Climatic trends for the Pyrenees mountain range and surrounding lowlands

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Abstract

Land use changes and climate change have been hypothesized to be the primary cause of reduced stream flows from watersheds of the Pyrenees Mountain range, supplying the surrounding lowlands of Spain and France. This study contributes a historical analysis of climate trends and land use change that drive the evolution of water availability originating in the Pyrenees Mountain range. Climatic data series from a range of meteorological stations located on the Pyrenees mountain range, as well as in lowland areas of northern Spain, Andorra and southern France, were analyzed. In addition, aerial photography data was used to quantify the expansion of forests on headwaters regions. The results show a slight decrease of precipitation for the western Pyrenees region, and significant increases in temperature over the last 50 years across the entire study area. Trends observed at high versus low elevation climate stations with the Pyrenees Mountain range were not substantially different. Increased evapotranspiration caused by climate warming as well as forest cover expansion on abandoned agricultural lands located on headwaters and valleys of the Pyrenees mountain range, appear to be a plausible explanation for decrease in water yield in the region. The results imply that under continued climate warming, the availability of future water resources to supply the needs of the population located downstream will be uncertain.

Table of contents

1. Study rationale and objectives

The abandonment of traditional agricultural lands across the Pyrenees Mountain range has lead to an expansion of forest cover located on the headwaters of rivers (Buendia et al. 2016a), which combined with changes in temperature, precipitation and snow cover and depth due to climate may have caused a decrease in water yield in the region (Lopez-Moreno et al. 2008). Under projected climate change, the availability of future water resources to supply the needs of the population located downstream is uncertain. The objective of this study is to document climate trends that drive the evolution of water availability originating in the Pyrenees Mountain range, by analyzing climatic trends over time, and on different elevations, as well as land-cover changes, under consideration of water balance. For the purpose of this study, climatic data series from a range of meteorological stations located on the Pyrenees mountain range, as well as in lowland areas of northern Spain, Andorra and southern France, are analyzed. In addition, aerial photography data is used to study the land-use changes over time, and to better quantify the expansion of forests on headwaters regions.

2. Literature review

2.1. What are the issues and the regional concerns?

The Mediterranean basin is considered to be one of the most sensitive areas to climate change in the world (López-Moreno et al. 2011) which is also related to the socio-economic vulnerability of its population (Barcikowska et al. 2019). The population growth, the rapid urbanization of the land, the expansion of industrial sites and the increase in tourism activities is leading to an increase in water demand for the population, which combined with the predicted climate change effects, this demand is uncertain to be met in the future (García-Ruiz et al. 2011). The Mediterranean basin is characterized by a low annual precipitation with high inter-annual variability, high evapotranspiration rates (Begueria et al. 2003) and a marked seasonality. In addition, the basin hosts a variety of landscapes, from hot and dry regions, to several humid mountain ranges (Lionello et al. 2006), which are sources of water supply for population located downstream (Amblar-Francés et al. 2020).

One of these mountain ranges, and the focus of this study, is the Pyrenees region, which is the natural border between France and Spain, with Andorra being located within these mountains. The area is delimited by the Mediterranean Sea on the East and the Atlantic Ocean on the west, characterized by a topography of mountains ranging from 500m to 3404m asl (above sea level) and a dense river network (Amblar-Francés et al. 2020). The Pyrenees is the source of water supply for the northern parts of Spain – regions of Catalonia, Aragon, Navarra, La Rioja, Castilla y Leon, Euskadi and Cantabria -, as well as for regions located on the south of France – Languedoc-Rousillon, Midi-Pyrenees and Aquitaine-. The Pyrenees mountain range hosts a combination of Mediterranean and Atlantic climates (Amblar-Francés et al. 2020), mostly ruled by the North Atlantic Oscillation (NAO), which highly influences the changes in temperature and precipitation, as well as, the occurrence of dry or wet winters (Barcikowska et al. 2019; El Kenawy et al. 2011; Lionello et al. 2006; López-Moreno 2005; López-Moreno et al. 2011). The Southern North Atlantic Oscillation (SNAO) has also been seen to play a role on the European climatology, regulating the summer atmospheric circulation, in particular (Barcikowska et al. 2019). However, El Niño Southern Oscillation (ENSO) and the East Atlantic (EA) atmospheric patterns also explain the weather variability within the Pyrenees region. In addition, an influence of the Scandinavian pattern is observed on the central Pyrenees (Lionello et al. 2006).

Nowadays, the Pyrenees region is facing rapid climatic changes which create uncertainty on the availability of water resources in the future (García-Ruiz et al. 2011). The climatic models predict, throughout the 21st century, a general increase in mean annual temperature and a decrease in annual and spring precipitation (Nogues Bravo et al. 2008), which in combination with a decrease in snow depth, an increase in evapotranspiration, the abandonment of agricultural lands and grasslands on slopes and the progressive expansion of forests and shrubs on the headwaters of rivers (Buendia et al. 2016a), as well as the growth of urban, industrial and touristic areas, and the expansion of agricultural lands on lowlands (Begueria et al. 2003), might lead to an increase in water demand and a future uncertainty on water resources availability (García-Ruiz et al. 2011) . As most of the water demand is located in lowland areas, several reservoirs were built in Mediterranean mountains to provide water for the population (López-Moreno et al. 2011). However, due to a reduction of snow accumulation and snowmelt processes, the future availability of these resources is uncertain. Mountains have a key role on water availability for the population and therefore special attention should be placed on conservation of mountain environments for water yield purposes (García-Ruiz et al. 2011), as well as on understanding how climate change might affect high elevations compared to lowlands, which leads to the starting point of this study.

2.2.What is known about the trends?

2.2.1. Global

The global warming that we are experiencing nowadays has been observed since the mid-20th century and has been mostly associated with human activities (Zhou 2021). An increase of approximately 0.6ºC during the 20th century has been observed globally (Easterling et al. 1997). The UN's Intergovernmental Panel on Climate Change (IPCC) released the Fifth Assessment Report, in which the findings from several studies are collected and represented. In summary, the global average surface temperature presented an increased about 0.85ºC (with real values shifting between 0.65 to 1.06 ºC) during the period 1880-2012 (5th IPCC Report: https://archive.ipcc.ch/pdf/assessment-report/ar5/syr/AR5_SYR_FINAL_All_Topics.pdf). Rangwala and Miller (2012) found a global increase in air temperature, over land, of 0.30ºC per decade, for the period 1975-2010, which is higher than the rate of ocean warming which was found to be 0.12ºC per decade, for the same time period. However, the changes in temperature over time should also be studied at a local and regional scale, to observe the impacts that these variations could have on humans and on the environment (El Kenawy et al. 2011). In addition, since the mid-20th century, the 5th IPCC report found that the troposphere has warmed and the lower stratosphere has cooled, which is a finding that should be further explored.

In addition, the IPCC is working on the 6th Assessment Report (https://www.ipcc.ch/report/ar6/wg1/resources/press), which found that, since 1980s, both Earth hemispheres underwent a pole ward shift due to changes in the mid-latitude storm tracks. The global averaged precipitation over land increased by 2% since the beginning of the 20th century, however with high variability at a spatial and temporal scale. During the 20th century, middle and high latitudes of the Northern Hemisphere experienced an increase of 0.5% to 1% per decade, in contrast with the Eastern Asia and the sub-tropics, where land-surface rainfall has declined in an average of 0.3% per decade, and on the tropics, the precipitation has increased by about 0.2 to 0.3% per decade over the 20th century (Dore 2005).

2.2.2. Europe and the Mediterranean Basin

The summary of the European State of the Climate (2020), compiled by the Copernicus Climate Change Service (C3S) http://doi.org/10.24381/43nj-sb24, showed the climatic trends, since 1980, for Europe. In particular, the winter of 2020 was 3.4ºC warmer relative to the period 1981-2010. In addition, the maximum and minimum temperatures on the northeastern part of Europe were 6ºC and 9ºC, respectively, warmer than the reference period mentioned before. The same report showed a no trend in precipitation since 1981 until 2020. However, a high variability of precipitation between regions and times of the year was observed during 2020, and a transition between a wet winter into a dry spring was found at the northwestern and central Europe regions.

In addition, a range of studies found an increase in the frequency of climatic extreme events in Europe, floods and droughts, in particular (Hov et al. 2013). For the Mediterranean Basin, a warming of 0.75ºC was observed (Giorgi 2002) during the 20th century, as well as an increase in mean annual temperature of 0.9ºC on the Pyrenees region (Nogues Bravo et al. 2008). El Kenawy et al. (2011) studied the changes in maximum, minimum and mean annual temperatures, as well as the diurnal temperature range (DTR), which corresponds to the difference between the increase in daily minimum and maximum temperatures, for the northeastern part of Spain, during the period 1920-2006. The study found an increase in mean annual temperature of 0.11ºC/decade, with enhanced warming during the spring and summer seasons (0.3ºC/decade) compared to autumn and winter seasons (0.15ºC/decade). Those findings led to a warming rate of 0.96ºC/87 years, from 1920 until 2006. In addition, maximum and minimum temperatures also increased during the period of study, with values of 0.08ºC/decade and of 0.14ºC/decade, respectively, being that an increase of 0.70ºC/87 years in maximum temperature and of 1.2ºC/87 years in minimum temperature. In one hand, El Kenawy et al. (2011) also found that the increase in maximum temperatures was more pronounced during the warmer seasons, 0.28ºC/decade for spring and summer, compared to an increase of 0.06ºC/decade during the colder seasons, autumn and winter. On the other hand, the authors found an increase of 0.25ºC/decade in minimum temperatures, during the colder seasons, compared to a warming rate of 0.16ºC/decade during the warmer seasons. Regarding the variability in DTR (TMAX – TMIN), the study found a decrease of -0.06ºC/decade from 1920 until 2006 due to a higher warming rate of annual minimum temperatures compared to annual maximum temperatures. These results coincide with those presented in the study done by Martínez et al. (2009), which found an annual decrease in DTR on the Catalonia region, over the period 1975-2004, with a relevant decrease of -0.9ºC/decade during the autumn season. The study also found an increase in annual maximum and minimum temperatures of 0.5ºC/decade during the period 1975-2004, with values reaching 0.8-0.9ºC/decade during spring and summer seasons. However, a decrease of -0.5ºC/decade in maximum temperatures was observed during autumn. The study done by El Kenawy et al. (2011) also observed that the rate of change in mean annual temperature, for the period 1960-2006 (+0.33ºC/decade), in northeastern Spain, increased at almost twice the rate of the period 1920-1959 (+0.15ºC/decade). In addition, the DTR trends shifted to positive values for the most recent period mentioned before, as the warming rate for annual maximum temperatures increased throughout the 1960-2006 period in comparison to the 1920-1959 period. Last, but not least, the warming was seen to be faster during summer and spring seasons compared to winter and autumn seasons. Favà Figueres et al. (2019) observed that the warming on northeastern Spain during the 20th century occurred in two phases, from 1920 until the 1950's, and from the 1970's onwards.

2.2.3. Pyrenees mountain range

Focusing on the area of study, the Pyrenees mountain range, to understand how different climatic factors have changed over time could help with forecasting future climatic conditions to fight water deficit. The climatic variability within the Pyrenees throughout the history has been addressed in a range of studies (Amblar-Francés et al. 2020; Begueria et al. 2003; Buendia et al. 2016a; Buisán et al. 2015; López-Moreno 2005; Nogues Bravo et al. 2008).

The frequency of extreme events on the area of study, such as intense rainfalls, has increased since the mid-20th century (Hov et al. 2013; Lionello et al. 2006). As mentioned on the first section of this study, the precipitation on the Pyrenees region is highly influenced by the North Atlantic Oscillation (NAO) and the East Atlantic pattern (EA) (Barcikowska et al. 2019). However, these factors need more consideration when studying the climatic trends on the European precipitation patterns (Blade et al. 2012). Buendia et al. (2016a) observed a decrease in precipitation for February and July, and for the period 1941 - 2009, with high variability depending on the period of time considered in the study.

Serrano-Notivoli et al. (2019b) studied the changes in temperature and precipitation on the whole Pyrenean mountain range, using daily data for the period 1981-2015 and monthly data for the period 1950-2015. The study found an increase in annual mean temperature of 0.2ºC/decade, and of 0.3ºC/decade for the spring and summer months, for the period 1950-2015. In addition, mean annual precipitation presented a high spatial variability, with a significant decrease in precipitation on the southernmost parts of the Pyrenees, being that decrease of -1.8%/decade for the period of study.

The changes in temperature and precipitation since 1940 until 2000 are also represented in a study done by Begueria et al. (2003) (https://doi.org/10.1579/0044-7447-32.4.283). However, they suggested that there is no enough evidence to define a clear annual climatic trend on the area of study, for the period of time before mentioned, as this period was characterized by a drier season from 1940 until 1955, followed by a humid period from 1955 until 1980, and, from 1980 until 2000, a drier season occurred again. Nevertheless, a relationship between precipitation and water runoff was found. The water yield decreased by about 30% between 1945 and 1995, which implies that a non-climatic factor, land-use change or plant cover, might have determined the fluctuations in discharge, in addition to the changes in temperature and precipitations within the area of study. Buendia et al. (2016a) studied the changes in runoff on the Pyrenees, from 1941 until 2009, and its possible relationship with climate change and land-use change. The authors found an increase in forest cover from 1987 until 2009, and concluded that this increase in afforested land was seen to have a strong influence (approximately 40%) on the decrease in runoff observed from 1980 onwards. In addition, the authors said that "Upward trends were detected for temperature and potential evapotranspiration, particularly during summer and winter months."

The small area covered by glaciers and ice in the Pyrenees was estimated to be over 2000 ha in 1850, and of 242.06 ha in 2016, meaning that a decrease in ice cover of 88.25% since 1850. In addition, the mean glaciated area loss was faster during the period 1984-2016, melting at a rate of 17.66 ha/year, in comparison to the melting rate of 10.95 ha/year during the 20th century (Rico et al. 2017). Related to snow cover, López-Moreno (2005) found a decrease in the snowpack, since 1980 until 2000, with high inter-annual variability and changes depending on the elevation, due to a decrease in precipitation in February and March associated with a positive trend of the

NAO index. Below 2200 m asl, the snow depth decreased an average of 17.4 cm for the period 1980-2000, and increased an average of 9.7cm in elevations above 2200 m asl, for the same period of time. From the results of this study, temperature seemed to be a driving factor in low elevation more than in high elevation areas. High fluctuations of snow depth in March and April were due to a marked inter-annual variability in precipitation. Lopez-Moreno and Garcia-Ruiz (2004) also found a marked correlation between precipitation and snow depth from December until March, and for April-May the temperature was found to be the main factor determining the snow depth.

2.3. What is trends are projected in the future?

2.3.1. Global

From the 5th IPCC report, a series of future scenarios (Representative Concentration Pathways – RCPs) were created for predicting future climatic trends. Those scenarios describe a range of greenhouse gases (GHG) emissions and concentrations on the atmosphere, combined with land-use changes and air pollutant emissions, starting from low GHG emissions (RCP2.6) to intermediate (RCP4.5 and RCP6.0) until very high GHG emissions (RCP8.5).

The 5th IPCC report predicts that the global mean surface temperature will increase under all the above mentioned scenarios (check “Table 2.1” from the report https://www.ipcc.ch/site/assets/uploads/2018/05/SYR_AR5_FINAL_full_wcover.pdf). For the period 2016-2035, the warming rate is expected to range between 0.3ºC to 0.7ºC relative to the reference period 1986-2005, and similar under all four RCPs scenarios. However, the more we move further into the 21st century, the more variability of predictions is associated with each scenario, in particular, the warming rate seems to be higher under the intermediate and very high GHG concentrated RCPs. In example, for the period 2046-2065, and for the RCP2.6 scenario, an increase between 0.4ºC and 1.6ºC is expected in comparison to the reference period (1986-2005), and of 1.4ºC to 2.6ºC under the highest concentrated scenario (RCP8.5). In addition, for the period 2081-2100, and under the RCP4.5, RCP6.0 and RCP8.5, the global average surface temperature is predicted to possibly increase more than 1.5ºC in comparison to the reference period, and for the RCP8.5 scenario, in particular, even possibly exceeding a warming of 2ºC under this same scenario. The global mean surface temperatures predicted are also compared with the warming over the ocean, which is predicted to be less than that over land. Last, but not least, under the predicted above mentioned global warming, the frequency of hot and cold extreme temperatures is expected to increase throughout the 21st century, with special attention to the occurrence of heat waves and their duration.

Regarding the changes in precipitation patterns, the 5th IPCC report predicts a non-uniform trend at a global scale, as these variations would be highly spatial dependent. In one hand, on higher latitudes and over the Pacific Ocean, under a RCP8.5 scenario, the average precipitation is expected to increase between 30 and 50%, for the period 2081-2100 in comparison with the reference period 1986-2005. On the other hand, and under the same scenario, on mid-latitudes and subtropical dry regions (i.e. the Mediterranean Basin and center America) the mean annual precipitation is expected to decrease, between -30% and -10% for the period 2081-2100, and in comparison with the reference period. As regards to the mid-latitudes wet regions (i.e. Southeast Asia and central Africa), the mean annual precipitation is expected to increase with values ranging between 0 to 20% for the same period of time mentioned before. In addition, an increase in the frequency of extreme precipitation events on mid-latitudes and over wet tropical regions is also expected, due to the increase in global average temperature, as well as an increase in areas affected by the monsoon precipitation and spatial changes in the distribution of El Niño-Southern Oscillation (ENSO).

2.3.2. Europe and the Mediterranean Basin

In Europe, changes in precipitation patterns could negatively affect the water availability for agriculture, domestic and industrial uses in lowlands. In addition, an increase in mean annual temperature of 2ºC over the Alps, is expected to lead to more extreme precipitation events, according to a study done by Beniston et al. (1997b). On a study done by Barcikowska et al. (2019), simulations of the future climatic scenarios on the Mediterranean basin are represented in "Figure 10", in which a warming between 2.5 and 5ºC, for the period 2061-2099, in comparison with the reference period 1961-1999 is predicted. In particular, this warming is expected to be higher on high elevation sites, such as the Alps and the Pyrenees, with values ranging between 4.5 and 6ºC. The same study predicted a decrease in total precipitation rate, on coastal areas, in particular, highlighting a decrease between -0.8 mm/day and -1mm/day on the northern part of Spain, for the period 2061-2099 and relative to the reference period above mentioned. In addition, the contrast between the expected decrease in precipitation on the Mediterranean basin compared to an expected increase in precipitation for the central, eastern and northern parts of Europe, can be clearly observed in "Figure 10" of Barcikowska et al. (2019) study.

Nogues Bravo et al. (2008) predicted the changes in temperature and precipitation for the 21st century, on the mountains located within the Mediterranean Basin, under four future socio-economic scenarios determined by lower to higher levels of GHG emissions. The authors selected the period 1961-1990 as the reference period to study the climatic variations over time. A general warming was predicted in all situations, with different magnitudes depending on the scenario. In particular, under the RCP 8.5 scenario, and for the Pyrenees region, the temperature would increase 3.1ºC during 2040-2069, in comparison to the mean annual temperature during the reference period mentioned before. Also, an increase of 5.2ºC during the period 2070-2099, compared to the reference period, is predicted. In addition, Lopez-Moreno et al. (2014) studied the Upper Aragón River Basin, an area located on the western part of the Pyrenees, and predicted, through Regional climate models (RCMs), an increase in mean annual temperature of 1.8ºC for the period 2021-2050 relative to the period 1970-2000, with variability among various climate and land-use change scenarios. The same study predicted a decrease of 10% in mean annual precipitation for the same period of time and relative to the 1970-2000 period, with seasonality, being the reduction in precipitation of 18% during summer and of 4% during winter. Lopez-Moreno et al. (2014) also added the land-use change factor on the predictions for estimating the future water availability in the region. The study found a decrease in annual runoff of 13.8%, in a scenario of no-changes in land cover, for the period 2021-2050 in comparison to the period 1970-2000, and a decrease of 29.6% is predicted for the same series of time, under general revegetation conditions.

The mean annual and spring precipitation in the Mediterranean Basin is expected to decrease throughout the 21st century, under all socio-economic scenarios mentioned before. Amblar-Francés et al. (2020) predicted the future changes in precipitation for the 21st century, on the Pyrenees mountain range. The study predicts a very high variability of precipitation at a spatial scale, which adds to the uncertainty on the evolution of precipitation in the future. However, the study does predict a general decrease in mean annual precipitation, particularly on the western area of the Pyrenees and during the spring season, and a decrease during autumn for the northeastern part of the region. Regarding the number of wet days, Amblar-Francés et al. (2020) predicts a slight increase on the eastern part compared to the northern part of the Pyrenees.

In addition, Nogues Bravo et al. (2008) compared the variability in climate for European mountain ranges, both located inside or outside the Mediterranean Basin. The decrease in mean annual and spring precipitation throughout the 21st century is seen to be a condition for mountain ranges located within the Mediterranean Basin. Therefore, those areas are thought to be particularly sensitive to the expected climate change effects (Lionello et al. 2006).

The decrease in ice cover, glaciers and snow depth observed during the 20th century in the Pyrenean region (López-Moreno 2005; Rico et al. 2017) is expected to continue throughout the 21st century, at a local scale, as this variable also depends on other factors such as slope and elevation (Nogues Bravo et al. 2008). This decrease in snow depth might lead to less available water for the population and a negative impact to the economy and tourism in the Pyrenean valleys (López-Moreno 2005).

2.3.3. Pyrenees mountain range

The predictions for the 21st century on the Pyrenees region are represented in the study done by Amblar-Francés et al. (2020), whose results are based on the combination of global and regional climatic models, considering the “Representative Concentration Pathways (RCP)” scenarios for future global emissions, from lower to higher GHG emission levels (RCP4.5, RCP6.0, RCP8.5). The variables studied are daily maximum and minimum temperatures and daily precipitation, from 1960 to 2100, taking the period 1986-2005 as reference period. During the 21st century, this same study predicts an increase in average daily maximum temperature is predicted, for all the Pyrenean area and under all projected scenarios, in particular, the warming is expected to occur in a higher rate during the end of the century, when the temperatures will have reached values between 4.0 to 6.3ºC relative to the reference period mentioned before (1986-2005). For the mean daily minimum temperatures, an increase is also predicted throughout the century and for the entire Pyrenees region. However, the values differ from the maximum temperatures and are expected to range from 3.2 to 4.9ºC by the end of the century, relative to the reference period. Amblar-Francés et al. (2020) also mentioned that the increase in temperature would be greater during summer seasons. In addition, the study predicted a decline in the number of frost days, mostly in the western part of the Pyrenees, and an increase of heat waves on the eastern part of the Pyrenees. The study also highlighted a decrease in soil moisture throughout the 21st century, due to a combination of warmer temperatures, a decrease in precipitation events and an increase in evapotranspiration. Last, but not least, Amblar-Francés et al. (2020) predicted that the warming will be more dependent on the RCP scenario, in particular, after 2050.

2.4.Elevation effects on climate change and its mechanisms

As mentioned at the beginning of this study, mountains have an important role on water availability for the populations inhabiting those areas, as well as for downstream areas, being of great importance within the hydrological cycle. In addition, mountain ranges are key elements of the climate system as its topography modifies the atmospheric circulation patterns. Also, they host a variety of ecosystems with high biodiversity and ecological value, as well as being important in a socio-economic level (Beniston et al. 1997a). Therefore, to study how climate change is occurring on high elevation sites is of relevant importance.

The effects of climate change on high elevation started earning interest among scientists since the 1980s (Kuhn and Olefs 2020). However, the main challenge when exploring mountainous areas nowadays is the absence of weather stations located at very high elevation sites with long-term records (Beniston et al. 1997a; Tudoroiu et al. 2016), in addition to the lack of climatic monitoring on these areas (Rangwala and Miller 2012). The high elevation combined with a lack of technology were obstacles for monitoring those sites. Nowadays, there is an increase in the number of studies that explore the changes in climate, mostly focused on precipitation and temperature changes over time, on high elevation areas. Some examples from the literature are the studies carried out by Rangwala and Miller (2012) and Beniston et al. (1997a) which explore the climatic variability in mountain ranges over the world.

Rangwala and Miller (2012) wanted to answer two questions with their study: “Does climate change effects differently on mountain regions compared to lowlands?”; “Do the rates of change vary between elevations within the same mountain range?” The authors compiled a range of literature for studying the elevation-dependent warming (EDW) on the Swiss Alps, the Colorado Rocky Mountains, the Tibetan Plateau/Himalayas and the tropical Andes. Afterwards, an explanation of the mechanisms that can produce EDW was presented in “Table 2”, being those: decrease in snow/ice albedo, increase in cloud cover, increase in specific humidity, increase in aerosols content on air and increase in soil moisture. Rangwala and Miller (2012) suggested to focus on studying the changes in daily minimum and maximum temperatures per season, instead of annually, due to the seasonality of the results obtained. The authors found that the EDW varies under specific spatial and temporal conditions, as the exact location of the study site (i.e. the latitude) strongly determines the sensitiveness to specific climatic variables. This high degree of complexity is also represented in the study done by Beniston et al. (1997b) which also associates this high variability of climatic results with the topography of the study area.

As mentioned above, the specific location of the mountain range and its variety of climates will determine the climatic factors that influence the warming in different elevations. In example, Justin R. Minder (2018) focused his study on the Western US Rocky Mountains and on understanding how the decrease in snow depth and albedo can influence the EDW in mountains. In addition, the study highlighted the seasonality of the EDW signal, as also mentioned in the study done by Rangwala and Miller (2012).

In Europe, Tudoroiu et al. (2016) studied the changes in temperature over the Eastern Alps for the period 1975-2010. The authors defined the possible EDW drivers such as snow/ice cover, clouds, water vapours, aerosols content on air and soil moisture. The results showed an increase in air temperature above the subalpine coniferous forests, 1.1ºC higher than above grasslands. However, the warming rate appeared to be more remarkable on low compared to high elevation areas, as an increase of 0.15-0.27ºC/decade was found on low elevations in contrast with a 0.12-0.49ºC/decade increase at high elevations. Tudoroiu et al. (2016) thought that this negative correlation between the warming rate and the elevation could be due to the land-use change on different elevations. Thus, the abandonment of pastures led to an expansion of forests which increased the retention of heat compared with open areas like grasslands located on higher altitudes. The study concludes saying that a positive elevation-dependent warming is not universal in mountain regions, highlighting the role of forest management practices on mitigating the effects of climate change on high elevations.

The negative correlation between the warming rate and the elevation is also observed on the Tibetan Plateau with high spatial and temporal variability (Gao et al. 2018).

The topography, combined with precipitation and temperature changes, is found to play a role on explaining the changes in snow depth. For the Pyrenees region, López-Moreno (2005) found that on elevations below 2200 m asl, the changes in snow depth are mostly explained by temperature variations, and above 2200 m asl, are mainly due to changes in precipitation.

Lopez-Moreno et al. (2020) studied the changes in snowpack on the Pyrenees mountain range, over the period 1958-2017, and for elevations 1500 and 2100 m asl. The study found a spatial variability, thus on the western part the decrease in snowpack was greater compared to the eastern part of the mountain range. In addition, when looking at the Pyrenees as a whole, the mean snow depth and snow cover duration decreased at 2100 m asl, during the period before mentioned. The authors concluded by saying that a "continuous warming in the Pyrenees since the beginning of the industrial period, and particularly the sharp increase since 1955, is a major driver explaining the snow cover decline in the Pyrenees".

Buisan et al. (2015) studied the changes in the number of snow days (NSD) and the number of precipitation days (NPD) for the period 1981-2010 on the Pyrenees mountain range. The authors found that the NSD was influenced by the elevation and the distance to the sea, and the NPD only by the distance to the sea. During the 1981-2010 period, the frequency of northwest and cyclonic weather types increased in the area of study, which influenced the NSD and NPD. The areas affected by the first weather type presented a decrease in NSD and NPD, and the areas under cyclonic weather systems presented an increase in these climatic variables. In addition, Buisan et al. (2015) mentioned that the observed results and trends might vary depending on the time-series selected.

2.5. Observed impacts on forestry, ecosystems and agriculture in the Mediterranean and Pyrenees mountain range

Climatic changes impact the atmosphere, lithosphere, cryosphere, biosphere and hydrosphere (Cheng 2020). In addition, the changes in temperature could have negative socio-economic and economic impacts (El Kenawy et al. 2011)

The Pyrenees region is of ecological importance and hosts many endemic species (Amblar-Francés et al. 2020). The predicted changes in temperature and precipitation patterns on the Mediterranean Basin within the 21st century, might lead to shifts in species composition and distribution (Nogues Bravo et al. 2008). In particular, plants adapted to lower altitudes would expand to higher elevations, and replace the actual community, or even push these species towards extinction. In addition, an expansion of vegetation adapted to drier and warmer conditions is also expected to occur within the Mediterranean mountains (Nogues Bravo et al. 2008).

Begueria et al. (2003) studied how changes in temperature and precipitation could influence water runoff in the central Pyrenees area, since 1940 until 2000. The increase in temperature and decrease in precipitation might lead to changes in water run-off and discharge in rivers, due to the reduction in snow cover, glaciers and permafrost (Nogues Bravo et al. 2008). A reduction in snow depth could lead to changes in plant and animal communities as well as changes in hydrological behavior (López-Moreno 2005). In particular, a decrease in spring flows was observed during the 20th century, for the Pyrenees region (López-Moreno and García-Ruiz 2004), which could highly impact the snowmelt processes and therefore, increase the need for finding more efficient actions to manage the water resources for lowlands population (López-Moreno et al. 2002). In addition, the changes on snow cover and snow pack could negatively affect the economy of the area of study, as winter sports are one of the main touristic attractions of the Pyrenees mountain range (López-Moreno 2005).

Global warming in Mediterranean mountains could also impact social sector and reduce the ecosystem capacity to offer ecological, educational and social services. The climate change effects, combined with land-use changes, could lead to an expansion of forests on abandoned pastures and agricultural lands (Nogues Bravo et al. 2008). This expansion of forests, or secondary succession, on abandoned agricultural lands was also observed in a study done by Lasanta et al. (2017) and in a study done by Buendia et al. (2016a).

The increase in winter discharges and decrease in spring run-off due to a decrease in snow depth, could negatively influence the water availability causing an economic loss for agricultural areas located on lowlands, as well as a soil moisture deficit on mountain agricultural lands, and an urgent need for adapting the water management and dam operation systems to provide with enough water for the population (Nogues Bravo et al. 2008). On a study done by Lopez-Moreno et al. (2014) and Buendia et al. (2016a), the importance of studying the combining effects of climate change and land cover for water availability purposes, is strengthen.

Land-use changes on the Pyrenees region were also studied by Molinillo et al (1997). The authors found that most of the hillslopes facing south on this region were used for growing cereals, such as wheat and barley, and the forests were managed by controlled fire and overgrazing. The study also found a decrease in the area occupied by agricultural land on the Pyrenees region. This change was due to the abandonment of farming land and the successive expansion of forests, shrubs and grazing meadows on those areas, since the 1940s. In addition, Camarero and Gutierrez (2004) found that the tree line position and the tree abundance is also sensitive to climatic changes. The study found a decrease in the advance of the tree line, on elevation, influenced by an increase in March temperature variability. In addition, due to the recent and the predicted long-term increase in temperatures on the Pyrenees mountain range, future vegetation shifts could be observed on forests located at the edge of its species distribution range, as it is already occurring with the silver fir forests, as its growth rate is already declining (Linares and Camarero 2012).

2.6. Review of available climate data resources

Several studies used meteorological stations to identify trends in climatic data (Begueria et al. 2003; Buisan et al. 2015). Buisan et al. (2015) studied the changes in the number of snow days and the number of precipitation days in winter, for the period 1981-2010, using data from meteorological stations, and Begueria et al. (2003) used weather and gauge stations as a source for climatic data series. Buendia et al. (2016a) studied the relationship between climatic trends and water runoff, over time, using non-parametric Mann-Kendall statistic.

The land cover changes, such as the evolution of glaciers extent (Lopez-Moreno et al. 2016), can be observed using historic aerial photographs. In addition, the variation in Snow depth over time can be studied using SAFRAN-Crocus simulations, and the Snow cover duration using MODIS observations (Lopez-Moreno et al. 2020).

From the literature, the following sources for climatic data were consulted for the purpose of this study:

- Monthly variation in climate for mean temperature and precipitation for the period 1901 - 2019: Climatic Research Unit (CRU). https://data.ceda.ac.uk/badc/cru/data/cru_ts/cru_ts_4.04

- Monthly variation in climate: Global Historical Climatology Network (GHCN).
- Jay H. Lawrimore, Matthew J. Menne, Byron E. Gleason, Claude N. Williams, David B. Wuertz, Russell S. Vose, and Jared Rennie (2011): *Global Historical Climatology Network - Monthly (GHCN-M), Version 3*. [/pub/data/ghcn/v4]. NOAA National Centers for Environmental Information. http://doi.org/10.7289/V5X34VDR
- Daily changes in temperature and precipitation: European Climate Assessment & Dataset project (ECA&D). https://www.ecad.eu/dailydata/datadictionarycountry.php?i7gl8i0is3c261e2kcha7hag68
- Monthly precipitation values obtained for the period 1901-2010:
- Castellanos-Acuna, Dante, & Hamann, Andreas. (2019). *A cross-checked global monthly weather station database for precipitation covering the period 1901 to 2010*. In Geoscience Data Journal. Zenodo. https://doi.org/10.5281/zenodo.3520885

In addition, other national databases that were not found in the literature review were consulted, to provide with further data for the purpose of this study. These databases are presented in the methodology section of the project.

2.7.Climate variables quantifying water deficits

However through the development of this study a quantification of the water availability was not yet carried out, it is important to know the climatic variables that might influence water deficits in the Pyrenees mountain range, for further development of this project.

The water from the rivers of the Pyrenees mountain range is stored in reservoirs and dams built on low elevation areas and lowlands to regulate and ensure the availability of water for the population. In particular, the rivers located on the south central and south western Pyrenees provide water for the agricultural lands of the Ebro Depression, and the water stored within the reservoirs of this area represents 59% of the annual water resources for the region (Begueria et al. 2003). Therefore, to study the past changes in water yield throughout the Pyrenees region, as well as predicting future water resources in the area, could help on defining forest management practices for water yield purposes and climate change mitigation (Begueria et al. 2003; Sahin and Hall 1996).

Buendia et al. (2016a) studied the trends in hydro-climatic data for the period 1941-2009. The variables of study were precipitation, potential evapotranspiration and temperature, analyzed on an annual and monthly scale, in addition to forest cover. Also, the changes in water runoff for the period mentioned above, were also studied as a variable reflecting the water availability in the Pyrenees region.

Begueria et al. (2003) studied the changes in water yield within the area of study, since mid 20th century, taking into account the variables precipitation, interception and evapotranspiration and using the following equation:

$$\mathrm{R} = \mathrm{P} - \mathrm{ET} \ ,$$

where R is the water runoff or water yield, P is precipitation and ET is evapotranspiration, considering the water intercepted by the vegetation, as well. Other variables such as difference in soil water storage ($\Delta soil$), snowpack ($\Delta snow$) and water located underground, in aquifers ($\Delta aquifers$), between the end and the start of the hydrological cycle, could also be considered, in particular, when looking at the catchment water balance in specific months. Thus, a more complex equation would be as follows:

$$R = P - (ET + \Delta soil + \Delta snow + \Delta aquifers)$$

In addition to the previous climatic variables, the land cover and land-use changes need to be taken into account when studying the changes in water yield within the Pyrenees region (Begueria et al. 2003; Buisan et al. 2015). Begueria et al. (2003) suggested to observe the monthly changes in precipitation and temperature and see if there is a relationship with water runoff. Therefore, depending on these observations, other non-climatic variables, such as land-use changes or % of forest cover might have an effect on the water yield of the area of study.

Last, but not least, a study done by Yang et al. (2014) on the Tibetan Plateau, also considered the heat exchange between the land surface and the different layers of the atmosphere, as well as the albedo due to the snow cover and deepness and the cloud coverage, as variables ruling the temperature variability over time.

As mentioned at the beginning of this section, to achieve the main objective of this study, climatic variables such as evapotranspiration should also be considered in combination with the observed climatic trends, for predicting future water availability for the population.

3. Methods

3.1.Area of study

The Pyrenees mountain range is located in southwestern Europe, delimiting Spain and France, with Andorra being located within this region (Fig 1). As mentioned on the introductory part of this study, the mountains range from 500m asl to more than 3000m asl, with the highest mountains located on the central part of the region (Fig 2). In addition, the Pyrenees host a dense river network, which can also be observed in Figure 2. The hydrological system is grouped into four main watersheds – the Adour-Garonne and the Rhone-Mediterranean, in France; the Ebro and the internal basins of Catalonia, in Spain –. As can be observed in Figure 3 a, the Spanish basins and the Rhone-Mediterranean basin supply water to lowland areas until reaching the Mediterranean Sea. However, the Adour-Garonne basin is the only watershed of the study that descends to the Atlantic Ocean. In addition, this watershed and the Ebro watershed seem to supply the largest amount of water for the population located on lowland areas. Considering that the Pyrenees cross several administrative boundaries, and following the four main basins supplying water to the northern parts of Spain, Andorra and the southern parts of France, six regions are delimited for the purpose of this study – Eastern and Western Pyrenees, Northwest and Northeast lowlands in France, and Southwest and Southeast lowlands in Spain (Fig 3 b). In other words, this study aims to provide information on climatic trends within the above mentioned regions, for further analysis in water availability for the provinces located within these regions, being that Catalonia, Aragon, Navarra, La Rioja, Castilla y Leon, Euskadi and Cantabria, in Spain; and regions of Languedoc-Rousillon, Midi-Pyrenees and Aquitane, in France.

Figure 1. Hillshade map of the area of study. The Pyrenees mountain range is delimited with an orange line. Map created using QGIS and using a shapefile with the delineation of the Pyrenees mountain range, obtained from the Pyrenean Observatory of Climate Change (https://www.opcc-ctp.org/en/geoportal)

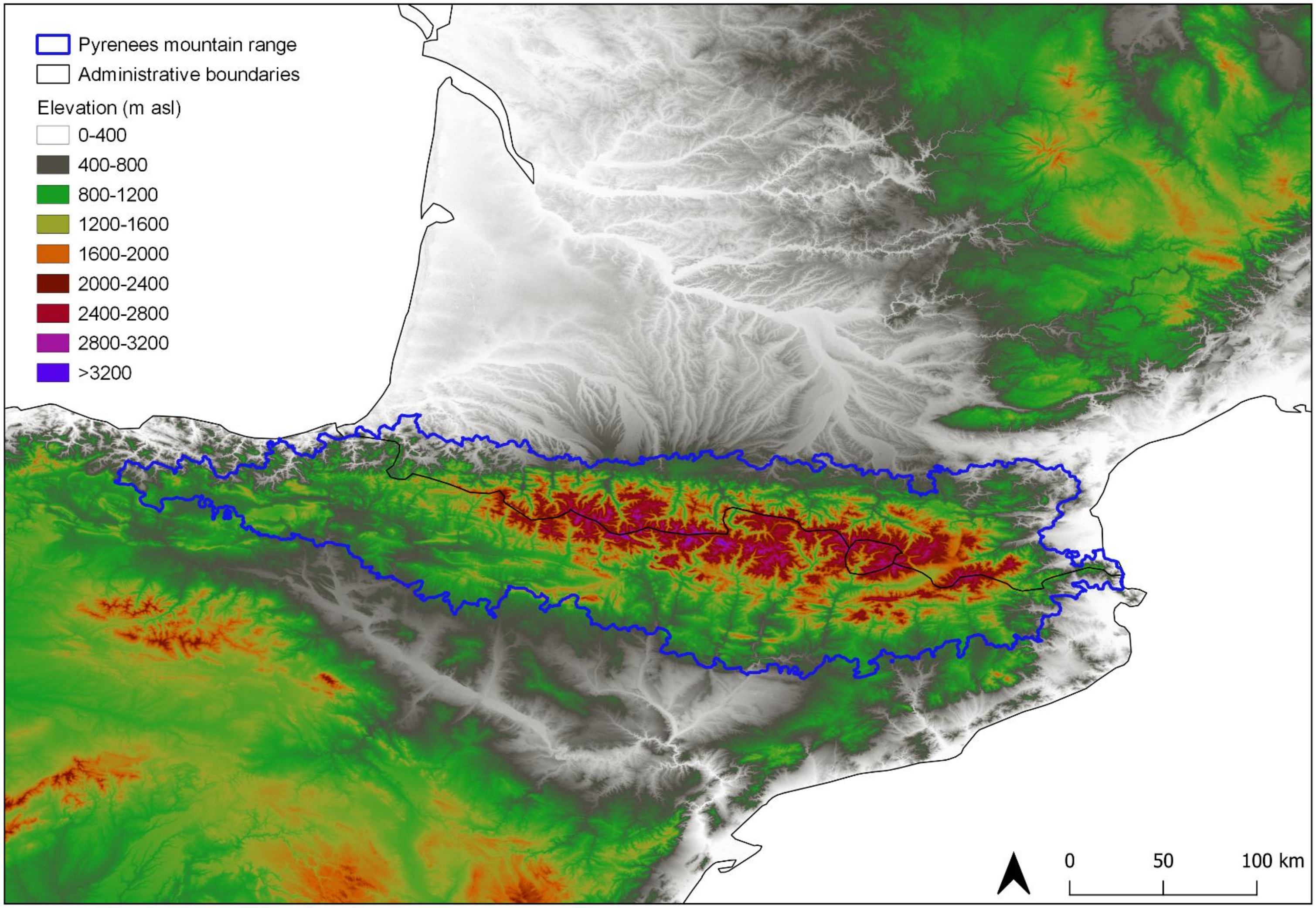

Figure 2. DEM of the area of study with the elevation values. Map created with QGIS, using a shapefile with the delineation of the Pyrenees mountain range obtained from the Pyrenean Observatory of Climate Change (https://www.opcc-ctp.org/en/geoportal), and a DEM obtained from the NASA's Earth Observing System Data and Information System (EOSDIS) (https://earthdata.nasa.gov/)

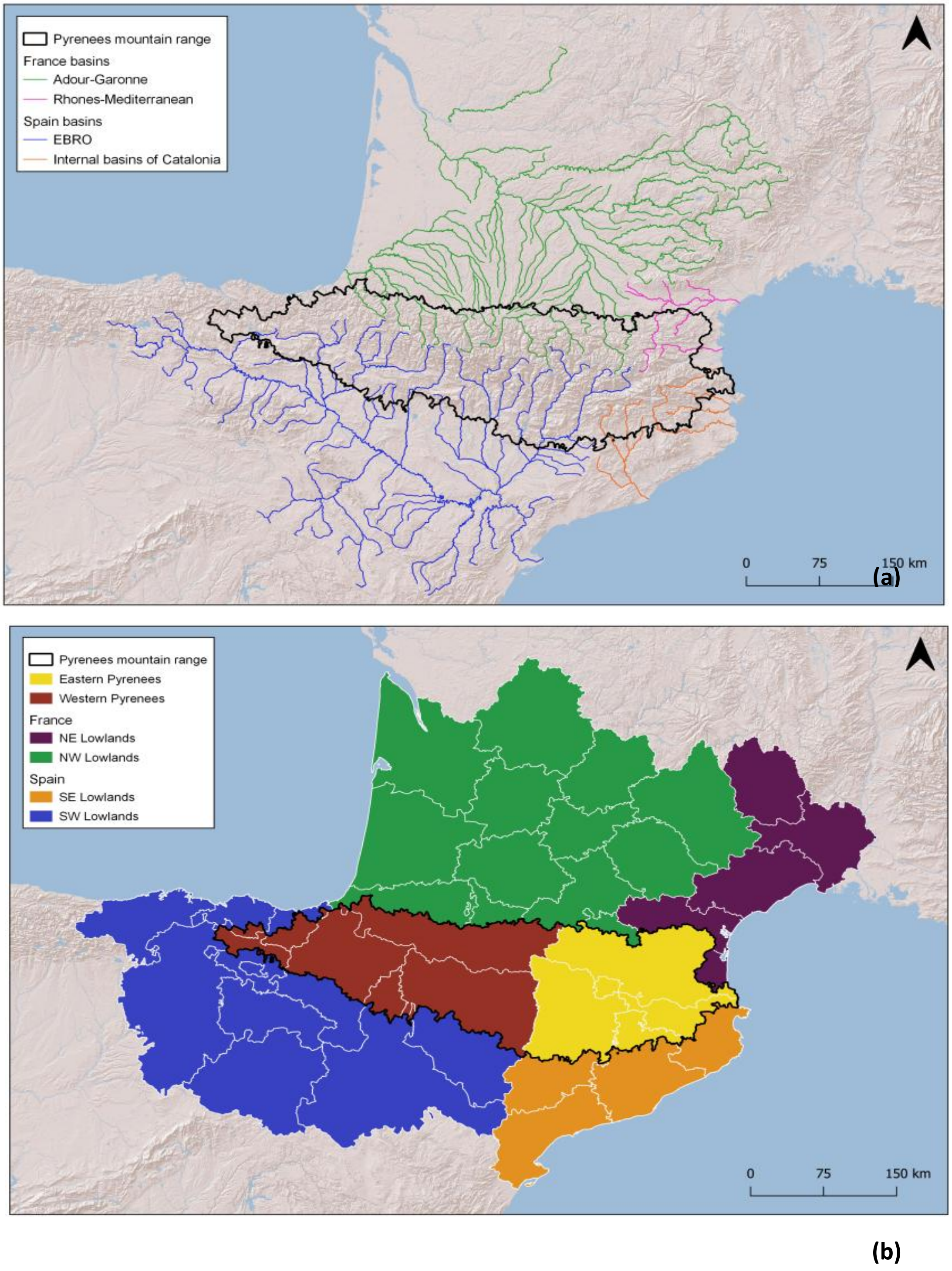

Figure 3. Main watersheds within the Pyrenees mountain range and lowland areas (a) and delineation of the six regions of the study, considering the main water basins (b). Map created using QGIS and shapefiles with the delineation of the Pyrenees mountain range obtained from the Pyrenean Observatory of Climate Change (https://www.opcc-ctp.org/en/geoportal), and of the river network obtained from the Europe Environment Agency open database (https://www.eea.europa.eu/data-and-maps/data/european-river-catchments-1)

3.2.Collection of climatic data

The climatic data was collected from meteorological stations located on the Pyrenees mountain range and lowland areas, and within the six regions of the study. The mean annual precipitation, mean annual maximum and mean annual minimum temperatures were calculated using monthly data from global, European and national databases with online open data access. The longest time series available per station was used. In Figure 4, the location of the precipitation (Fig 4 a) and temperature (Fig 4 b) stations used for this study is visually represented on a map, organized per length of data, in years.

As can be observed in Figure 4, the location and quantity of stations varied depending on the climatic variable studied. Particularly, for evaluating the changes in mean annual precipitation over time the information from 468 stations was collected, in comparison to the 292 stations used for studying possible trends in maximum and minimum temperature on the area of study. In addition, the sources of data varied depending on the variable studied.

The period 1901 – 2021 was covered for precipitation and temperature and for the six regions of the study, through the collection of weather stations records from the following databases:

- Monthly mean precipitation values for Spain, France and Andorra, and for the period 1901-2010: Castellanos-Acuna, Dante, & Hamann, Andreas. (2019). *A cross-checked global monthly weather station database for precipitation covering the period 1901 to 2010*. In Geoscience Data Journal. Zenodo. https://doi.org/10.5281/zenodo.3520885.
- The meteorological stations used for the creation of this database belong to the Climatic Research Unit (CRU), the European Climate Assessment & Dataset project (ECA&D), the Global Historical Climatology Network (GHCN) and the Food and Agriculture Organization (FAO).

- Daily changes in maximum and minimum temperature for Spain, France and Andorra, obtained from the Global Historical Climatology Network (GHCN&D) (https://www.ncei.noaa.gov/products/land-based-station/global-historical-climatology-network-daily), and from the European Climate Assessment & Dataset project (ECA&D) (https://www.ecad.eu/dailydata/datadictionarycountry.php?i7gl8i0is3c261e2kcha7hag68)

- Daily precipitation, daily maximum and minimum temperature values for the Navarra Region, located on the northwest of Spain, obtained from the regional government meteorological site in collaboration with the State Meteorological Agency of Spain (AEMET) - http://meteo.navarra.es/estaciones/descargardatos.cfm
- Monthly mean precipitation, maximum and minimum temperature values for Catalonia Region, located on the northeast of Spain, for the period 1950-2020. Obtained from the regional Meteorological Service (Meteo.cat) (https://www.meteo.cat/wpweb/climatologia/serveis-i-dades-climatiques/series-climatiques-historiques/)

The distribution of meteorological stations varied along the six regions of the study, with the highest number of stations located on the Southeast lowlands (SE-Lowlands), with 252 stations for precipitation (Table 1), and 155 stations for temperature (Table 2), and the lowest on the Northeast lowlands (NE-Lowlands), with 19 stations for precipitation (Table 1) and 5 for temperature (Table 2). In general, the amount of meteorological stations was higher in Spain than in France due to a lack of available climatic data on the northern lowlands for the period of study.

In addition, the distribution of stations varied along different elevations, with the highest station being located on the Eastern Pyrenees (E-Pyrenees), at 2535 m asl, and the lowest on the SE-Lowlands, at 1m asl. In general, as can be observed in Table 1 and 2, more available climatic data was found on high elevation areas on the E-Pyrenees, in comparison to the Western part of the mountain range. Also, the quantity of stations as well as the length of recorded data was higher in low compared to high elevation areas (Table 1, 2 and Fig 4).

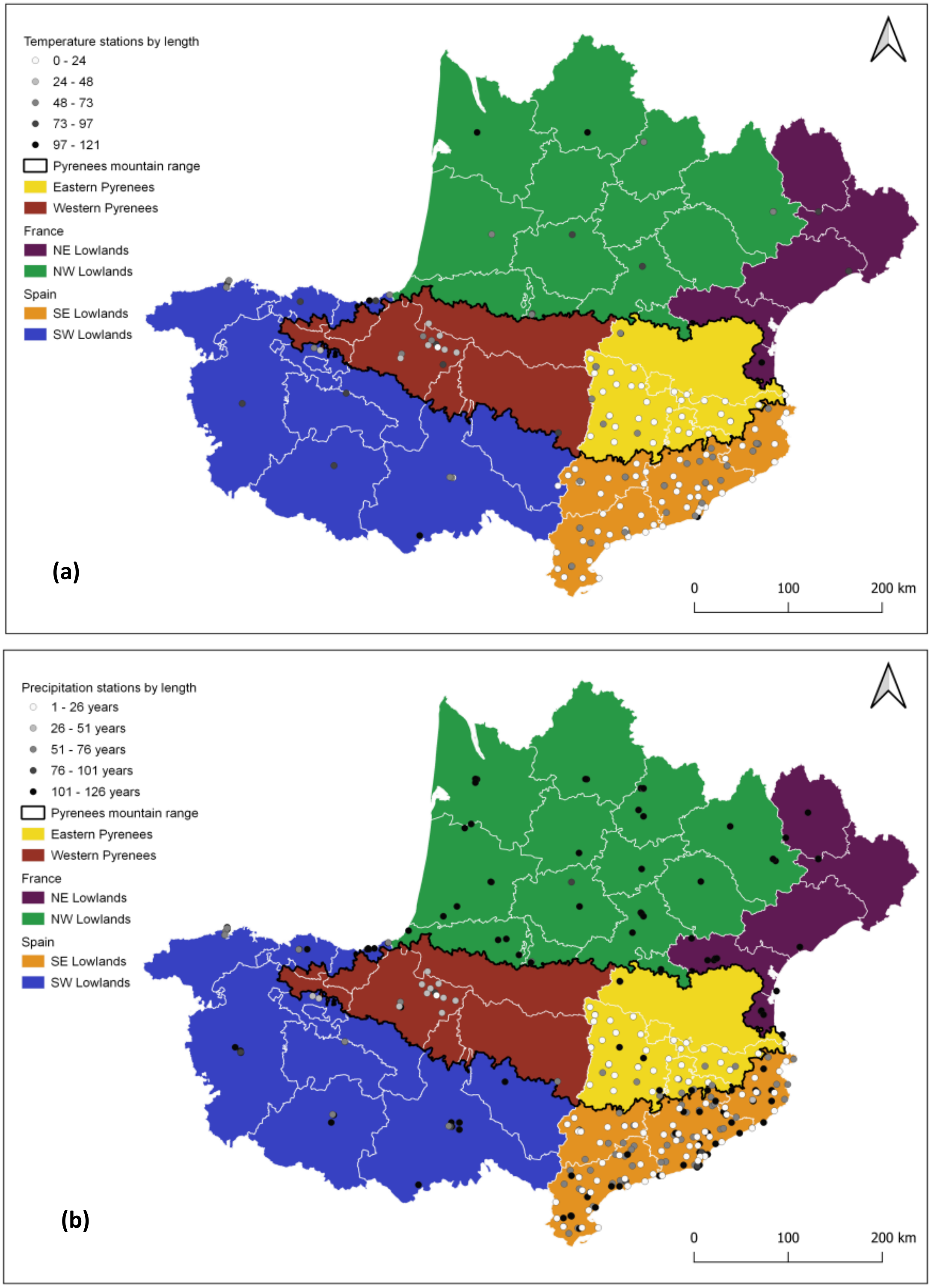

Figure 4. Location of the meteorological stations used in this study divided by length of available climatic data. The top figure represents the stations from which the monthly precipitation data was obtained (a) and the bottom figure represents the ones from which the maximum and minimum temperature data were obtained (b).

Table 1. Basic station statistics for mean annual precipitation (PRCP).

Distribution per region		Distribution of elevation (m asl)					
Region	N. of stations	Min	1st Qu.	Median	Mean	3rd Qu.	Max.
NE-Lowlands	19	15	44.5	128	357.9	314.5	1567
E-Pyrenees	85	82	566	823	1129	1971	2535
SE-Lowlands	252	1	46.25	176	276	399	1712
NW-Lowlands	46	12	59.5	152.5	248.9	299.2	932
W-Pyrenees	22	16	442	541	522.2	699.5	1050
SW-Lowlands	44	4	67.25	259	407.5	779	1082
Total	468	1	72	286	455.5	598	2535

Table 2. Basic station statistics for mean annual maximum (TMAX) and minimum temperatures (TMIN).

Distribution per region		Distribution of elevation (m asl)					
Region	N. of stations	Min	1st Qu.	Median	Mean	3rd Qu.	Max.
NE-Lowlands	5	2	2	42	331	42	1567
E-Pyrenees	77	158	433	849	1118	2143	2535
SE-Lowlands	155	1	56	179	306.1	421	1971
NW-Lowlands	13	47	61.9	260	301.9	384	720
W-Pyrenees	16	42	454.8	617	608.6	747	1050
SW-Lowlands	26	4	64	257	387.3	521	1082
Total	292	1	98	341	545.4	738	2535

4. Results and discussion

Considering that the Mediterranean basin is one of the most sensitive areas to climate change in the world (Barcikowska et al. 2020; Lionello et al. 2006; López-Moreno et al. 2011) the understanding of past climatic trends is very important for future climate and water availability predictions. As mentioned in previous studies (El Kenawy et al. 2011; Nogues Bravo et al. 2008; Serrano-Notivoli et al. 2019a), an increase in mean annual temperature and a slight decrease in mean annual precipitation is expected in this area for the 21st century, as well as more frequent extreme weather events, such as floods and droughts (Hov et al. 2013; Lionello et al. 2006). However, these predictions may vary at a regional or local scale because of the complexity of factors that might influence the weather, such as atmospheric circulation patterns and topography (Lionello et al. 2006). Therefore, these variables should be taken into account when analyzing the past climatic trends as well as for estimating the future climate on the Mediterranean Basin.

For the purpose of this study, the variability in mean annual precipitation, mean annual maximum and minimum temperatures was studied for the period 1901-2021, and for the six regions of the study. First of all, the data was visually represented in plots divided per region to visually identify climatic trends occurred during the 20th century until nowadays (Fig 5). Secondly, only the Eastern and Western Pyrenees regions were selected to study the weather variability among different elevations (Fig 6). Last, but not least, to test for significance, a linear regression model was applied to all of the above mentioned plots and for the period 1950-2021, to analyze the most recent trends (Tables 3, 5 and 8). In addition, the regression model was also carried out per region and by season, to observe any possible seasonality in the data (Table 4, 6 and 7).

4.1.Climatic evolution per region

4.1.1. Trends in mean annual precipitation

The mean annual precipitation presents a high inter-annual variability for all the period studied and for all six regions. As can be observed in Figure 5, all the regions seemed to follow the same pattern of changes in precipitation, however the Western Pyrenees (W-Pyrenees) showed the highest precipitation values, ranging from 1280 mm/year to 2265 mm/year, probably due to its proximity with the Atlantic Ocean and the influence of the atmospheric circulation patterns such as the North Atlantic Oscillation (NAO) and the ENSO, as was previously studied by (Lionello et al. 2006). The other regions have similar mean annual precipitation values ranging from 400 mm/year to 1300 mm/year, being the SE-Lowlands the driest region in the study with values ranging between 400 mm/year and 950 mm/year. In addition, on Figure 5, a slight decrease in precipitation can be visually recognized from 1975 onwards for the regions Northeast, Northwest and Southwest lowlands (NE, NW & SW-Lowlands).

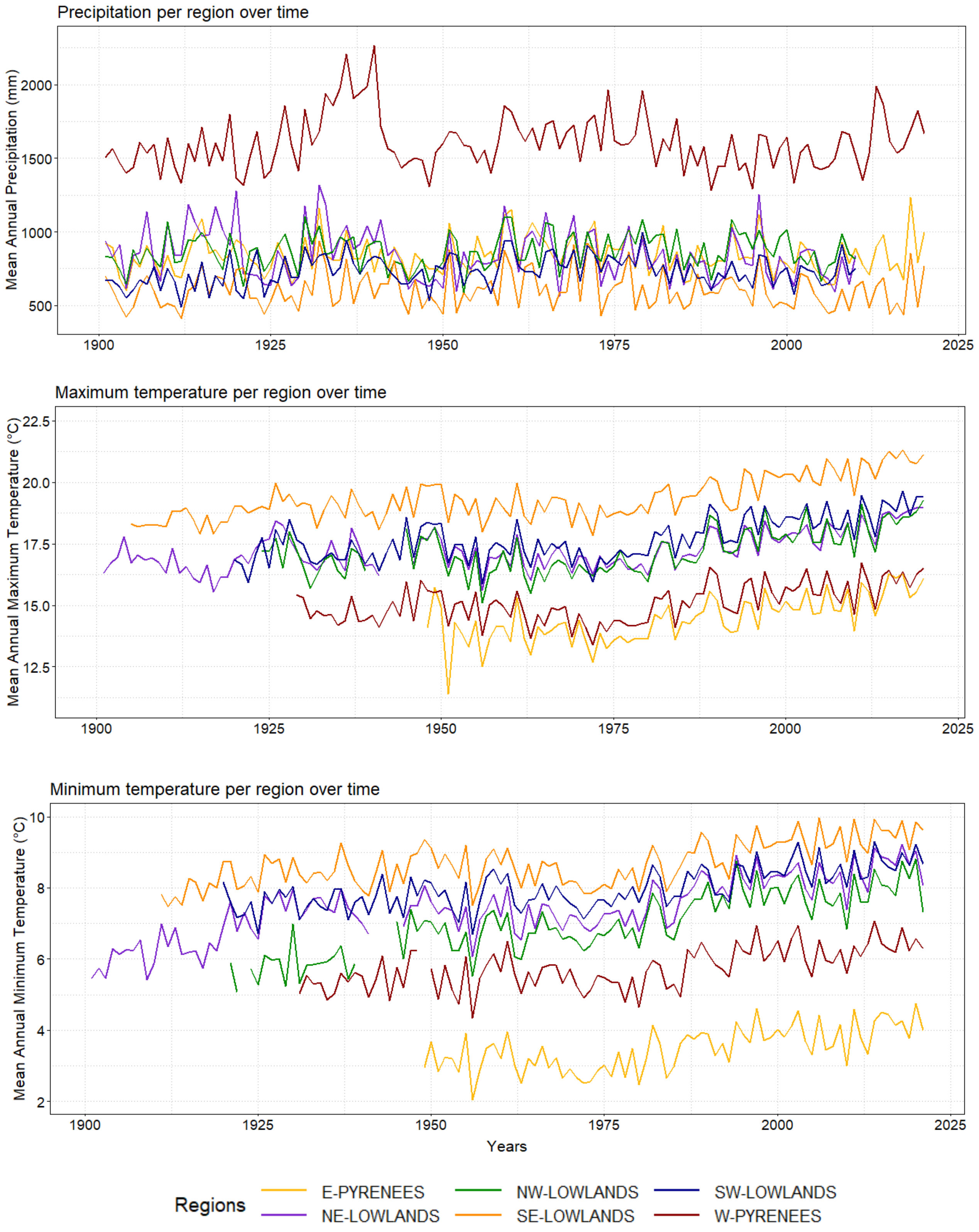

Figure 5. From top to bottom: Changes in mean annual precipitation, mean annual maximum and minimum temperatures over the period 1901-2021, divided by region.

To determine the consistency of these results, a statistical linear regression model was applied for the period 1950-2021 and for the six regions of the study. The results are presented in Table 3. As can be observed, all regions present adjusted p-values >0.05 which means that the climatic trends that might be visually identified in Figure 5 are not statistically significant. However, the tendency, slope or rate of change, in precipitation over time was obtained for each region and needs to be considered for the purpose of this study. These values suggested an increase in mean annual precipitation from 1950 to 2021 for the regions E-Pyrenees, NW and SW-Lowlands, being that of 1.34mm/decade, 4.2mm/decade and 6.51mm/decade, respectively. In contrast, Table 3 shows a decrease in precipitation for the regions W-Pyrenees, NE and SE-Lowlands, with slopes of -0.53mm/decade, -13.21mm/decade and -0.63mm/decade, respectively. These findings reflect the no long-term trends found in a study done by Begueria et al. (2003), as well as the high variability in precipitation between regions. In addition, as the precipitation is expected to continue decreasing throughout the 21st century in this area (Nogues Bravo et al. 2008), it makes it more sensitive to climate change. However, to deeply understand how mean annual precipitation has been changing and will change over time, taking into consideration that this variable is local-dependent, other factors such as the atmospheric circulation patterns, before mentioned in a study done by Lionello et al. (2006), the topography of the area of study, and the land-use changes (Lopez-Moreno et al. 2014) should be added into the equation.

In addition to the previous results, by looking at Table 3, from 1950 to 2021, a decrease of precipitation occurred on the eastern lowland regions (SE and NE-Lowlands) compared to the western lowlands (NW and SW-Lowlands) which experienced an increase in mean annual precipitation. This difference could occur due to an influence of a Mediterranean climate on the eastern lowlands, which is drier in contrast to the western lowlands, which are influenced by the humid Atlantic climate and the atmospheric circulation patterns associated with it (Amblar-Francés et al. 2020).

Table 4 shows the results of the linear regression model applied in all six regions of the study by season (Winter, Spring, Summer and Autumn). As mentioned in the introductory part of this research, the mean annual precipitation presents a high inter-annual variability (Begueria et al. 2003; López-Moreno 2005). However, it also presents intra-annual variability as it changes between seasons of the year, as can be observed in Table 4. However the trends observed are not statistically significant (adjusted p-values >0.05), a general decrease in mean annual precipitation for the region NE-Lowlands can be observed during all seasons, and for the period 1950-2021, being this decrease more pronounced during the autumn season (-6.07mm/decade). Continuing the before mentioned difference between the eastern and the western regions, in Table 4 the SE-Lowlands mean annual precipitation also decreased but only during winter and summer seasons. However, the precipitation patterns on the E-Pyrenees region slightly increased during the period of the study, with the biggest increase occurring during winter and spring seasons, with values of 0.41mm/decade and 0.51mm/decade, respectively. This difference in precipitation could be due to the topography of the region in contrast with the stations located on lower elevation areas.

Table 3. Linear regression statistics for mean annual precipitation (PRCP), by region

Region	Adjusted p-value	Slope (mm/decade)
NE-Lowlands	0.063	-13.21
E-Pyrenees	1	1.34
SE-Lowlands	1	-0.63
NW-Lowlands	0.953	4.2
W-Pyrenees	1	-0.53
SW-Lowlands	0.158	6.51

Table 4. Linear regression statistics for mean annual precipitation (PRCP) per region, and by season.

	Winter (DJF)		**Spring (MAM)**		**Summer (JJA)**		**Autumn (SON)**	
Region	Adjusted p-value	Slope (mm/decade)	Adjusted p-value	Slope (mm/decade)	Adjusted p-value	Slope (mm/decade)	Adjusted p-value	Slope (mm/decade)
NE-Lowlands	1	-0.03	0.554	-3.77	0.136	-3.34	0.298	-6.07
E-Pyrenees	1	0.41	1	0.51	1	0.15	1	0.34
SE-Lowlands	1	-0.44	1	0.19	1	-0.75	1	0.37
NW-Lowlands	0.993	2.21	1	1.14	1	-0.33	1	1.18
W-Pyrenees	0.956	3.2	1	-1.23	1	-0.46	1	-1.33
SW-Lowlands	0.956	2.16	0.784	2.04	1	1.13	1	1.18

4.1.2. Trends in mean annual maximum and minimum temperatures

Mean annual maximum (TMAX) and minimum temperatures (TMIN) also showed inter-annual variability with similar patterns between regions. As can be observed in Figure 5, the annual temperature values vary depending on the region. For the maximum temperatures, the higher values occurred on the SE-Lowlands, with mean annual values ranging from 17.84 to 21.31ºC, followed by the lowlands located in France (NE and NW-Lowlands) and the SW-Lowlands, with values ranging from 15.10 to 19.63ºC. Last, the Western and Eastern Pyrenees (W and E-Pyrenees) had the least mean annual maximum temperature values over time, ranging from 11.4 to 16.29ºC for the E-Pyrenees, and from 13.4 to 16.74ºC for the W-Pyrenees.

As regards to the minimum temperatures, all regions followed similar patterns over time but with a higher difference in mean values between the W and the E-Pyrenees, in comparison to the TMAX trends commented before. Like previously observed on the TMAX plot, the SE-Lowlands represented the warmest area in the study, also when looking at TMIN values, ranging from 7.48 to 9.97ºC. The SE-Lowlands is followed by the SW-Lowlands, NE-Lowlands and NW-Lowlands, respectively, with values ranging from 5.07 to 9.30ºC. Last, the Pyrenees area showed the lowest TMIN, being the E-Pyrenees the coldest region in the study with values ranging from 2.04 to 4.76ºC, and 4.35 to 7.07ºC for the W-Pyrenees region.

In Figure 5 an increase in TMAX and TMIN from 1975 onwards, approximately, can be visually identified. After pursuing a linear regression model for the period 1950-2021, the adjusted p-values obtained for all the regions are smaller than 0.05, which determines a strong significance to the observed increase in maximum and minimum temperatures (Table 5).The TMAX on the E-Pyrenees increased 0.3ºC/decade, which is the highest warming rate compared to other regions. Followed by the SW, SE and NW-Lowlands with an increase in TMAX of 0.19, 0.18

and 0.18ºC/decade, respectively. Last, the W-Pyrenees, with an increase of 0.15ºC/decade and the NE-Lowlands at a rate of 0.12ºC/decade. As regards to the minimum temperature, the NW and NE-Lowlands showed the most significant increase with values of 0.25 and 0.19ºC/decade, respectively, followed by the E-Pyrenees with an increase of 0.18ºC/decade. Last, the SW and SE-Lowlands with increases of 0.13ºC/decade, and the W-Pyrenees region with values of 0.12ºC/decade.

Table 5. Linear regression statistics for mean annual maximum (TMAX) and minimum temperature (TMIN), by region.

	TMAX			**TMIN**		
Region	Adjusted p-value		Slope (ºC/decade)	Adjusted p-value		Slope (ºC/decade)
NE-Lowlands	5.7E-10	***	0.12	2.21E-24	***	0.19
E-Pyrenees	6E-10	***	0.30	4.18E-09	***	0.18
SE-Lowlands	1.9E-19	***	0.18	6.36E-14	***	0.13
NW-Lowlands	2.0E-08	***	0.18	2.21E-24	***	0.25
W-Pyrenees	4.0E-08	***	0.15	4.18E-09	***	0.12
SW-Lowlands	4.1E-13	***	0.19	1.55E-13	***	0.13

The asterisk identifies the p-values that are significant at the 0.05 level. **Note: *** p<0.001 ; ** p<0.01 ; *p<0.05**

The trends in TMAX and TMIN for the period 1950-2021 were also studied by season. A linear regression model was applied for all the regions and the results represented in Tables 6 and 7. As can be observed in Table 6, the maximum temperature increased in all regions for the period of study, in particular during the summer season. The E-Pyrenees region showed the highest increase in TMAX with a rate of 0.45ºC/decade during summer. In contrast, however the TMAX also increased in the W-Pyrenees region, the warming rate was not as high as in the E-Pyrenees. The SW-Lowlands also showed an increase in TMAX, particularly during summer, with a warming of 0.2ºC/decade during this season and from 1950 to 2021. These findings coincide with those in a study done by El Kenawy et al. (2011), who found an increase in TMAX over the

Pyrenees, in particular during spring and summer seasons, and for the period 1920-2006. However, in our study, this only applies for the E-Pyrenees region, as the TMAX increased more during winter and summer for the W-Pyrenees region.

The TMIN values in all regions also increased for the period of study and the trends are statistically significant for all the regions (adjusted p-value >0.05 ; Table 7). The minimum temperature particularly increased in the NW-Lowlands for the period 1950-2021. As can be observed in Table 7, the warmest season of the year hosted the larger increase in TMIN values for all the regions, with a warming rate of 0.34ºC/decade occurred in the NW-Lowlands. In addition, the TMIN increased at a higher rate on the E-Pyrenees, being that of 0.23ºC/decade in summer, in comparison to the W-Pyrenees, where increased at a rate of 0.14ºC/decade in summer. This finding coincide with the previous results on TMAX, shown in Table 6. In addition, our findings differ from those from El Kenawy et al. (2011), who found a higher rate of increase in TMIN compared to TMAX, particularly during the months of summer and spring for the Pyrenees mountain range, and for the period 1920-2006. In our study, the TMIN showed a higher increase during winter and summer on the E and W-Pyrenees regions, and the TMAX increased at a higher rate than the TMIN for the period 1950-2021, for both regions.

Taking into consideration that, as explained in the previous section, the west of the area of study is more humid than the east, the observed changes in TMAX and TMIN during the 20th century could help on defining the areas at risk of water scarcity in the future. The eastern regions, in particular the SE-Lowlands, showed the highest values in maximum and minimum temperatures throughout the period 1950-2021 (Figure 5) compared to the other regions of the study. This finding, combined with an increase in TMAX and TMIN of 0.18 and 0.13ºC/decade, respectively, and a decrease in PRCP of -0.63mm/decade during the period 1950-2021, could bring uncertainty on the future water availability in the SE-Lowlands. Also, the PRCP decreased on the NE-Lowlands at a rate of -13.21 mm/decade, where the TMAX and TMIN increased (0.12 and 0.19ºC/decade, respectively). Therefore, this region could also suffer from water scarcity in the future, in particular during summer when the TMAX and TMIN showed higher warming rates. The E-Pyrenees did not experience a decrease in precipitation during the 20th century, however, the TMAX significantly increased in this area, at a rate of 0.30ºC/decade, particularly during the summer months. As shown in Table 7, the same applies for TMIN on the E-Pyrenees. As mentioned before, the PRCP did not decrease in this region, however, the increase in temperature combined with land use changes, and other factors such as topography, could also help on forecasting the future water availability in the area and on adjacent lowlands.

As regards to the western regions of the study (W-Pyrenees, SW and NW-Lowlands), the TMAX and TMIN showed the least increase by decade on the W-Pyrenees, however mean annual precipitation decreased in the area. This trend is not statistically significant but should be taken into account for foreseeing the future water yield for the population. The PRCP did not decrease on the SW and NW-Lowlands, however the TMIN significantly increased at a higher rate on the NW, in particular during summer (0.25ºC/decade) for the period 1950-2021.

Table 6. Linear regression statistics for mean annual maximum temperature (TMAX) per region, and by season.

	Winter (DJF)			**Spring (MAM)**			**Summer (JJA)**			**Autumn (SON)**		
Region	Adjusted p-value		Slope (ºC/decade)	Adjusted p-value		Slope (ºC/decade)	Adjusted p-value		Slope (ºC/decade)	Adjusted p-value		Slope (ºC/decade)
NE-Lowlands	6.2E-05	***	0.12	5.7E-03	**	0.08	1.0E-05	***	0.14	2.3E-06	***	0.13
E-Pyrenees	4.5E-04	***	0.23	1.2E-04	***	0.3	3.4E-08	***	0.45	1.3E-03	**	0.2
SE-Lowlands	1.2E-08	***	0.16	1.1E-02	*	0.17	3.0E-12	***	0.22	6.4E-10	***	0.17
NW-Lowlands	3.1E-04	***	0.18	2.8E-03	**	0.16	5.7E-05	***	0.22	9.1E-04	***	0.15
W-Pyrenees	1.3E-04	***	0.17	1.1E-02	*	0.12	5.9E-05	***	0.17	1.3E-03	**	0.14
SW-Lowlands	3.5E-07	***	0.19	1.2E-04	***	0.18	2.9E-08	***	0.22	4.3E-06	***	0.18

Table 7. Linear regression statistics for mean annual minimum temperature (TMIN) per region, and by season.

	Winter (DJF)			**Spring (MAM)**			**Summer (JJA)**			**Autumn (SON)**		
Region	Adjusted p-value		Slope (ºC/decade)	Adjusted p-value		Slope (ºC/decade)	Adjusted p-value		Slope (ºC/decade)	Adjusted p-value		Slope (ºC/decade)
NE-Lowlands	2.0E-06	***	0.14	2.1E-12	***	0.16	3.1E-20	***	0.25	6.3E-13	***	0.2
E-Pyrenees	4.8E-03	**	0.17	6.9E-04	***	0.16	3.3E-07	***	0.23	6.5E-04	***	0.16
SE-Lowlands	2.0E-06	***	0.14	1.7E-04	***	0.09	1.1E-09	***	0.16	5.3E-05	***	0.11
NW-Lowlands	1.1E-05	***	0.2	2.1E-12	***	0.25	3.2E-21	***	0.34	6.8E-10	***	0.23
W-Pyrenees	4.3E-04	***	0.15	2.4E-02	*	0.07	9.6E-07	***	0.14	2.9E-04	***	0.11
SW-Lowlands	4.3E-04	***	0.12	9.4E-04	***	0.09	7.3E-11	***	0.17	4.0E-06	***	0.13

Applicable to the above tables: The asterisk identifies the p-values that are significant at the 0.05 level. **Note: *** p<0.001 ; ** p<0.01 ; *p<0.05**

4.2. Climatic evolution per elevation

In addition to the study of the regional climatic trends, the same analysis was carried out for two different elevation levels within the Pyrenees mountain range. For this purpose, only the meteorological stations located within the Pyrenees were selected. From these stations, 50% were considered to be located on low elevation areas and 50% on high elevation areas, with different elevation values for precipitation and temperature. The weather variability for different elevations within the Pyrenees is represented in Figure 6. The periods of time represented are 1901-2021 for precipitation, and 1940-2021 for maximum and minimum temperature.

Like it was observed on the analysis of climatic trends per region, the mean annual precipitation also showed a high inter-annual variability within the Pyrenees mountain range, with values ranging from 600mm to 1283mm/year for low elevation areas, and from 1168mm to 1960mm/year for high elevation areas. In addition, a slight decrease in mean annual precipitation can be visually percieved from 1950 onwards for low elevation areas, in particular (Fig 6). As regards to the changes in temperature over time, the TMAX values were different depending on the altitude with values ranging from 14.8 to 19.4ºC for low elevation areas, and from 7.8 to 11.7ºC for high elevation areas. The same occurred for the TMIN, with values ranging from 4.5 to 7.08ºC for low elevation areas and from -0.08 to 3.0ºC for high elevation areas. In addition, an increase trend can be visually identified from 1980 onwards, approximately, for both maximum and minimum temperature plots (Fig 6).

A linear regression model was also implemented to test for significance in the observed trends, and for the period 1950-2021. As can be observed in Table 8, there is no statistically significant decrease in precipitation for both low and high elevation areas, as the adjusted p-values are larger than 0.05. However, a decreasing can be observed in Figure 6 for both elevation levels, as well as their regression slopes represented in Table 8. In particular, PRCP decreased on high elevation areas at a rate of -10.98mm/decade, in comparison to low elevation areas (-3.17mm/decade). A significant increase in TMAX can be observed in both elevation levels, with a higher rate of increase above the 850m asl (0.3ºC/decade) compared to lower areas (0.21ºC/decade). This dynamic applies also for the TMIN values, which significantly increased from 1950 to 2021, at a rate of 0.22ºC/decade for high elevation areas and 0.17ºC/decade on low elevation areas. Nogues Bravo et al. (2008) found an increase in mean annual temperature on the Pyrenees at a rate of 0.9ºC/decade, during the 20th century. As mentioned on the previous section of the study, when analyzing the climatic trends per region, the findings of this study differ from those in El Kenawy et al. (2011) study, as the TMAX warming rate on the Pyrenees was higher than the TMIN warming rate for the period 1950-2021.

Table 8: Linear regression statistics per region and by elevation levels. (**Note: *** p<0.001 ; ** p<0.01 ; *p<0.05)**

	PRCP (>or< 810m asl)		**TMAX** (>or< 850m asl)			**TMIN** (>or< 850m asl)		
Elevation	Adjusted p-value	Slope (mm/decade)	Adjusted p-value		Slope (ºC/decade)	Adjusted p-value		Slope (ºC/decade)
High	0.295	-10.98	2.9E-09	***	0.3	9.1E-09	***	0.22
Low	0.387	-3.17	2.4E-06	***	0.21	7.0E-10	***	0.17

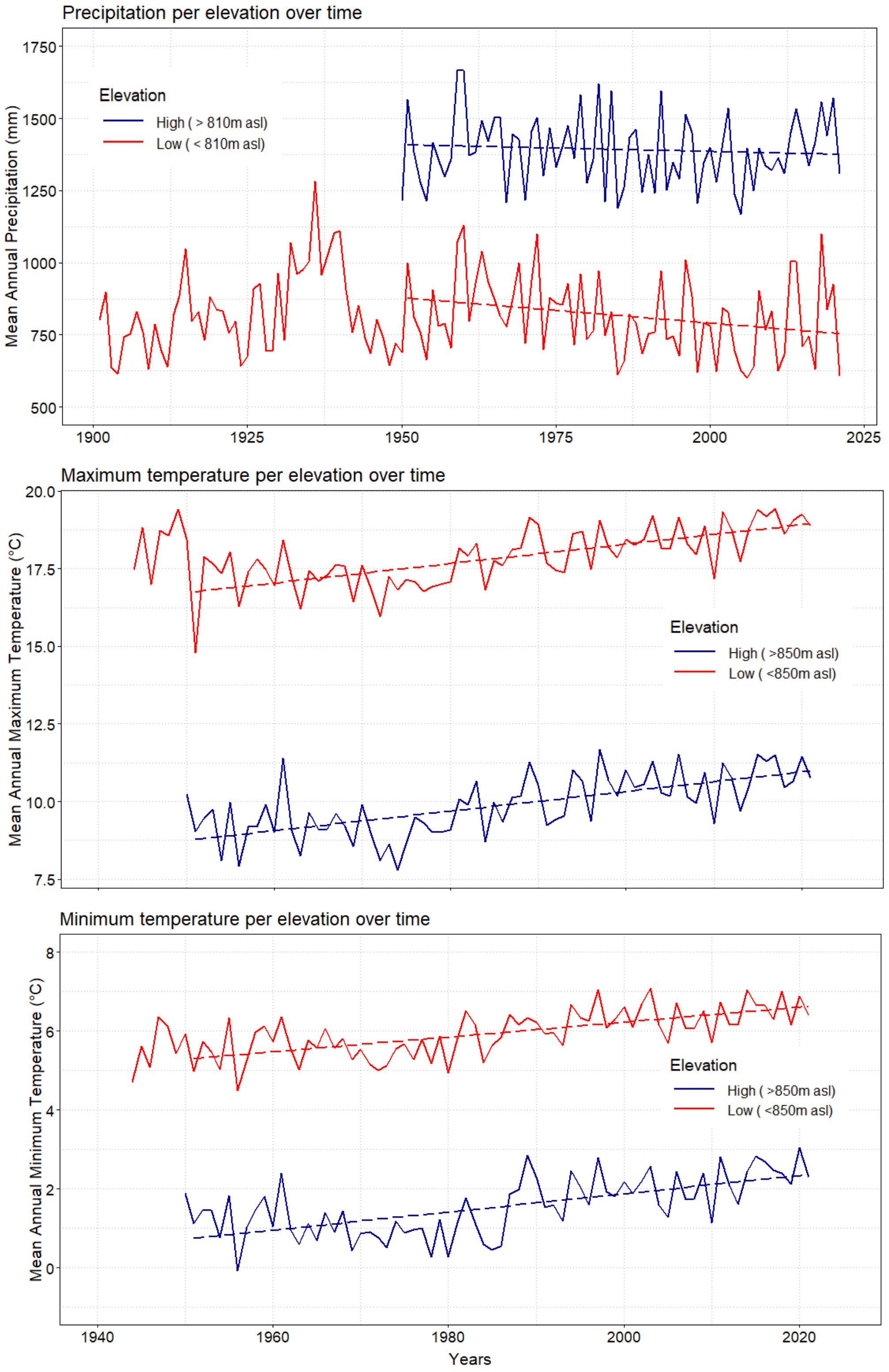

Figure 6. From top to bottom: Changes in mean annual precipitation, mean annual maximum and minimum temperatures over the period 1901-2021 and 1940-2021, respectively, for high and low elevation areas located on the Pyrenees mountain range. The regression trends are also represented in a dashed line.

4.3.Influence of non-climatic factors

A positive correlation between temperature and elevation was found in this study which contrasts with previous research carried out in other mountain ranges of the world, such as the Tibetan Plateau (Gao et al. 2018) and the Eastern Alps (Tudoroiu et al. 2016). However, because an expansion of forests on lowlands was observed for the Pyrenees region (Buendia et al. 2016b; Tudoroiu et al. 2016) during the 20th century, the warming rate could increase on low elevation areas due to the abandonment of agricultural land and an increase in retained heat (Tudoroiu et al. 2016). In addition, other variables such as evapotranspiration, soil moisture and water runoff should also be considered when studying the water availability in the area of study, like it was already carried on studies done by Buendia et al. (2016b), Nogues Bravo et al. (2008) and Amblar-Francés et al. (2020).

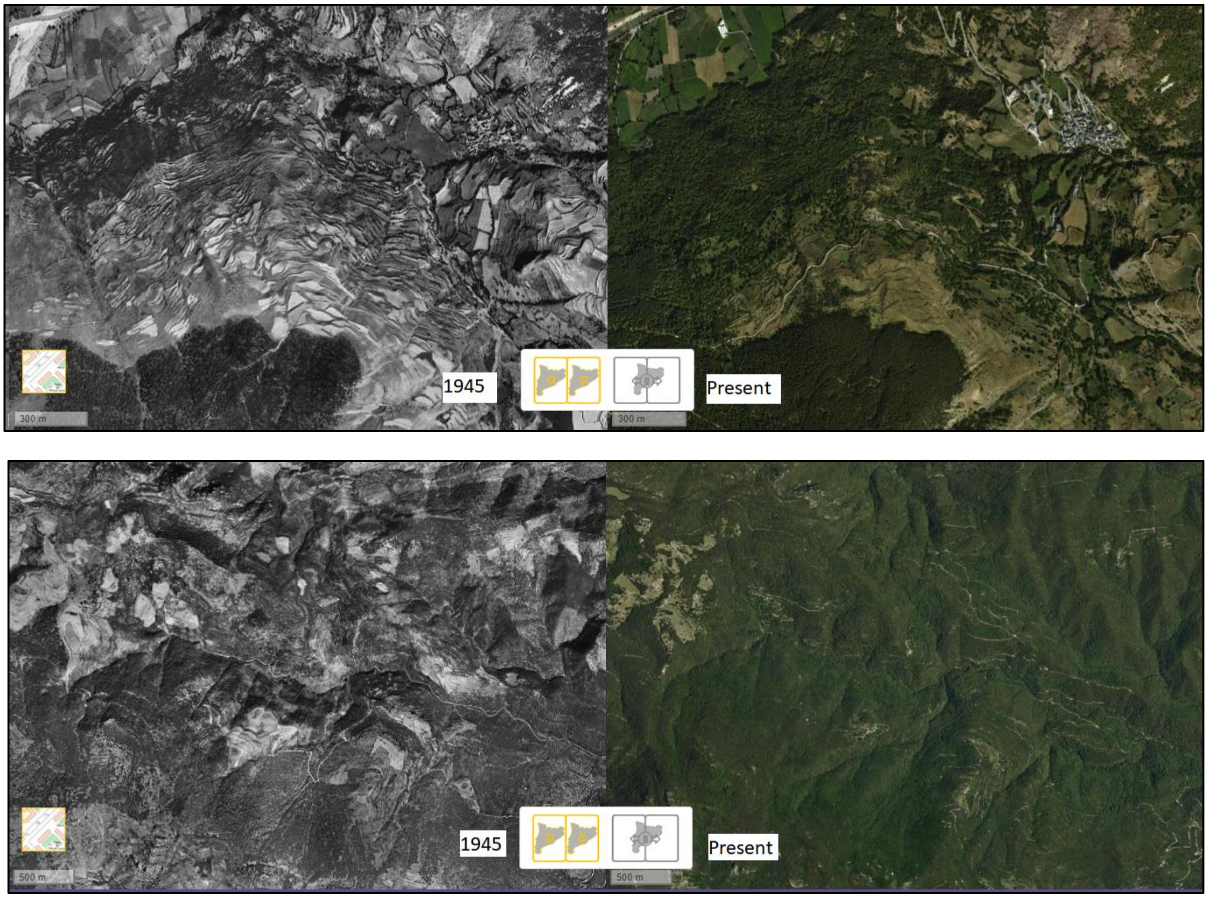

Figure 7: (From top to bottom) Satellite images focusing on the central Pyrenees area and Eastern Pyrenees area. Comparison between 1945 and 2021 to observe the expansion of forests on abandoned agricultural lands. Obtained from the Institute of Cartography and Geology of Catalonia (https://www.icgc.cat/Ciutada/Destacats/Aplicacions-mobils/L-Ull-del-temps)

5. Conclusions

As mentioned throughout the literature review of this study, during the 20th century, a general increase in temperature and a high inter-annual variability for precipitation were observed for the Mediterranean Basin and in the Pyrenees mountain range. In this study, also the lowlands surrounding these regions were analyzed to study the changes in the mean annual maximum and minimum temperatures, and the mean annual precipitation over time, in different areas and elevations.

After the compilation and analysis of climatic data, we found an increase in mean annual maximum and minimum temperatures for all the regions, and for the period 1950-2021, which coincide with results from similar studies analyzed in the literature review. The mean annual precipitation data showed high variability between regions, with a general decreasing trend on the eastern regions in comparison to the western regions, due to a possible influence from the Mediterranean Sea and from the Atlantic Ocean, respectively.

As regards to the Pyrenees mountain range, the mean annual precipitation evolution over time varied from the west to the east, showing a decrease on the W-Pyrenees region, except for the winter months, and a slight increase on the E-Pyrenees region. The east and the west showed similar trends for mean annual maximum and minimum temperatures, with a peak during summer, being the warming rate higher on the E-Pyrenees. In contrast to a previous study done by El Kenawy et al. (2011), the increase in temperature was faster on high compared to low elevation areas. In addition, the rate of increase was higher for maximum than for minimum temperatures, which differ from the results found in other mountain ranges of the world (Gao et al. 2018; Tudoroiu et al. 2016) but coincide with future predictions done by Amblar-Francés et al. (2020) for the Pyrenees mountain range. Last, but not least, since 1950 the forest has been expanding on abandoned agricultural lands located on headwaters and valleys of the Pyrenees mountain range, and this phenomenon could influence the warming rate on low elevation areas on the future, as well as the water runoff and the potential evapotranspiration amount.

For the purpose of this research, and considering the climatic trends observed in the area of study, non-climatic factors such as land-use change, topography, snow cover and depth, albedo, soil moisture and evapotranspiration should also be taken into account for calculating the water balance within the area of study, and for predicting the water availability in the future. Therefore, this could be the first step for further exploring and developing this study, and to provide with future forest management practices to adapt and mitigate climate change on the Pyrenees mountain range.

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