2013) for a daily homogenized temperature dataset in Australia.

In Figure 8 the annual anomaly series before (QC) and after (HO) the homogenization procedure are presented, with solids lines showing the mean value for all series, respectively. The impact of homogenization is shown, especially for Tmin for which the reduction in the annual variability is higher, similar to the results of Brunet et al. (2006).

3.4. REGIONAL ANOMALY CLIMATE SERIES

To obtain a representative signal of long-term precipitation and temperature evolution for the period 1910–2013 in the central Pyrenees, regional time series are calculated to show the mean and extreme state of Pyrenees climate (following Brunet *et al.*, 2006; Saladié *et al.*, 2008).

Regional anomaly series for PPT, Tmax and Tmin have been obtained for annual and seasonal time periods; winter (December to February), spring (March to May), summer (June to August) and autumn (September to November). For each series considered the mean (total) temperature (precipitation) was determined for each resolution and the mean value for the base period (1961–1990) was calculated as $\overline{T}$ ($\overline{PPT}$). Then the anomaly series can be calculated as

$$\Delta T_{obs}(t) = T_{obs}(t) - \overline{T_{obs}} \quad (1)$$

for temperature, and as

$$\Delta PPT_{obs}(t) = \frac{PPT_{obs}(t) - \overline{PPT_{obs}}}{\overline{PPT}_{obs}} \tag{2}$$

for precipitation.

To take into account the bias that the varying sample size may introduce on timeseries formed as average of individual timeseries (Osborn *et al.*, 1997), the regional series have then been calculated by the equation

$$Y(t) = X(t)\sqrt{\frac{n'(t)}{n'(n=N)}} \tag{3}$$

being

$$n'(t) = \frac{n(t)}{1 + (n(t)-1)\bar{r}} \ , \tag{4}$$

where n is the number of records, $\bar{r}$ is the mean correlation between all pairs of time series, N is the maximum sample size, $X(t)$ is the original regional mean time series and $Y(t)$ is the desired time series with a variance independent of sample size.

3.5 RELIABILITY OF THE HOMOGENIZED REGIONAL SERIES

To assess the quality of the homogenized regional series developed here, the homogenized dataset obtained by the Pyrenees Climate Change Observatory (OPCC, http://www.opcc-ctp.org/en/actions/climate; Cuadrat *et al.*, 2013) for the period 1950–2010 is used to compute the regional anomaly series by the same methodology presented in this work. The coefficient of correlation is compute between both regional anomaly series for each variable. The lowest correlation value was 0.8 for annual precipitation and the highest was

0.95 for spring maximum temperature. This good agreement between both dataset for the common period corroborates validity of the presented regional anomaly series. However, it must be noted that small inhomogeneities may remain in our Central Pyrenees dataset, due to the lack of metadata availability, inherent uncertainties associated with statistical homogenization, and the complexity of alpine climates.

The quality of the homogenized regional climate series obtained can also be seen in the good agreement between the regional anomaly series and individual observatory series. The regional anomaly series captures the climate signal of the study area, returning high and significant correlation coefficients between the regional climate series and each individual anomaly series for all variables and temporal resolutions. The annual spatial distribution of correlation coefficients (Figure 9) shows that PPT has the highest variability (minimum value 0.6), while Tmax correlation coefficients are very similar (minimum value 0.8) and Tmin correlation coefficients are between 0.6 and 0.8. Due to a non-constant spatial distribution of the observatories, the highest correlations are found with the highest density of observatories.

The seasonal correlations between the regional series and individual series for PPT (Figure 10) show that winter is the most spatially coherent (correlation values between 0.5 and 0.9), while summer the correlations coefficient are somewhat lower (around 0.7). These differences can be explained by the fact that summer precipitation events are generally associate with convective processes which can affect small areas of the Pyrenees, while winter precipitation events are more connected with large scale processes that affect the whole Pyrenees region (Llasat and Puigcerver, 1997).

On the other hand, the lowest values (0.7) of seasonal Tmax correlation coefficients are found in winter, while summer the minimum correlation coefficient is 0.8 (Figure 10). Seasonal Tmin correlation coefficients show the opposite behavior, with summer minimum correlation coefficients around 0.7 and winter slightly higher at 0.8. This difference may be related to the less solar radiation during winter month at this latitude (Barry, 1992) and to the impact of topography, which can have a large impact on minimum temperatures, particularly during clear nights (Trewin, 2005).

4. CENTRAL PYRENEES TEMPERATURE AND RAINFALL, 1910–2013

4.1. REGIONAL TRENDS, 1910–2013

For all regional anomaly series, a trend analysis has been performance using Mann-Kendall test and following the application described by Wang and Swail (2001) in two different periods: for the whole series (1910–2013) and for the recent period (1970–2013). This technique avoids the dependence on autocorrelation for the significance of trends, which can be overestimated by other analysis. The last period has been selected because from1970 the increase in temperatures across Spain is known to be large (Brunet *et al.*, 2007). Significance of trends was evaluated using the Student's t test ($p < 0.05$)(Wilks, 2011).

The total number of series used is 35 for PPT, 18 for Tmax and 20 for Tmin as only the monthly homogenized series which have at least 80% of the values in the base period are used (and dismissing Barcelona observatory which is not representative of the study area). Figure 11 shows the annual regional anomaly series for PPT, Tmin and Tmax and the trends obtained. For the whole series (1910–2013), PPT trend is –0.64 %/decade, Tmax trend is 0.11 ºC/dec and Tmin trend is 0.06 ºC/dec, while for the period 1970–2013, PPT trend is –2.70 %/dec, Tmax trend is 0.57 ºC/dec and Tmin trend is 0.23 ºC/dec. These trends are significant in the case of temperature and non-significant for PPT due to its large inter-annual variability.

PPT anomalies series for central Pyrenees are dominated by a high inter-annual variability, however, negative trends are found in all seasons (Figure 12) except for spring during the period 1970–2013. The greatest difference between the seasonal trends is found in winter, when the change in the trends between both periods is greater than –7 %/dec. This decrease in winter precipitation is in agreement with López-Moreno (2005), who identified a decrease in snowpack depth for the period 1950–1999. On the other hand, an increase in the precipitation trend of 2.25 %/dec is found in autumn. These differences may suggest a shift in the rainfall distribution of seasons, however dynamical studies are required to determine the cause of these findings.

Tmax seasonal anomaly series (Figure 13) shows a clear positive trends, with only winter showing a non-significant trend for the period 1910–2013. The increase in trend values comparing both periods may suggest a higher impact of climate change in the study area for the recent 1970–2013 period. The warmer months of spring and summer display the greatest trends, an interesting result given the potential impact of heat waves and extremes on the regional population and environment, (e.g. Peña *et al.,* 2015a). Trends of Tmin seasonal anomaly series (Figure 14) are not as large as those for Tmax, with two non-significant periods (spring 1910–2013 and winter 1970–2013). The significant trends for the whole series are 0.12 ºC/dec in winter, 0.07 ºC/dec in summer and 0.09 ºC/dec in autumn, while, for the period 1970–2013, trends are 0.27 ºC/dec in summer, 0.31 ºC/dec in autumn and 0.40 ºC/dec in spring. Table 4 summarizes all the computed trends for both periods taking into account the significance level.

4.2. CENTRAL PYRENEES CLIMATE VARIABILITY, 1910–1949

As well as an extended trend analysis, the addition of homogenized climate data for the 1910–1949 period over the Central Pyrenees also allows for the examination of interannual climate variability in the region during the first half of the 20th century. Considering the threshold of ±10%, dry (wet) years can be defined as those years with anomaly PPT below than -10% (10%), while normal years are those years with anomaly PPT between -10 and 10%. For the newly recovered period 1910–1949 analyzed in this paper (Table S4 and Figure 11), 12 (30% of years) dry years and 7 (18%) wet are registered compare to the 26 (41%) dry and 17 (27%) wet years for the next period 1950–2013 for annual regional anomaly series. The number of normal years, 21, doesn't change between periods but represents the 53% of years for the newly recovered period and the 33% for the modern period. This result suggests that precipitation variability in the central Pyrenees may be becoming more extreme.

Following the filtered anomaly PPT series by a 5-year moving average (Figure 11), six years of positive PPT values (1914–1919), largely associated with wet conditions in 1915 and 1919. The 20's are close to normal as shown in the filtered series shows, presenting 4 dry years and 1 wet but spread out over time. The four first years of the 30's were extremes, alternating wet and dry years, and two wet and one dry year were observed later (1936–1938) during the Spanish Civil War. A drought emerges towards the end of the 40's, with four dry years registered from 1944 to 1949, and continues to the mid 50's.

Seasonal series show fewer normal years, especially in winter, for which only 9 years were normal for the newly recovered period 1910–1949 and 3 for the period 1950–2013. Half of the years were dry for winter PPT series in the 1910–1949 period. The longest wet period was recorded for 1915–1917. In the summer PPT series the longest dry period is observed for 14 years, between 1916 and 1929, during which no wet year was recorded.

For temperature the threshold for hot and cold years is selected as ±0.5 ºC (Table S4). As it would be expected given the temperature trends, the percentage of hot years increases in the modern period (1950–2013) with respect to the newly recovered period (1910–1949) while the percentage of cold years decreases. In particular, Tmax presents 18 hot years out of the last 20 years of the series (1994–2013). The number of normal years remains close to constant for Tmax and Tmin in annual and seasonal resolution.

Tmax annual regional series shows high variability in periods of 4 to 6 years even individual extremes years until the 40's decade when a long hot period is shown from 1943 to 1950 when 6 hot years were observed. In winter and summer, the percentage of hot years increase by 14 % for the period 1950–2013 with respect to the newly recorded period, while in summer the percentage of cold years decreased by 12 %.

The annual regional anomaly Tmin series is roughly characterized by three periods: a cold period from 1910 to 1925; a normal period between 1926 (which was hot) and 1942 for which all years were normal except 1935 (which was cold); a hot period from 1943 to 1949 when 4 hot years were observed. The percentage of cold years was reduced to the half in the period 1950–2013, while the percentage of hot years is almost double. In winter, only three hot years were observed for the early period, given the longest period of cold and normal years of 13 years between 1937 and 1949. In summer, the 6 cold years observed for the newly period are found until 1917.

4.3. DEPENDENCE OF TRENDS ON ALTITUDE

To conduct a preliminary evaluation of the impact of climate change at different altitudes, trends of annual anomalies for the individual series used to compute the regional anomaly series were calculated for 1961–1990 and 1970–2013, using those series with a minimum of 80% of monthly data for 1961–1990. The trends do not show any relation to altitude (Figure 15 and Table S5). PPT trends are negative in the period 1961–1990 for all series, while for the period 1970–2013 three series show positive non-significant trends. Tmax trends are all positive in both periods, however, there are three negative significant trends for Tmin during the period 1961–1990. The number of significant trends for PPT decreases in the recent period, while for Tmax there is an increase in the number of significant trends. All Tmin trends are significant for both periods. For PPT, these behaviors are due to the high inter-annual variability, illustrating the important differences in the trends analysis that can occur when different short periods are evaluated. For temperature, the well-known trend increase since the mid 70's in Europe (IPCC Working Group I, 2001) is clear in the analysis of these individual series as well as the regional series (section 4).

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6. CONCLUSIONS

High quality regional anomaly series of PPT, Tmax and Tmin have been obtained for the longest quality controlled and homogenized dataset for the central Pyrenees during the period 1910–2013. Due to the length and quality of the presented regional anomaly series, new possibilities for climate analysis and paleoclimate proxy calibration are now available. The importance of quality control and homogenization procedure has been highlighted by the accomplished procedures since several flagged values and inhomogeneities have been detected in the observed series. Improving series and their reliability is demonstrated by the comparison between the quality controlled and the homogenized data, the spatial correlation analysis and the comparison with an independent dataset for the regional anomaly series.

Trend analysis has shown a highly significant increase in temperatures and important inter-annual precipitation variability, without significant trends, over the central Pyrenees, with some difference between seasonal behaviors and larger temperature trends during the recent period 1970–2013 than the whole period 1910–2013. The trends of annual regional anomaly series are 0.11 ºC/dec for Tmax and 0.06 ºC/dec for Tmin for the period 1910–2013, and 0.57 and 0.23 ºC/dec for the period 1970–2013, respectively. No altitude dependence is found for trends in the study area.

The percentage of normal annual PPT years decreases in the period 1950–2013 respect the newly recovered period 1910–1949, increasing dry and wet years. Furthermore, the number of cold years in Tmin and Tmax annual regional series decreases comparing both periods while the number of hot years increase. The regional anomaly series will be made available for scientific purposes via the following web site: http://www.c3.urv.cat/data1.html

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SUPPORTING INFORMATION

The list of observatories used in the present study is provided as a supplementary Table S1 which shows the code of the observatory, the geographical information and the length and completeness of the series. Table S2 shows composite series and Table S3 lists the homogenized series. Table S4 presents the distribution of total and percentage of wet/dry and cold/hot years between the newly 1910–1945 and the latest 1950–2013 periods. Trend values for each observatory are shown in Table S5.

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Table 1. Table 1. Number of flagged values considered suspicious of being wrong after visual inspection for each daily quality control test and variable and summary for those values corrected or rejected (modified to missing data).

Number of suspicious values detected by QC procedure and visual checking										
QC test	Number of corrected values by variable			Number of rejected values by variable			Total number of modifications			
	PPT	Tmax	Tmin	PPT	Tmax	Tmin	PPT	Tmax	Tmin	All

Outliers	9	19	15	8	161	161	17	180	176	373
Duplicated dates	-	-	-	-	-	-	-	-	-	5
Too-large	1	0	0	0	0	0	1	0	0	1
Jumps	-	0	1	-	8	1	-	8	2	10
Tmaxmin	-	10	26	-	128	107	-	138	133	271
Zero PPT	10	-	-	16616	-	-	16626	-	-	16626

Table 2. Number of outliers identified by the monthly quality control procedure in the PPT, Tmax and Tmin series.

	PPT	**Tmax**	**Tmin**
Total number of series	60	48	48
Number of series with outliers detected	8	24	18
Number of outliers detected	368	115	45

Table 3. Number of break points detected for each variable by the HOMER homogenization procedure.

	PPT	**Tmax**	**Tmin**
Not supported by metadata	64	167	143
Supported by metadata	9	11	13
Maximum number of break points for a series	6	8	7
Total number of break points	73	178	156

Table 4. Trend for annual and seasonal regional central Pyrenees series for PPT, Tmax and Tmin. Significant trends ($p < 0.05$) are shown in bold.

	Trend PPT (%/dec)		Trend Tmax (ºC/dec)		Trend Tmin (ºC/dec)	
	1910-2013	1970-2013	1910-2013	1970-2013	1910-2013	1970-2013
Annual	-0.64	-2.70	**0.11**	**0.57**	**0.06**	**0.23**
Winter	-0.77	-8.59	0.06	**0.29**	**0.12**	-0.05
Spring	-1.17	0.66	**0.13**	**0.87**	0.02	**0.40**
Summer	-0.70	-4.62	**0.17**	**0.74**	**0.07**	**0.27**
Autumn	-0.30	1.95	**0.08**	**0.43**	**0.09**	**0.31**

TEMPERATURE AND PRECIPITATION REGIONAL CLIMATE SERIES OVER THE CENTRAL PYRENEES DURING 1910–2013

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ABSTRACT

Quality controlled homogenized regional anomaly series of temperature and precipitation are obtained for the central Pyrenees for the period 1910–2013. A 0.1 ºC/decade positive trend is found for minimum and maximum annual temperature exceeding the significance level of 0.05 for the whole studied period. A significant warming is found in all seasons except boreal spring in minimum temperature and winter in maximum temperature. The annual regional precipitation anomaly series shows a high inter-annual variability and a slightly negative non-significant trend of -0.6 %/decade. Non-significant negative trends of precipitation are found in all seasons for the whole period examined. Considering the recent period 1970–2013, values of temperature trends are generally higher than those obtained for the whole period. For this latest period, all maximum temperature trends are significant while only the minimum temperature trend in winter is non-significant. Spring is the season that presents the greatest warming, with 0.9 ºC/decade for maximum temperature and 0.4

ºC/decade for minimum temperature. Evaluating the same period for precipitation anomalies, trends in the annual, winter and summer series remain negative, while spring and autumn trends are positive although non-significant. This series represents the longest homogenized climate dataset available for the central Pyrenees region, including the newly recovered period 1910–1949, offering new possibilities for climate analysis and paleoclimate proxy calibration.

KEYWORDS: mountain climate; climate change; quality control; homogenization; trend analysis; Pyrenees

1. INTRODUCTION

The Pyrenees range is located in Western Europe and forms a natural boundary between Spain and France (Ariño *et al.*, 2012) with Atlantic and Mediterranean climatic influences (Beguería *et al.*, 2003).

Due to its biological richness and water resources, the Pyrenees are a valuable ecosystem that is important for local and regional development of tourism (Marín-Yaseli and Martínez, 2003), energy production, agriculture (Beguería *et al.*, 2003; López-Moreno *et al.*, 2008) and biodiversity (Regato, 2015).

Studying the climate in mountainous regions such as the Pyrenees differs from other environments because they are remote, making it difficult to record data using standard observational methods. Additionally, alpine regions experience large climate variability over short distances, due to local conditions (Barry, 1992). For example, a recent study of the number of precipitation and snow winter days for the period 1981–2010 in the western and central Pyrenees shows a relationship between these variables and the weather types in the mountain range (Buisan *et al.*, 2015). These results highlight the importance of long term observations for reliable climate analysis.

Climate change does not affect all regions equally: the warming rate can be different and even opposite between different areas (Brunet *et al.*, 2007), with mountain ranges being particularly vulnerable to climate change (Beniston, 2003).

Future climate scenarios show a mean decrease in precipitation and increase in temperature for the next century in the Spanish Pyrenees region (López-Moreno *et al.*, 2008), accompanied by a sharp reduction in the thickness and duration of snowpack (López-Moreno *et al.*, 2009). The seasonal projected precipitation analysis indicates an intensification of extremes: an upward trend of drought periods and a rise in the number of days with intense precipitation events (López-Moreno and Beniston, 2008). The number and intensity of warm and very warm days and nights (daily maximum and minimum temperature exceed the percentiles 90th and 99th, respectively) during winter is also projected to increase during the next decades, more in the Pyrenees than the surroundings areas (López-Moreno *et al.*, 2014). Similar results are found (an increase in temperature and a reduction in the number of frost days) were also obtained in the north western Mediterranean Basin, again highlighting importance of observational databases in these vulnerable and topographically complex areas (Barrera-Escoda *et al.*, 2014).

For other purposes, such as paleoclimatic studies, a thermopluviometric knowledge is necessary to calibrate natural records (proxies) against instrumental climate data (Romero-Viana *et al.*, 2008; Abrantes *et al.*, 2009; Peña *et al.*, 2015b), and the results of the calibration can be affected by the quality of the instrumental data (Brönnimann, 2015). Previous reconstructions in the Pyrenees used high-quality instrumental data that were not completely representative of the study area. See for example: Dorado Liñán et al. (2012), in which only six observatories were used, two of them far from the Pyrenees; Büntgen et al. (2008), in which instrumental series from a single close observatory were used, only reconstructing local climate; or in Esper et al. (2015), in which the observational gridded dataset CRU3.1 was used, computing the average temperature over the study area, against the recommendation of the CRU3.1 authors not to use this dataset for trend analysis without comparing with other sources due to the non homogenized conditions of the individual series (Harris *et al.*, 2014).

In addition to the above, it is recommended by GCOS (Global Climate Observing System) Climate Monitoring Principles (Aguilar *et al.*, 2003), that quality control and homogenization procedures have to be applied to any instrumental data being used to examine long-term climate variability and change.

In the Pyrenees, some studies of quality control and homogeneity of temperature have been undertaken for different spatial and temporal scales using diverse analytical approaches. One high-altitude series was checked for homogeneity using a bivariate test by Bücher and Dessens (1991); Esteban et al. (2012) and Cuadrat et al. (2013) used HOMER (HOMogenization software in R, Mestre et al., 2013), the same multiple break point homogenization method used in the present work, however they only analysed data from three observatories in Andorra and the whole Pyrenees region during the shorter 1950–2010, respectively. On the other hand, precipitation trends have been studied in a quality controlled and homogenized dataset for the north eastern Iberian Peninsula, showing the highest values of precipitation intensity in the Pyrenees with decreasing trends for the period 1955-2006 (López-Moreno *et al.*, 2010), but without any autocorrelation testing or significant level considered. The present work deals with the complete analysis: precipitation and temperature for all series in the central Pyrenees and including the newly recovered period 1910–1949.

In the present study, a high quality and long-term (1910–2013) regional anomaly series for precipitation (PPT) and maximum (Tmax) and minimum temperature (Tmin) is developed for the central Pyrenees. Quality control and homogenization procedures have been applied to obtain reliable regional anomaly series. Daily quality control has been implemented using Extra QC routing from RClimdex Software (user guide and software available in http://www.c3.urv.cat/data.html) while HOMER, a state-of-the-art homogenization method developed during the Action COST-ES0601 (HOME), has been applied, having been previously tested on temperature data in the study area (Pérez-Zanón *et al.*, 2015). Following homogenization, the regional anomaly series have been calculated applying the Osborn correction (Osborn *et al.*, 1997) that avoids the bias introduced due to the varying sample data.

In section 2 the data are presented, before being subjected to a detailed quality control procedure and homogenization in section 3. Using regional anomalies of Tmax, Tmin and PPT, climate variability and change in the central Pyrenees is examined in section 4, focusing on the whole 1910–2013 period as well as the recent 1970–2013 period. The quality of the homogenized regional series is tested in section 5, comparing this series to individual observatory series as well as independent homogenized datasets for the Pyrenees region. Final conclusions are drawn in section 6.

2. DATA

Daily PPT, Tmax and Tmin records have been provided by the Spanish National Meteorology Agency (AEMET) and the Catalonia Meteorological Service (SMC). These records came from 155 observatories having either manual or automatic observations (155 series of PPT and 126 series of Tmax and Tmin). The data series available from these observatories are of various lengths and cover the period 1910–2013. At the beginning of the study period, these series are not as complete as would be desired. For this reason and to support the homogenization procedure, four series were added from the high-quality Spanish Daily Adjusted Temperature Series (SDATSv2, Brunet *et al.*, 2006) quality controlled databank from observatories located in Pamplona, Huesca, Barcelona and Zaragoza. The spatial distribution of observatories is shown in Figure 1 while the covering period and percentage of available data is shown in Table S1 for the 155 series in the Pyrenees. The annual amount of available daily data for PPT is higher than for both Tmax and Tmin for the whole study period, due to the historical interest in precipitation measurement by the hydroelectric power stations in the Pyrenees. Figure 2 shows the amount of available daily data for each variable annually. The impact of the Spanish Civil War (1936–1939) is visible by the decrease in available data during that period.

3. BUILDING A HOMOGENIZED CENTRAL PYRENEES DATASET, 1910–2013

3.1 QUALITY CONTROL

From the recording process until the final analysis of climate time series, some errors may be introduced in the data due to changes in the observation place (relocation), measuring instrument or sheltering structure (which allows good air flow across the thermometers but prevents heating from direct sunlight), time of observation, observer, land use and cover, urbanization or because of manipulating (such as unit conversions), formatting, transmitting and archiving data methods. For this reason, Quality Control (QC) procedures are applied to detect and identify these errors (Aguilar *et al.*, 2003). ExtraQC routines from RClimdex software, developed through the International Expert Team on Climate Change

Detection and Indices (http://www.c3.urv.cat/data/soft/rclimdex_extraqc.zip) have been used.

Before running the Extra QC routines, the files containing time series should be formatted as the software requires. This step illustrates the need of QC, since some incorrect dates were detected: six dates were corrected and 12 lines were removed because of date repetition.

Taking into account the recommendations from Aguilar et al. (2003), gross errors, tolerance, internal consistency and temporal coherency have been checked and summarized in the following statistics for cases that were considered suspect, and evaluated for temporal and spatial coherency, after being flagged by the software:

- Outliers: Values exceeding a threshold defined for lower (upper) bound as the percentile 25 (75) less (plus) three times the interquartile.
- Duplicated dates: includes all dates which appear more than once in a data file.
- Toolarge: reported precipitation daily values exceeding 200 mm and temperature daily values exceeding 50 ºC.
- Jumps: those records where the temperature difference with the previous day is greater than or equal to 20 ºC.
- Tmaxmin: includes all those cases where maximum temperature is lower than minimum temperature.

Another check was applied to evaluate long continuous periods of null precipitation (called Zero PPT) that are likely due to observation or instrument error.

For the three variables (see Table 1), a total amount of 3,744,719 values were checked, from which 17,286 values (0.5%) were flagged as errors after applying the previous criteria and their revision. In total, 99.5% of the flagged suspect data were rejected by replacing the original value to missing data and 0.5% (91) corrected following visual inspection. Most of the rejected data (96.2%) were consecutive zero values of precipitation recorded at six observatories: almost a year (334 days) in Barbastro and a total amount of 9281 days for Pobla de Segur.

Apart from these errors, the most useful indicator to detect suspect values was the Outlier filter. For temperature, 271 incoherent values (Tmax < Tmin) were found.

3.2. DEVELOPMENT OF COMPOSITE SERIES

After applying the daily QC, the distances between observatories were evaluated in order to develop long-term series. A total of 63 PPT time series and 37 Tmax and Tmin time series were merged into composite groups, with a maximum of six observatories per group (Table S2). The date of the combination was recorded to be considered in homogenization analysis (see section 3.3). If two merged series had available overlapped data, the most completed was selected. After revising the geographical features, the maximum distance accepted in combinations was 29 km, however the mean distance between the rest of observatories is 2 km. The maximum difference in altitude was 167 m.

Monthly averages of Tmax and Tmin were then calculated with the missing data tolerance of no more than 7 non-consecutive or 5 consecutive missing daily values for a month (Pérez-Zanón *et al.*, 2015). Applying the same criteria to PPT, 138 values of the monthly amount (0.27 % of the total monthly values) were calculated even though those months included missing values (Figure S1).

Time series must satisfy minimum requirements in terms of length and completeness to run the homogenization software HOMER. For that reason, series with less than 270 monthly values were dismissed, except for Bossots observatory which had 254 monthly values for Tmin and Tmax in 22 years. After combining data and considering the minimum length requirements, 48 Tmin and Tmax series were included in the final dataset prepared for homogenization while 60 PPT series were available (Table S3).

Due to the interactive nature of HOMER, the homogenization procedure was applied over monthly Tmin and Tmax in two separate groups of observatories: those which have more than one year of data before 1940 and a period longer than eight years of consecutive data (21 series) were considered long series and the remaining series (27) which were considered short series and include only data from 1940. The 60 monthly PPT series were all examined at the same time.

Monthly quality control was then applied to the previously described group of series to detect additional outliers, using the Fast QC routine included in HOMER, by visual comparison of the monthly and annual differences series within each group. Then, some incoherent monthly values were removed by comparing to neighboring observatories. For example, for the PPT recorded in Agramunt observatory, no complete year of data is available for the period 1928–1934, only 47 monthly values. This makes it impossible to calculate the annual mean or to apply break detection correctly. Figure 3 shows the histogram of the number of monthly values removed by decade, which shows a bias at the beginning of the study period due to the incompleteness and the quality of the series for PPT. For temperature, the maximum number of data removed occurs in the 1940’s, when most of the series began. Table 2 summarizes the number of detected monthly outliers by variable.

3.3. HOMOGENIZATION

Most long-term meteorological observations are affected by non-climatic factors such as local environment or instrumental changes (Peterson *et al.*, 1998; Brunet *et al.*, 2006). One of these factors can be observatory relocation, which is affecting our combined dataset. To correct the series for these kinds of errors, it is necessary to check the homogeneity of the series with statistical tools and/or neighborhood comparison and, if required, correct the series. The applied homogenization method is a modern one, developed during the HOME Cost Action (Venema *et al.*, 2012), called HOMER (Mestre *et al.*, 2013). HOMER was selected because it includes the best segments and features of some other state-of-the-art methods such as PRODIGE (Caussinus and Mestre, 2004), ACMANT (Domonkos, 2011) and Joint Detection (Picard *et al.*, 2011) and was tested in a homogenization case of study of temperature in the study area (Pérez-Zanón *et al.*, 2015).

HOMER is an interactive method which allows the user to introduce metadata such as how, where and by whom data was recorded (Brunet *et al.*, 2002; Aguilar *et al.*, 2003), and uses the expertise of the climatologist to evaluate the influence of a statistically detected break point. The features of ACMANT detection included in HOMER also allows the detection of the month of a break point in case metadata aren't available. However, ACMANT detection and the "month assess" procedure are only available for temperature data after the first correction, due to the need for a reference series (previously homogenized series) to be computed. The dates of combination of series, recorded during composite series development (section 3.2) are unfortunately the only metadata available in this study for temperature data. However, for PPT homogenization, the metadata information available in Saladié (2003) was considered, although, it was not introduced in HOMER to avoid overestimating the number of break points detected.

The key steps of applying HOMER to achieve homogenized monthly series are summarized in Figure 4. This procedure is repeated as many times as it is necessary to detect inhomogeneities, taking into account that in the first steps the breaks detected may have a higher amplitude than those detected in next steps, to check them against metadata and accept or discard those breaks which could be highlighted by the detection methods in previous executions. The homogenization procedure is considered completed when the annual plots of pairwise detection (automatic generated by the software after each correction) do not highlight the same break point more than five times in the inspected series, and the visual comparison between the annual QC time series and the homogenized output doesn't show any suspicious signal of inhomogeneity.

A total of 407 inhomogeneities were detected (1.2 for PPT and 3.3 for Tmax and Tmin per observatory on average). Table 3 summarizes the total number of break points, including those supported by metadata and the maximum number of break points in one series by variable. The maximum number of break points is 13 for the three variables in one series. For temperature data, most of the series had to be corrected: for Tmin all series had at least one break point detected, and for Tmax only two series had no breaks points detected. A total 26 PPT series have been considered homogeneous as no break points were detected. The lowest break point amplitude in absolute value with supporting metadata was 0.07 ºC for Tmin and 0.11 for PPT (log-transformed precipitation data). Ten break points with supporting metadata were simultaneously detected in Tmin and Tmax.

Figure 5 shows the annual number of break points detected and the fraction of break points per series, taking into account the number of series with at least the 80% (10 months) of the data available for that year. The maximum number of break points detected were in 1931 with six break points for PPT, 1971 for Tmax with 12 break points and 1976 with seven break points for Tmin. In the case of PPT, this maximum number of breaks detected may coincide with the decrease in the number of available observatories during the 1930's. However in the case of temperature, a change in the signal is detected in the 1970's. For the density of the number of break points per series available, the maximum values are recorded at the beginning of the study period: 1916 for PPT, 1921 for Tmax and 1938 for Tmin. These results are due to the low number of data available, and in the case of Tmin, it coincides with the Spanish Civil War (1936–1939).

Figure 6 shows the distribution of the number of series according to the number of break points detected (left panel) and the number of break points detected by decade (right panel). For PPT, between zero and one break point were detected in two-thirds of the series (40 series). The number of break points in a series then decreases rapidly, with six break points the maximum for one series. For temperature, most of the series were corrected using between two and three break points, and a maximum of eight (seven) break points were necessary for one (two) series for Tmax (Tmin). The number of break points by decade indicates that our dataset is a good station network (as only 6 Tmax and Tmin series have more than 1 break per decade) considering the previously mentioned difficulties associated with obtained observed series in mountainous areas, and the fact that one break point for mean temperature series in the European western region is expected between every 15 and 20 years (Venema *et al.*, 2012).

Another important factor in assessing the impact of homogenization is the amplitude of the break points detected. Figure 7 shows the frequency distribution of the break points amplitude by variables. Most of the break points are not too large (<|2|), which could be considered a good signal of the network quality data. These results are also similar to the break point amplitude showed by Brunet *et al.* (2006) for SDATSv2 and Trewin (2013) for a daily homogenized temperature dataset in Australia.

In Figure 8 the annual anomaly series before (QC) and after (HO) the homogenization procedure are presented, with solids lines showing the mean value for all series, respectively. The impact of homogenization is shown, especially for Tmin for which the reduction in the annual variability is higher, similar to the results of Brunet et al. (2006).

3.4. REGIONAL ANOMALY CLIMATE SERIES

To obtain a representative signal of long-term precipitation and temperature evolution for the period 1910–2013 in the central Pyrenees, regional time series are calculated to show the mean and extreme state of Pyrenees climate (following Brunet *et al.*, 2006; Saladié *et al.*, 2008).

Regional anomaly series for PPT, Tmax and Tmin have been obtained for annual and seasonal time periods; winter (December to February), spring (March to May), summer (June to August) and autumn (September to November). For each series considered the mean (total) temperature (precipitation) was determined for each resolution and the mean value for the base period (1961–1990) was calculated as $\overline{T}$ ($\overline{PPT}$). Then the anomaly series can be calculated as

$$\Delta T_{obs}(t) = T_{obs}(t) - \overline{T_{obs}} \tag{1}$$

for temperature, and as

$$\Delta PPT_{obs}(t) = \frac{PPT_{obs}(t) - \overline{PPT_{obs}}}{\overline{PPT}_{obs}} \tag{2}$$

for precipitation.

To take into account the bias that the varying sample size may introduce on timeseries formed as average of individual timeseries (Osborn *et al.*, 1997), the regional series have then been calculated by the equation

$$Y(t) = X(t)\sqrt{\frac{n'(t)}{n'(n = N)}} \tag{3}$$

being

$$n'(t) = \frac{n(t)}{1 + (n(t) - 1)\bar{r}} \ , \tag{4}$$

where n is the number of records, $\bar{r}$ is the mean correlation between all pairs of time series, N is the maximum sample size, $X(t)$ is the original regional mean time series and $Y(t)$ is the desired time series with a variance independent of sample size.

3.5 RELIABILITY OF THE HOMOGENIZED REGIONAL SERIES

To assess the quality of the homogenized regional series developed here, the homogenized dataset obtained by the Pyrenees Climate Change Observatory (OPCC, http://www.opcc-ctp.org/en/actions/climate; Cuadrat *et al.*, 2013) for the period 1950–2010 is used to compute the regional anomaly series by the same methodology presented in this work. The coefficient of correlation is compute between both regional anomaly series for each variable. The lowest correlation value was 0.8 for annual precipitation and the highest was 0.95 for spring maximum temperature. This good agreement between both dataset for the common period corroborates validity of the presented regional anomaly series. However, it must be noted that small inhomogeneities may remain in our Central Pyrenees dataset, due to the lack of metadata availability, inherent uncertainties associated with statistical homogenization, and the complexity of alpine climates.

The quality of the homogenized regional climate series obtained can also be seen in the good agreement between the regional anomaly series and individual observatory series.

The regional anomaly series captures the climate signal of the study area, returning high and significant correlation coefficients between the regional climate series and each individual anomaly series for all variables and temporal resolutions. The annual spatial distribution of correlation coefficients (Figure 9) shows that PPT has the highest variability (minimum value 0.6), while Tmax correlation coefficients are very similar (minimum value 0.8) and Tmin correlation coefficients are between 0.6 and 0.8. Due to a non-constant spatial distribution of the observatories, the highest correlations are found with the highest density of observatories.

The seasonal correlations between the regional series and individual series for PPT (Figure 10) show that winter is the most spatially coherent (correlation values between 0.5 and 0.9), while summer the correlations coefficient are somewhat lower (around 0.7). These differences can be explained by the fact that summer precipitation events are generally associate with convective processes which can affect small areas of the Pyrenees, while winter precipitation events are more connected with large scale processes that affect the whole Pyrenees region (Llasat and Puigcerver, 1997).

On the other hand, the lowest values (0.7) of seasonal Tmax correlation coefficients are found in winter, while summer the minimum correlation coefficient is 0.8 (Figure 10). Seasonal Tmin correlation coefficients show the opposite behavior, with summer minimum correlation coefficients around 0.7 and winter slightly higher at 0.8. This difference may be related to the less solar radiation during winter month at this latitude (Barry, 1992) and to the impact of topography, which can have a large impact on minimum temperatures, particularly during clear nights (Trewin, 2005).

4. CENTRAL PYRENEES TEMPERATURE AND RAINFALL, 1910–2013

4.1. REGIONAL TRENDS, 1910–2013

For all regional anomaly series, a trend analysis has been performance using Mann-Kendall test and following the application described by Wang and Swail (2001) in two different periods: for the whole series (1910–2013) and for the recent period (1970–2013). This technique avoids the dependence on autocorrelation for the significance of trends, which can be overestimated by other analysis. The last period has been selected because from1970 the increase in temperatures across Spain is known to be large (Brunet *et al.*, 2007). Significance of trends was evaluated using the Student's t test ($p < 0.05$)(Wilks, 2011).

The total number of series used is 35 for PPT, 18 for Tmax and 20 for Tmin as only the monthly homogenized series which have at least 80% of the values in the base period are used (and dismissing Barcelona observatory which is not representative of the study area).

Figure 11 shows the annual regional anomaly series for PPT, Tmin and Tmax and the trends obtained. For the whole series (1910–2013), PPT trend is –0.64 %/decade, Tmax trend is 0.11 ºC/dec and Tmin trend is 0.06 ºC/dec, while for the period 1970–2013, PPT trend is –2.70 %/dec, Tmax trend is 0.57 ºC/dec and Tmin trend is 0.23 ºC/dec. These trends are significant in the case of temperature and non-significant for PPT due to its large inter-annual variability.

PPT anomalies series for central Pyrenees are dominated by a high inter-annual variability, however, negative trends are found in all seasons (Figure 12) except for spring during the period 1970–2013. The greatest difference between the seasonal trends is found in winter, when the change in the trends between both periods is greater than –7 %/dec. This decrease in winter precipitation is in agreement with López-Moreno (2005), who identified a decrease in snowpack depth for the period 1950–1999. On the other hand, an increase in the precipitation trend of 2.25 %/dec is found in autumn. These differences may suggest a shift in the rainfall distribution of seasons, however dynamical studies are required to determine the cause of these findings.

Tmax seasonal anomaly series (Figure 13) shows a clear positive trends, with only winter showing a non-significant trend for the period 1910–2013. The increase in trend values comparing both periods may suggest a higher impact of climate change in the study area for the recent 1970–2013 period. The warmer months of spring and summer display the greatest trends, an interesting result given the potential impact of heat waves and extremes on the regional population and environment, (e.g. Peña *et al.,* 2015a). Trends of Tmin seasonal anomaly series (Figure 14) are not as large as those for Tmax, with two non-significant periods (spring 1910–2013 and winter 1970–2013). The significant trends for the whole series are 0.12 ºC/dec in winter, 0.07 ºC/dec in summer and 0.09 ºC/dec in autumn, while, for the period 1970–2013, trends are 0.27 ºC/dec in summer, 0.31 ºC/dec in autumn and 0.40 ºC/dec in spring. Table 4 summarizes all the computed trends for both periods taking into account the significance level.

4.2. CENTRAL PYRENEES CLIMATE VARIABILITY, 1910–1949

As well as an extended trend analysis, the addition of homogenized climate data for the 1910–1949 period over the Central Pyrenees also allows for the examination of interannual climate variability in the region during the first half of the 20th century. Considering the threshold of ±10%, dry (wet) years can be defined as those years with anomaly PPT below than -10% (10%), while normal years are those years with anomaly PPT between -10 and 10%. For the newly recovered period 1910–1949 analyzed in this paper (Table S4 and Figure 11), 12 (30% of years) dry years and 7 (18%) wet are registered compare to the 26 (41%) dry and 17 (27%) wet years for the next period 1950–2013 for annual regional anomaly series. The number of normal years, 21, doesn't change between periods but represents the 53% of years for the newly recovered period and the 33% for the modern period. This result suggests that precipitation variability in the central Pyrenees may be becoming more extreme.

Following the filtered anomaly PPT series by a 5-year moving average (Figure 11), six years of positive PPT values (1914–1919), largely associated with wet conditions in 1915 and 1919. The 20's are close to normal as shown in the filtered series shows, presenting 4 dry years and 1 wet but spread out over time. The four first years of the 30's were extremes, alternating wet and dry years, and two wet and one dry year were observed later (1936–1938) during the Spanish Civil War. A drought emerges towards the end of the 40's, with four dry years registered from 1944 to 1949, and continues to the mid 50's.

Seasonal series show fewer normal years, especially in winter, for which only 9 years were normal for the newly recovered period 1910–1949 and 3 for the period 1950–2013. Half of the years were dry for winter PPT series in the 1910–1949 period. The longest wet period was recorded for 1915–1917. In the summer PPT series the longest dry period is observed for 14 years, between 1916 and 1929, during which no wet year was recorded.

For temperature the threshold for hot and cold years is selected as ±0.5 ºC (Table S4). As it would be expected given the temperature trends, the percentage of hot years increases in the modern period (1950–2013) with respect to the newly recovered period (1910–1949) while the percentage of cold years decreases. In particular, Tmax presents 18 hot years out of the last 20 years of the series (1994–2013). The number of normal years remains close to constant for Tmax and Tmin in annual and seasonal resolution.

Tmax annual regional series shows high variability in periods of 4 to 6 years even individual extremes years until the 40's decade when a long hot period is shown from 1943 to 1950 when 6 hot years were observed. In winter and summer, the percentage of hot years increase by 14 % for the period 1950–2013 with respect to the newly recorded period, while in summer the percentage of cold years decreased by 12 %.

The annual regional anomaly Tmin series is roughly characterized by three periods: a cold period from 1910 to 1925; a normal period between 1926 (which was hot) and 1942 for which all years were normal except 1935 (which was cold); a hot period from 1943 to 1949 when 4 hot years were observed. The percentage of cold years was reduced to the half in the period 1950–2013, while the percentage of hot years is almost double. In winter, only three hot years were observed for the early period, given the longest period of cold and normal years of 13 years between 1937 and 1949. In summer, the 6 cold years observed for the newly period are found until 1917.

4.3. DEPENDENCE OF TRENDS ON ALTITUDE

To conduct a preliminary evaluation of the impact of climate change at different altitudes, trends of annual anomalies for the individual series used to compute the regional anomaly series were calculated for 1961–1990 and 1970–2013, using those series with a minimum of 80% of monthly data for 1961–1990. The trends do not show any relation to altitude (Figure 15 and Table S5). PPT trends are negative in the period 1961–1990 for all series, while for the period 1970–2013 three series show positive non-significant trends. Tmax trends are all positive in both periods, however, there are three negative significant trends for Tmin during the period 1961–1990. The number of significant trends for PPT decreases in the recent period, while for Tmax there is an increase in the number of significant trends. All Tmin trends are significant for both periods. For PPT, these behaviors are due to the high inter-annual variability, illustrating the important differences in the trends analysis that can occur when different short periods are evaluated. For temperature, the well-known trend increase since the mid 70's in Europe (IPCC Working Group I, 2001) is clear in the analysis of these individual series as well as the regional series (section 4).

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6. CONCLUSIONS

High quality regional anomaly series of PPT, Tmax and Tmin have been obtained for the longest quality controlled and homogenized dataset for the central Pyrenees during the period 1910–2013. Due to the length and quality of the presented regional anomaly series, new possibilities for climate analysis and paleoclimate proxy calibration are now available. The importance of quality control and homogenization procedure has been highlighted by the accomplished procedures since several flagged values and inhomogeneities have been detected in the observed series. Improving series and their reliability is demonstrated by the comparison between the quality controlled and the homogenized data, the spatial correlation analysis and the comparison with an independent dataset for the regional anomaly series.

Trend analysis has shown a highly significant increase in temperatures and important inter-annual precipitation variability, without significant trends, over the central Pyrenees, with some difference between seasonal behaviors and larger temperature trends during the recent period 1970–2013 than the whole period 1910–2013. The trends of annual regional anomaly series are 0.11 ºC/dec for Tmax and 0.06 ºC/dec for Tmin for the period 1910–2013, and 0.57 and 0.23 ºC/dec for the period 1970–2013, respectively. No altitude dependence is found for trends in the study area.

The percentage of normal annual PPT years decreases in the period 1950–2013 respect the newly recovered period 1910–1949, increasing dry and wet years. Furthermore, the number of cold years in Tmin and Tmax annual regional series decreases comparing both periods while the number of hot years increase. The regional anomaly series will be made available for scientific purposes via the following web site: http://www.c3.urv.cat/data1.html

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SUPPORTING INFORMATION

The list of observatories used in the present study is provided as a supplementary Table S1 which shows the code of the observatory, the geographical information and the length and completeness of the series. Table S2 shows composite series and Table S3 lists the homogenized series. Table S4 presents the distribution of total and percentage of wet/dry and cold/hot years between the newly 1910–1945 and the latest 1950–2013 periods. Trend values for each observatory are shown in Table S5.

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Table 1. Table 1. Number of flagged values considered suspicious of being wrong after visual inspection for each daily quality control test and variable and summary for those values corrected or rejected (modified to missing data).

Number of suspicious values detected by QC procedure and visual checking

QC test	Number of corrected values by variable			Number of rejected values by variable			Total number of modifications			
	PPT	Tmax	Tmin	PPT	Tmax	Tmin	PPT	Tmax	Tmin	All
Outliers	9	19	15	8	161	161	17	180	176	373
Duplicated dates	-	-	-	-	-	-	-	-	-	5
Too-large	1	0	0	0	0	0	1	0	0	1
Jumps	-	0	1	-	8	1	-	8	2	10
Tmaxmin	-	10	26	-	128	107	-	138	133	271
Zero PPT	10	-	-	16616	-	-	16626	-	-	16626

Table 2. Number of outliers identified by the monthly quality control procedure in the PPT, Tmax and Tmin series.

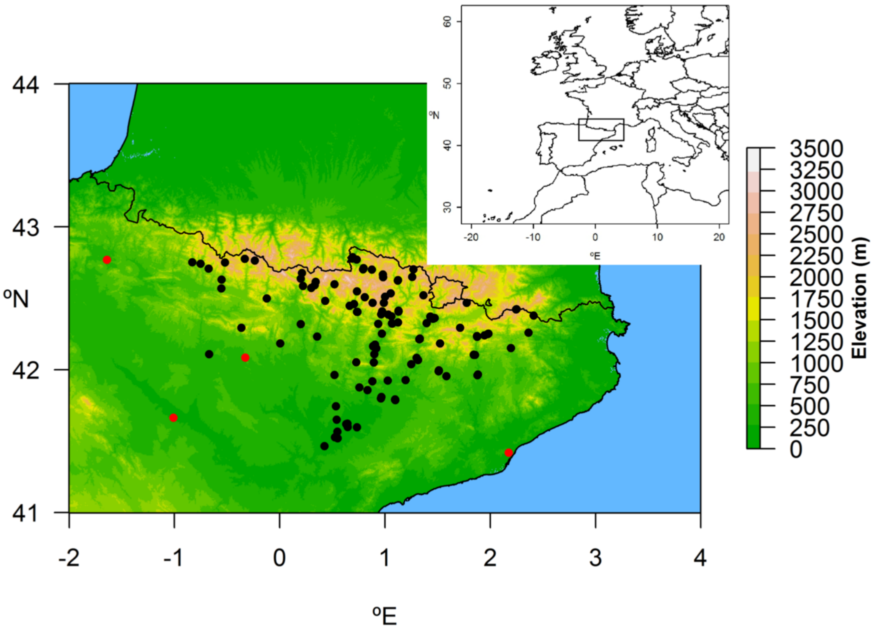
	PPT	Tmax	Tmin
Total number of series	60	48	48
Number of series with outliers detected	8	24	18
Number of outliers detected	368	115	45

Table 3. Number of break points detected for each variable by the HOMER homogenization procedure.

	PPT	**Tmax**	**Tmin**
Not supported by metadata	64	167	143
Supported by metadata	9	11	13
Maximum number of break points for a series	6	8	7
Total number of break points	73	178	156

Table 4. Trend for annual and seasonal regional central Pyrenees series for PPT, Tmax and Tmin. Significant trends ($p < 0.05$) are shown in bold.

	Trend PPT (%/dec)		Trend Tmax (ºC/dec)		Trend Tmin (ºC/dec)	
	1910-2013	1970-2013	1910-2013	1970-2013	1910-2013	1970-2013
Annual	-0.64	-2.70	**0.11**	**0.57**	**0.06**	**0.23**
Winter	-0.77	-8.59	0.06	**0.29**	**0.12**	-0.05
Spring	-1.17	0.66	**0.13**	**0.87**	0.02	**0.40**
Summer	-0.70	-4.62	**0.17**	**0.74**	**0.07**	**0.27**
Autumn	-0.30	1.95	**0.08**	**0.43**	**0.09**	**0.31**



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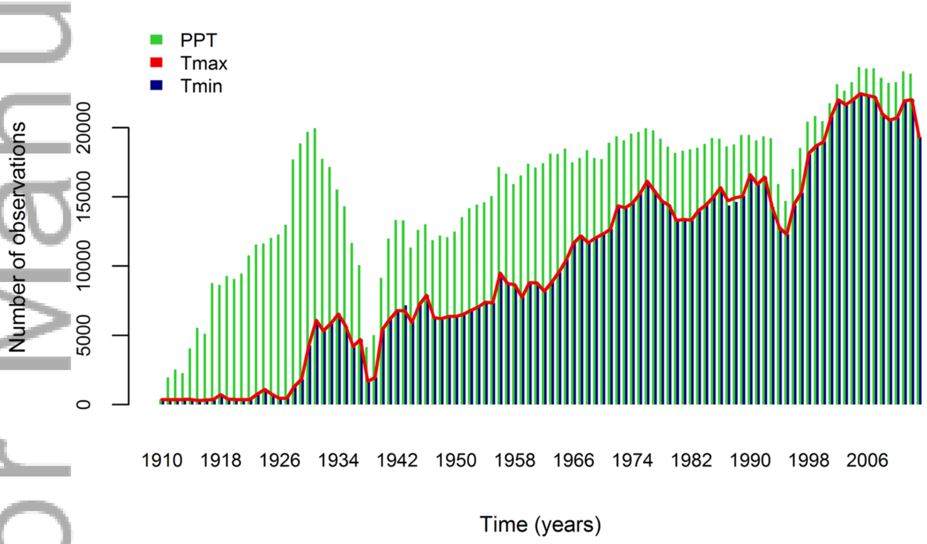

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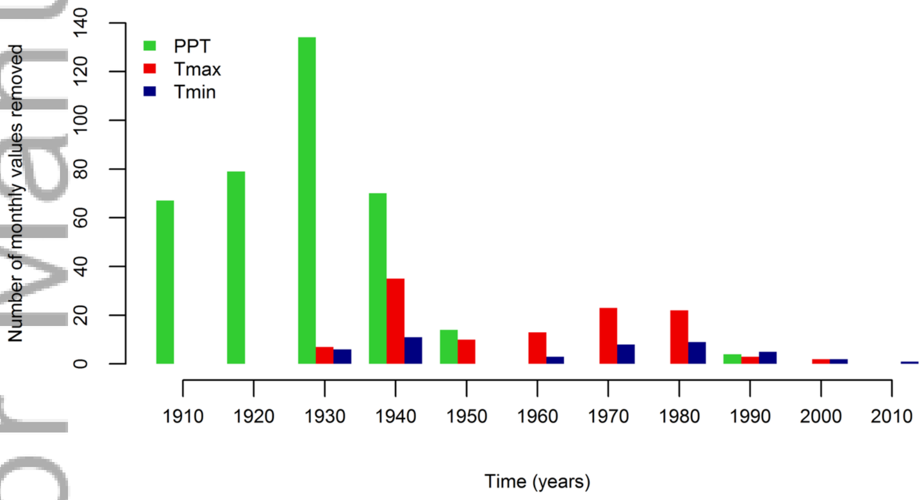

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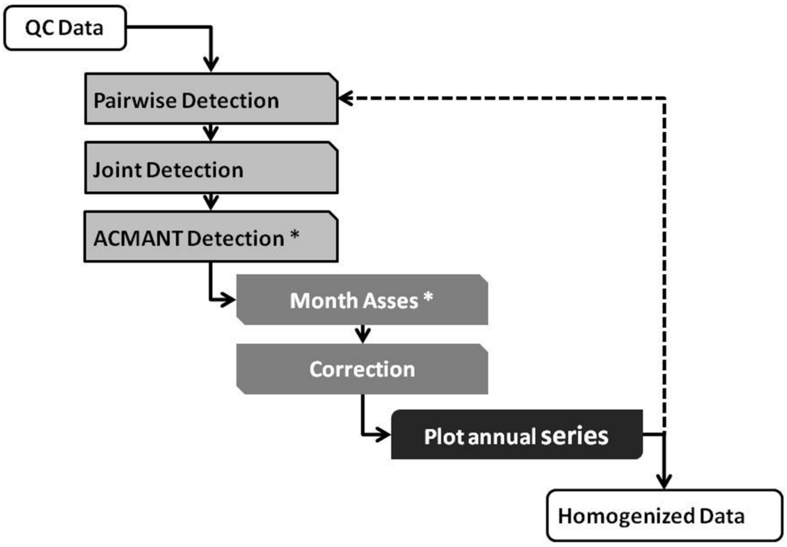

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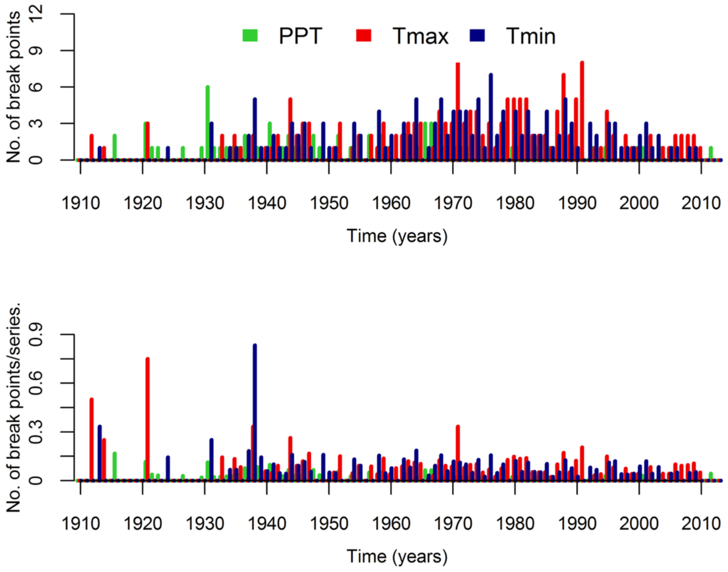

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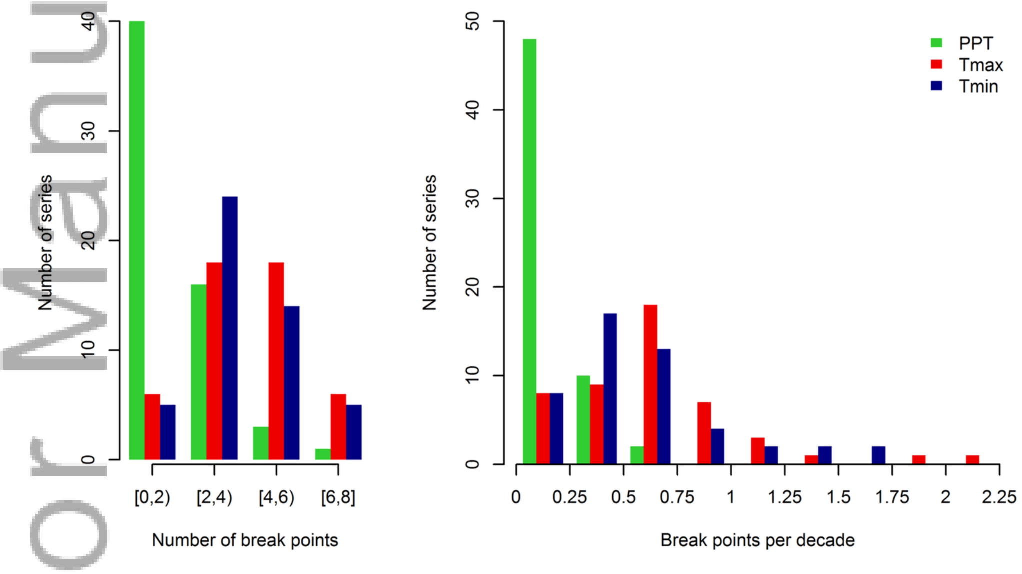

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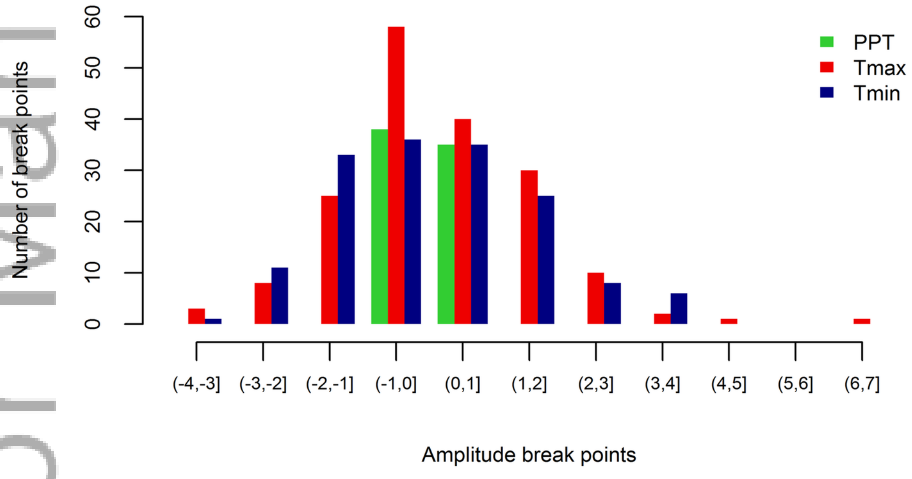

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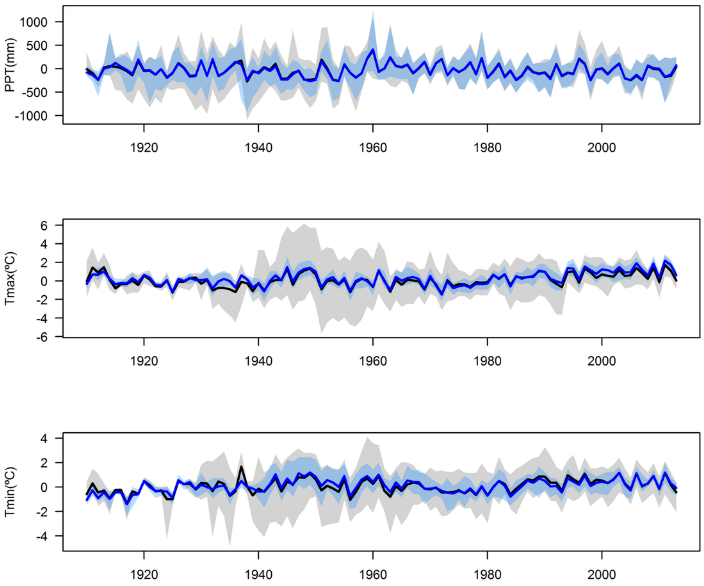

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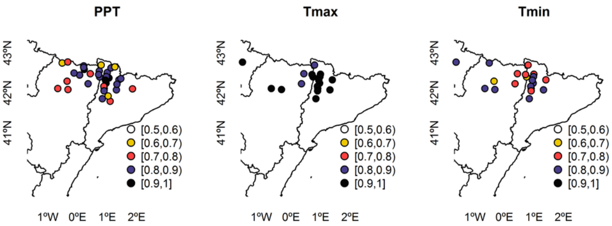

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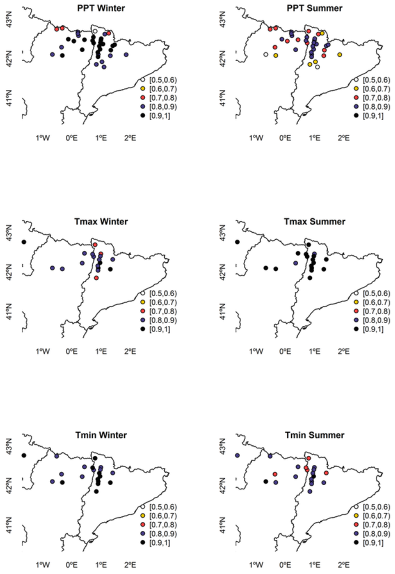

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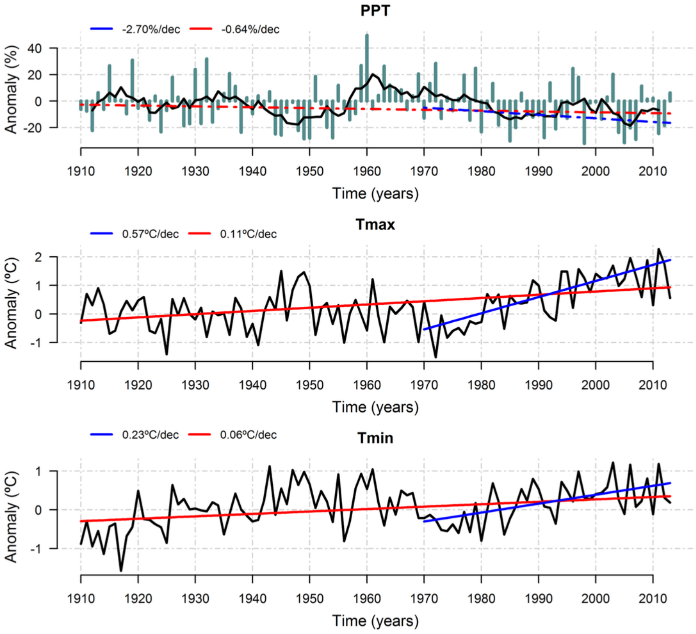

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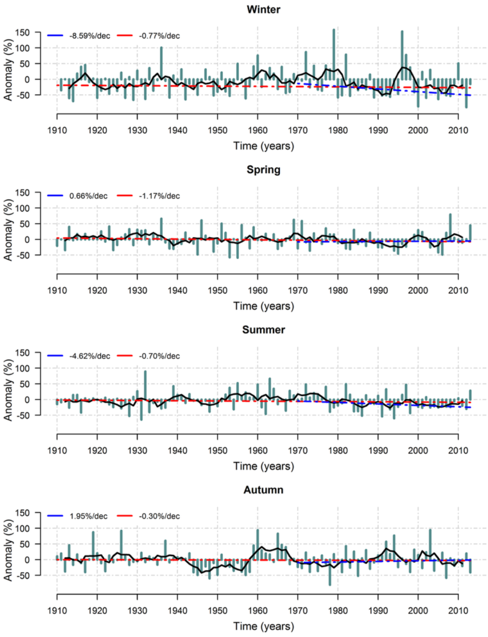

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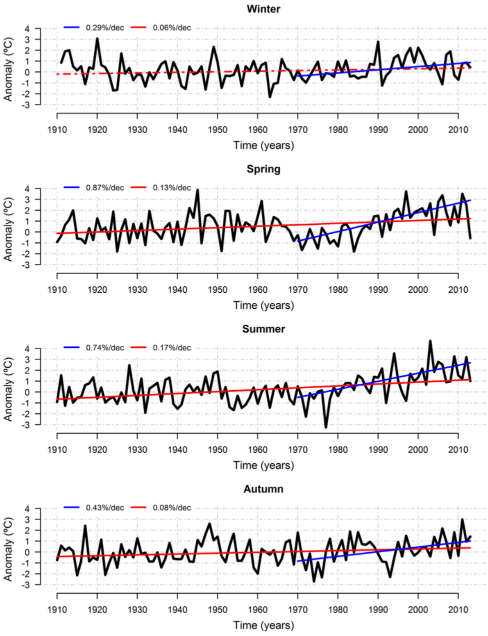

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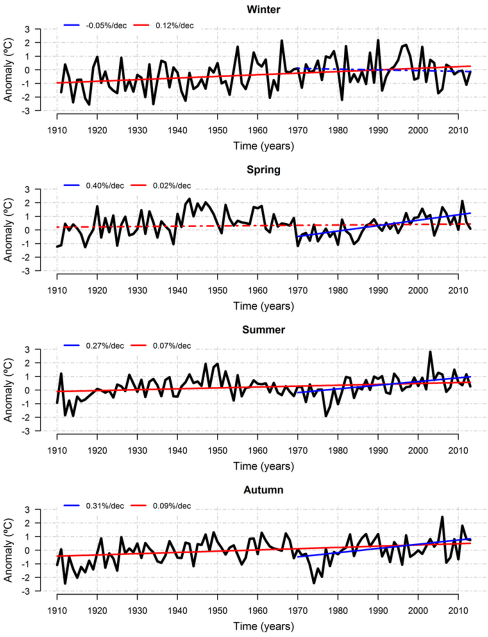

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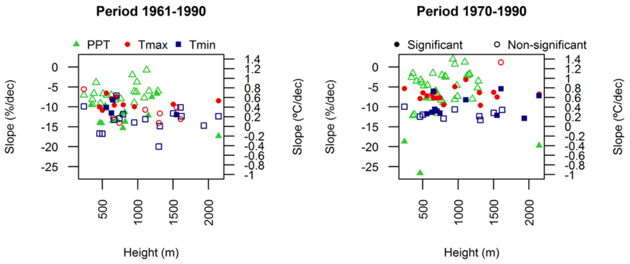

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