Master thesis – GEO 511

Climatic influence on tree-ring growth of a *Quercus ilex* forest in Supramonte (Sardinia, Italy)

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Abstract

Dendroclimatology and dendroecology aim to measure and analyze tree-rings in order to reconstruct past climate conditions or past ecological situations. *Quercus ilex* is the most representing tree species in the mediterranean region. However, as an evergreen, hard-leaved species, there are certain difficulties in analyzing its wood structure. In the Mediterranean area in general, tree-rings sometimes are hard to identify. In fact, due to the lack of seasonality trees may not have a clear winter stop. Main problems are intra-annual density fluctuations. Trees can build false rings or double rings, which are results of coping with extreme droughts. Another problem which can appear, which is known more for tropical woods, are wedging rings. This difficulties in measuring holm oak tree-rings are the reason why only scarce dendroclimatological and dendroecological studies have been done so far. But exactly because of its longevity, holm oak would serve the best as one of the investigated mediterranean species. Six holm oak samples were analyzed in Supramonte (Nuoro, Sardinia). They were crossdated and statistically analyzed. Pointer years were fitted to temperature and precipitation to see if they responded to extreme events, such as dry periods. Furthermore, correlations and responses were calculated with DENDROCLIM2002 to find out in which months, tree growth reacted the most with temperature and precipitation and if there had already been a change due to globally rising temperatures. Additionally basal area increments of the ring-widths were calculated to see whether climatic responses were more evident than the one calculated with ring-widths data. Crossdating was possible but only two of six samples showed a correlation with each other. Unfortunately pointer years could not be matched with extreme climate events. Nevertheless, DENDROCLIM2002 provided reasonable results. Positive correlation and response was found with December of the previous year and an even stronger signal achieved the negative correlation and response of June and July temperatures. Finally results appeared to be more reliable with ring-widths than with basal area increments in DENDROCLIM2002. In conclusion one of the main limits of this study is the number of samples. Six samples, in fact, do not fulfill the necessary statistical criteria for reliable statements. Therefore, further studies with higher number of samples need to be done to have statistical relevant evidences, thus pointer years are able to be assigned to extreme climate events. Nevertheless, it was possible to measure the longest chronology for holm oak with 239 years so far.

List of Figures

List of Tables

List of abbreviations

A.D.	After death (of Jesus), indication for time.
a.s.l.	Above sea level
CDI	Cross Date Index
GLK	*Gleichläufigkeit*
GLS	Level of significance of *Gleichläufigkeit*
IDAF	Intra annual density fluctuation
RW	Ring-width
TV	T-value of Student T Test
TVBP	T-value of Student T Test (Baillie and Pilcher)
Temp_mean	Annual average temperature
T_max	Maximum temperature
T_min	Minimum temperature
WSL	Swiss Federal Institute for Forest, Snow and Landscape Research

1 Introduction

Tree-ring growth is affected by many environmental factors such as drought, frost, snow avalanches, fire, floods, rock fall, insects or climatic changes (Schweingruber, 1996). These influences interfere with tree growth, which can be detected by dendrochronological methods. All trees are subject to climate, although highly site specific, climate is one of the key factors to which trees react in all spatial and temporal scales (Speer, 2010). It is the major limiting factor, shaping areal distribution of species across continents. As climate is not constant between years, trees sometimes grow more and sometimes less, because it undergoes different kinds of stress. By ”growth”, it is meant the building of wider or narrower rings. By comparing ring-widths with climate, evidences that extreme climate events are found in tree-rings can be found (Schweingruber et al., 1990). When detected how tree-rings react to climate condition, climate can be reconstructed reliably for many years back (Speer, 2010). Past temperature and precipitation patterns have been successfully reconstructed by tree-ring growth measurements (Fritts, 1976), as trees are inevitably exposed to and dependent on climate. Once it is known how trees reacted to past climate conditions, the information can be used to forecast the trend of climate and how trees are possible going to react (Speer, 2010).

Holm oak (*Quercus ilex* L.), also known as holly oak, is an evergreen (subgenus *sclerophyllodris*), hardwood species and is considered to be the most representing species for the mediterranean terrestrial ecosystem (Campelo et al., 2009; Coombes & Debreczy, 2011; Schweingruber, F. H. 2005). Holm oak forests are widely spread especially in the western Mediterranean Basin and, therefore, play an important role in the landscape (Romane and Terradas, 1992). In 1990 the “Centre d’Ecologie Fonctionelle et Evolutive” (CEFE, Montpellier, France) and the “Centre de Recerca Ecològica I Aplicacions Forestals” (CREAF, Barcelona, Spain) decided to establish workshops on holm oak to better understand its importance for the mediterranean vegetation. It was also stated that there were some attempts in measuring the wood production and tree-rings (Susmel et al., 1976), but the methods were too time consuming and imprecise (Romane and Terradas, 1992). Nevertheless, over the past years there has been an increasing interest in holm oak and its importance for the mediterranean woodlands, as well as for climate reconstructions (Cherubini et al., 2003). Despite all the difficulties in the analysis, there are high expectations that climate variability can be detected in tree-ring growth differences and that there are reasonable possibilities of providing a long chronology thanks to better understandings of tree-ring growth patterns (Cherubini et al., 2003).

Most of the tree-ring studies have been conducted in temperate regions, because a clear winter induced reduction in cell’s lumen size, is detectable (Fritts, 1976; Schwiengruber, 1996). To obtain a winter stop in mediterranean species trees in higher elevation were chosen to be analyzed and therefore, only a few focused on mediterranean species at lower elevation, where it is possible that there are two stops in the vegetative period (Cherubini et al., 2003). These species have rarely been used in dendrochronology because of the complicated seasonality of the mediterranean climate, which often causes the formation of intra-annual density fluctuations (IADFs), that cannot be easily distinguished (Battipaglia et al., 2010; Campelo et al., 2007; Cherubini et al., 2003). IADF are irregularities in ring growth as a result of coping with drought related events, also known as “double rings” or “false rings” (Battipaglia et al., 2010). They were reported in holm oak by Campelo et al. (2007) and Cherubini et al. (2003). A knowledge gap developed around the growth patterns of *Quercus ilex*. This gap needs to be filled. In general, it would be useful to have long-term chronologies in the mediterranean area for dendroclimatological purposes (Campelo et al., 2007). Since holm oak is a long-living tree it would be more than suitable to use it (Campelo et al., 2007).

Supramonte is a region in central Sardinia with a pure holm oak forest. So far there was only one study (Susmel et al., 1976) which dealt with tree-rings analysis in Supramonte. Considering holm oak, thus far, there has been little attempt (such as: Campleo et al., 2009; Cartan-Son, 1992; Cherubini et al., 2003; Gea-Izquierdo et al., 2009; Gea-Izquierdo et al. 2011) to provide long time dendroclimatological data, even though being one of the most diffuse species in Sardinia. The chronologies of the named studies do not go much back in time (until 1868). Supramonte could change this as it is considered to be an old-growth forest.

Considering the trend of global climate, it is clear that the mediterranean vegetation is going to be subject to major stress and therefore it is necessary to better understand the magnitude of climatic response shown by species (Lindner et al., 2010). Each species is characterized by specific needs, which leads to clear borders in their distribution area and where the environmental conditions become critical they may disappear (Gaston, 2009). In the past, there has been large-scale natural events and species were able to find a refuge or adapt to the new climate conditions (Michaud et al., 1992). However, due to the anthropogenic influences, climate change is occurring at a much faster rate (Bazzaz, 1992). Lindner et al. (2010) mentioned that the change might be happening too fast for long-living species as trees, included holm oak, to adapt themselves to the new conditions. They continue warning that for the mediterranean area, the threat is even higher due to the present over or under forest management. The increase in temperature may cause higher photosynthetic activities in northern Europe (Saxe et al., 2001), while, for the mediterranean region less precipitation and increase in temperature is expected. Drought events become more frequent and more severe (IPCC, 2007). Several scientist (Cherubini et al., 2003; IPCC, 2007; Peñuelas, 2001; Piñol et al., 1998) claim, that as the temperatures are increasing, soil moisture is decreasing and drought events are becoming more frequent and more severe for the mediterranean vegetation. Moreover, droughts are recognized to be the most limiting growth factor for holm oak (Campleo et al., 2009; Cartan-Son, 1992; Cherubini et al., 2003; Gea-Izquierdo et al., 2009; Gea-Izquierdo et al., 2011). For this reason it is important to understand if species can adapt themselves in short time and if, how species are coping with the new confronted situation. Desertification occurs mainly due to human influence, but there are hypothesis that droughts can accelerate desertification and at the same time it is believed that the mediterranean ecosystem contributes a major part against desertification (Le Houérou, 1996).

Campelo et al. (2009) detected that the Autumn months October – December from the previous year and January from the current year had a positive correlation to tree-ring growth. While, Cartan-Son et al. (1992) for example found evidence in holm oak in a coppice stand located in south France that ring-widths are not correlated to annual mean rainfall but to precipitation in June and July. Another important finding was the edge-effect after a clear-cut on shoots. Both reactions were positive correlated and resulted in increased radial growth. Cherubini et al. (2003) found correlations in tree growth with February and September precipitation. Gea-Izquierdo et al. (2009) found positive correlation to tree growth with late spring and early summer precipitation and a negative correlation with the previous August and the current July temperatures. Gea-Izquierdo et al. (2011) findings were, that holm oak at warmer sites are more threatened by rising temperatures than the ones at colder sites.

Tree-rings are a great natural archive of climate information (Hughes, 2002). One of the most outstanding strength of dendroclimatology is the capability to match a tree-ring with a calender year with a high precision and acuracy as well as the length of these chronologies and the reliable interaction from the climate with the tree-rings and the growing understanding of other mechanism which control ring-growth (Hughes, 2002). But there are also weaknesses or lack in understanding certain growth reactions (Hughes, 2002). Reaction in growth is based on the local climate and not globally (Hughes, 2002). The growth might be limited to only a few months a year or there is a delayed signal by a year. The detrending of the chronology can lead to the removal of the wannted climatic signal in order to get rid of the age and size trend as well as the interactions with neighbors (Hughes, 2002). From the present state of knowledge the following research question will be investigated during this thesis.

Is it possible to measure the ring-widths in holm oak?

In order to ensure a positive answer to this question the Supramonte at an altitude of 950 m a.s.l. area was chosen as the sample site. Even for a mediterranean region such an altitude should have more pronounced winters with a clear winter break.

Can pointer years be assigned to the extreme values in temperature or precipitation, or both?

To answer this question pointer years were calculated for all samples. It was distinguished between positive and negative pointer years. They were implemented in different climate diagrams to find a match.

Is the reaction from local temperature and precipitation visible in holm oak ring-widths?

As tree-ring growth is primarily limited to water availability in the mediterranean area(Cherubini et al., 2003), the central focus lay on precipitation. This question was answered by analyzing and interpreting the outputs of the DENDROCLIM2002 program.

Are there significant differences in the DENDROCLIM2002 outputs when running it with BAI input files instead of ring-widths?

The BAI is a standardized ring-width curve. Principal differences are the shape of the curve and the unit which is mm^2. This question was answered by analyzing and interpreting the outputs of the DENDROCLIM2002 program.

Is there an effect of climate variability which can be recognized in the ring-width pattern? Should this be possible, a ring-width chronology for Sardinia could be built and the climate of the past 250 years reconstructed.

Ring-width curve and climate diagrams were analyzed visually and possible outcomes discussed.

2 Research site and topic

2.1 Research species holm oak

Holm oak is an evergreen species (subgenus *sclerophyllodris*), and it is one of the most representative in the mediterranean region (Campelo et al., 2009; Coombes and Debreczy, 2011; Schweingruber, F. H. 2005). *Quercus* belongs to the family of *Fagaceae* and is represented by 450 species (Coombes and Debreczy, 2011; Schweingruber, 2011). In the subgenera *sclerophyllodirs* tree-rings are diffuse-porous and the bark is square-fissured and blackish (Schweingruber, 2011). The wood basic density is 0,74 g/cm^3 (Crivellaro and Schweingruber, 2013), one of the highest values among the mediterranean species.

The leaves are ovate to elliptic, reaching sizes of 8 cm long and 5 cm wide. They possess a leathery texture and they have a dark green and smooth upper side and a gray and hairy under side. Both leaves and acorns appear in a wide variety of sizes, colors and shapes, which make the identification more difficult. Flowering period is between spring and early summer. (Coombes and Debreczy, 2011)

There have been different ways to define the distribution area of holm oak. Coombes and Debreczy (2011) included the whole abutting land to the Mediterranean Sea, whereas Delzon et al. (2013) proposed approximately the same excluding the Egyptian and Libyan coast, including more the Spanish and Moroccan country side as it shown in the Fig. 1. Holm oak can be found in different altitudes, from Thermo-Mediterranean (0 m a.s.l.) to Montane-Mediterranean (2800 m a.s.l.), depending on the latitude and the region (Achhal et al., 1979; Quezel, P. 1979; Barbero et al., 1992). The wood of holm oak is known for its strength and durability and is used for furniture, flooring and charcoal, although it is a low productive species (Cartan-Son et al., 1992; Coombes and Debreczy, 2011). The preferred sites are on calcareous substrates (Schweingruber, 2005).

2.2 Supramonte

Supramonte is situated around 950 meters a.s.l. It is a *Quercetum-ilicis* forest left on Sardinia, with an estimated age of 500 years and with no logging activities recorded in the recent centuries. All sampled trees were taken within an area of one square kilometer inside the Supramonte forest. The research site is situated in the south of the Supramonte region. It is close to Funtana Bona which is located in about 10 km air distance south-south-east from Orgosolo.

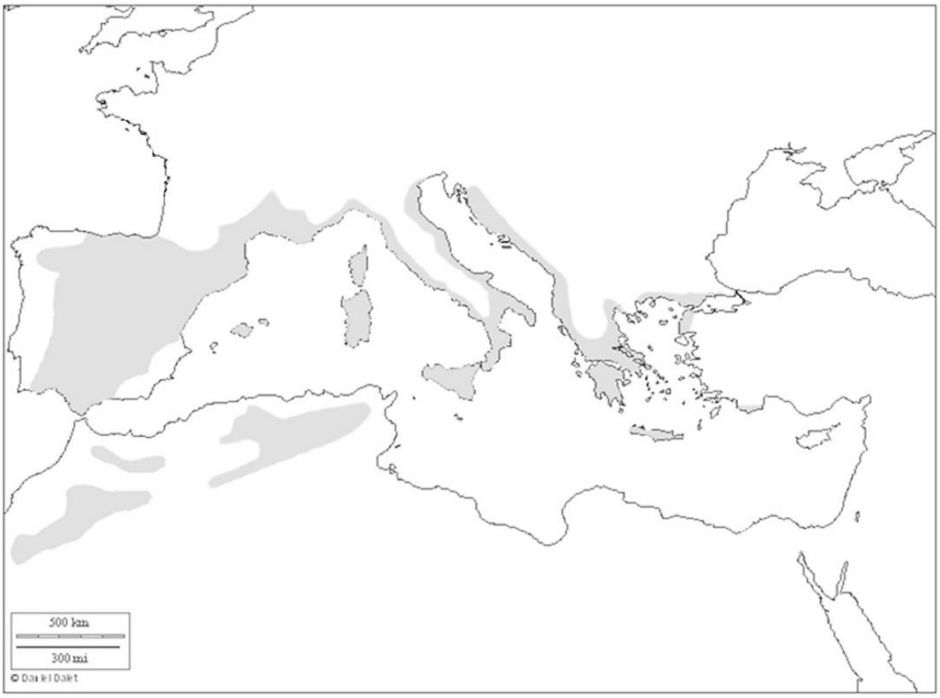

Fig. 1: The grey area indicates the distribution of Quercus ilex in Europe proposed by Delzon et al. (2013)[1]. The data which resulted in this map were established by Barbero et al. (1992)2, Michaud et al. (1995)3 and the raw data from the French National Forest Inventory[4].

2.3 Climate

The mediterranean climate is known for hot and dry summer with a drought period from June to August and more pronounced precipitation during the winter (Kottek et al., 2006). The definition of drought can vary for different regions (McKee et al., 1993). Drought in the mediterranean climate can be defined as two consecutive months with a shortage of precipitation in combination with high temperatures as is shown by the gap area in the Fig. 2. Csa and Csb are the two climate classification for the mediterranean climate. The Csa (*C:* warm temperate, *s:* summer dry, *a:* hot summer) is the most common and also the one for

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[1] Delzon, S., Urli, M., Samalens, J. C., Lamy, J. B., Lischke, H., Sin, F., ... & Porté, A. J. (2013). Field evidence of colonisation by Holm oak, at the northern margin of its distribution range, during the Anthropocene period. PloS one, 8(11), e80443.

[2] Barbero M., Loisel R., Quézel P. (1992): Biogeography, ecology and history of Mediterranean Quercus ilex ecosystems. Plant Ecol 99: 19–34.

[3] Michaud H., Toumi L., Lumaret R., Li TX., Romane F., et al. (1995): Effect of geographical discontinuity on genetic variation in Quercus ilex L.(holm oak). Evidence from enzyme polymorphism. Heredity 74: 590–606.

[4] (http://inventaire-forestier.ign.fr/edb/query/show-query-form#consultation_panel, (last access: 30th August 2014)

Supramonte. This classification is based on Wladimir Köppen, last released by Rudolf Geiger and updated by Kottek et al. (2006). The classification for Csa is done as in the following example:

Psmin < Pwmin: Driest summer month < driest winter month

Pwmax > 3 Psmin: Precipitation richest winter month > 3 times driest summer month

Psmin < 40 mm: driest summer month < 40 mm precipitation

Tmax ≥ +22° C: warmest month ≥ +22° C

Climate values in Fig. 2 were calculated for the meteorological station of Nuoro (altitude: 533 m a.s.l.) for a 30 years period from 1982-2011. The annual mean temperature is 13,9 °C and a total amount of 627.3 mm precipitation falls on average during a calendar year. In average the rainiest month is November (96.5 mm) and driest is July (13.2 mm). The highest monthly mean temperatures are measured in August (22.8 °C) and the lowest in January (6.9 °C). The difference in temperature from the coldest to the hottest month is 15.9 °C and in precipitation it is an amount of 83.3 mm.

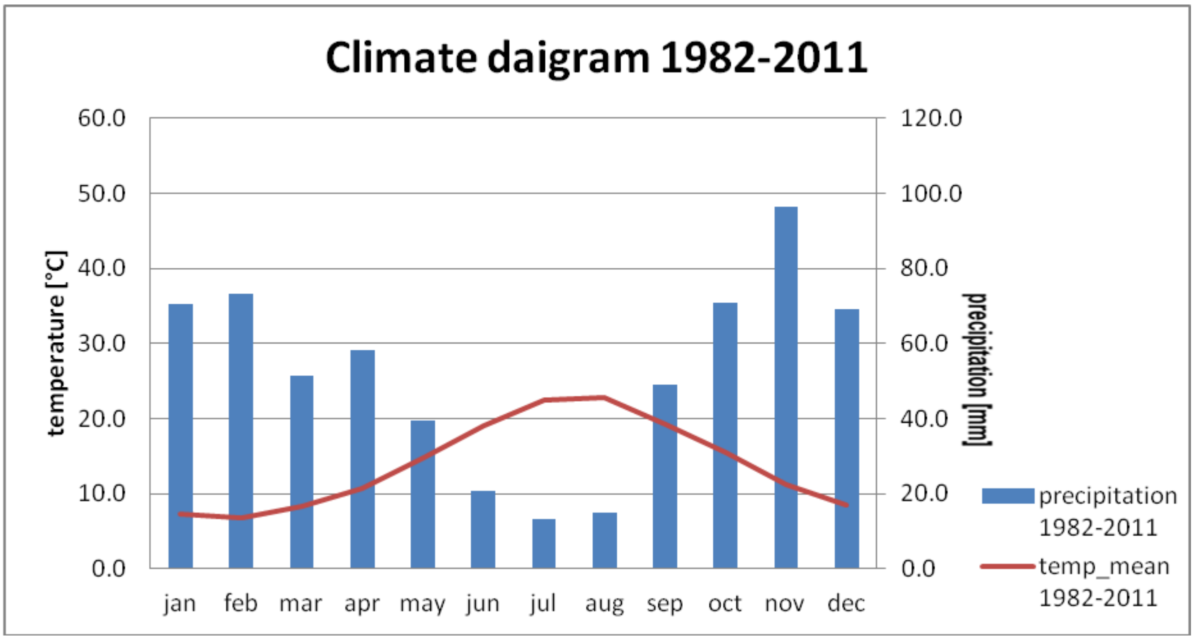


Fig. 2: Diagram was calculated with climate data from the CRU database (Climate Research Unit, University of East Anglia, Norwich, UK). Blue is the precipitation in millimeters and red is the monthly mean temperature.

2.4 Geology and soil

The geology of Sardinia, is very diverse. The Supramonte is situated on carbonate platform sediments from the Trais in the Upper Cretaceous as shown by De Vivo et al. (1998). However, no soil samples were taken. But estimations were registered, when analyzing the holes done by the roots from the fallen holm oak trees. Soil depth was not more than 50 cm. According to the classification from EEA and JRC, (2010) the dominant soils in the Supramonte area are Luvisols. Luvisols are fertile soils with clay accumulation in the subsoil. Finally they describe the area as an hilly site with parental material from calcareous sediments and mediterranean to subtropical climate.

2.5 Vegetation

The Vegetation on the site was a *Quercus ilex* forest only and, as mentioned before, wet. Trees were standing in distances of 7 to 10 meters and had dense canopies. The canopy of the trees let only a few light through to the ground. Therefore, no shrub layer was found, which must result in a low shoot ratio. There was a litter layer on the surface. Holm oaks were between 25 and 30 meters high.

3 Material and methods

3.1 Fieldwork

3.1.1 Site selection

In order to be able to exclude certain environmental effects from the analysis, different parameters were checked during the sampling site selection. For example, the selected site was inside the forest, so that wind should not be a factor to interfere with tree growth, as it is for those trees at the forest border. The chosen area was flat to avoid exposition irregularities such as advantages of water supply due to a depression or tension wood. Another reason to choose the Supramonte area was the age of the forest: this is the oldest oak forest in Sardinia and apparently one of the only old-growth *Quercetum-ilicis* forest left in the mediterranean area, with an estimated age of 500 years. Desirably trees of up to 500 years were hoped to be sampled, even if it was allowed to get stem disks only form already dead trees. Furthermore, local foresters told that the forest was never logged in the recent centuries. Although this last statement could be not completely reliable, it was the best site to find some of the oldest holm oak trees in Sardinia.

3.1.2 Sample selection

Taking cores with a borer from holm oak, and analyzing them is nearly impossible because of the high wood density, as mentioned before and as shown in previous works (Cherubini et al., 2003; Gea-Izquierdo et al., 2009). Therefore, the collection of stem disks was preferred. Overall eight stem disks were chainsawed in the Supramonte near Nuoro (Sardinia) with diameters ranging from 65 cm to 81 cm. The stem disks were taken at tree height between 50 cm and 100 cm. Thus, trees are some years older than what the stem disks can show. In a first step three samples were taken in November 2012 and further five in May 2013. Samples were dried in Bono at the garage of "Ente Foreste" in Nuoro itself. By the end of August 2013 the stem disks were brought from Sardinia to the WSL at Birmensdorf for examinations. The transportation was decided to be done by car. For transportation reasons six of the eight stem disks were cut into stripes. Otherwise the samples would have been too heavy to transport.

3.2 Laboratory work

3.2.1 Sample preparation

All samples were sanded with the sanding machine (sandpaper used: 60, 80, 100, 120, 150, 180, 240, 320, 400). The samples were sanded so that the transversal cross section could be analyzed horizontally and to avoid errors in later ring-width measurements. To ensure horizontality of the large samples, pedestals were used, while sanding as well as for the measurements. The two samples, which were entire stem disks were tried to be cut into smaller pieces in order to perform measurements. However, one of them resulted to be too thin to be resized for the analyses and had to be discarded. The other was successfully resized and measured. Overall 7 samples were obtained for ring-width measurements.

3.2.2 Tree-ring measurement

All samples were measured at the Swiss Federal Institute for Forest, Snow and Landscape Research (WSL) in Birmensdorf. Ring-width measurements were acquired using the "TSAP" ring-width measuring program and the Lintab table (RINNTECH, Heidelberg, Germany). For accurate measurements a stereomicroscope (magnification 6.4-40 × Wild M3Z Leica, Germany) was used. Best magnification results were decided to be between 10x and 16x. Normal practice for time orientation on samples, requires to mark every decade with a dot, two dots for the '50 years and three dots all centuries. However, as the rings were very narrow, each one was marked with a pencil to facilitate the measurement. The ring-widths of all seven stem disks were measured from opposite sides. This means that for each stem disk two chronologies were obtained. Measures were taken from bark to the pith. Stem disk n.3

could only be measured from one side because on the other side the contrast was not allowing a full measurement from the bark to the pith. Stem disk n.6 was measured from two different sides but only one of the two chronologies could be measured due to low quality of the second chronology after the year 1885. In all measurements there were uncertain rings due to lack of contrast or too homogenous wood. Such rings or parts were separately marked in TSAP. This was done for the cross-dating part, in order to track possible errors more easily.

3.2.3 Crossdating

Two main acknowledged methods to measure the quality of series are used in dendrochronology. The *Gleichläufigkeit (GLK)* (no English translation available) and t-values (Eckstein and Bauch 1969). The *Gleichläufigkeit* is a test to measure the quality of the conformity of the annual growth change, while the t-Test is sensitive to the reaction of extreme values like pointer years. Overlap indicates the number of years the two series overlap. GSL means the significance of the *Gleichläufigkeits-value* (* $p \geq 95.0\%$, ** $p \geq 99.0\%$, ***$p \geq 99.9\%$). It is measured as followed:

$$Glk = \sum (yi_j = x_{ij}) \text{ in } \% \tag{1}$$

The value for a specific year is compared to the previous in two chronologies, attributing a positive, negative or neutral value. *Gleichläufigkeit* is the sum of all years which values in both chronologies are either positive, negative or identical divided through the number of years. Summarizing, *Gleichläufigkeit* means looking at the trends of the curves and comparing them. The result is given in percentage whereas 100% is identical or perfect match, and 50% is random common ground.

TV stands for the standard t-test t-value. TVBP is a t-value after detrending, obtained by a moving average with bandwith of 5 and logarithmic transformation to base *e* (Baillie and Pilcher 1973). It is measured as followed:

$$t = \frac{CC * \sqrt{n-2}}{\sqrt{(1-CC)^2}} \tag{2}$$

Cross-Date Index (CDI) is a combination of the two parameters *Gleichläufigkeit* and TV (Rinn, 2003). It is measured as followed:

$$CDI = \frac{(G - 50 + 50 * \sqrt{\frac{overlap}{\max overlap}}) * T}{10} \tag{3}$$

To avoid irregularities in ring-widths, each sample was measured twice and crossdated. This procedure has also the advantage that possible missing rings, very narrow rings or measure mistakes can be detected. From the seven stem disks, six were able to be crossdated. For sample n.3, only one of the two chronologies was reliable, therefore, it could not be crossdated. Sample n. 6 could be crossdated, although the overlapping part of both chronologies was short due to the fact that one of the chronologies could not be fully measured.

While analyzing the crossdated samples, high *Gleichläufigkeit*-values between SM_QI_4_mean and SM_QI_5_mean could be observed but with a shift of 50 years. The *Gleichläufigkeits*-value was too high to be ignored Fig. 3. That’s the reason why this shift was thought to be real. Dead trees, so called “snags”, in fact can be standing for long time, with no production of new rings (Cherubini et al., 2002; Dickson et al. 1983).

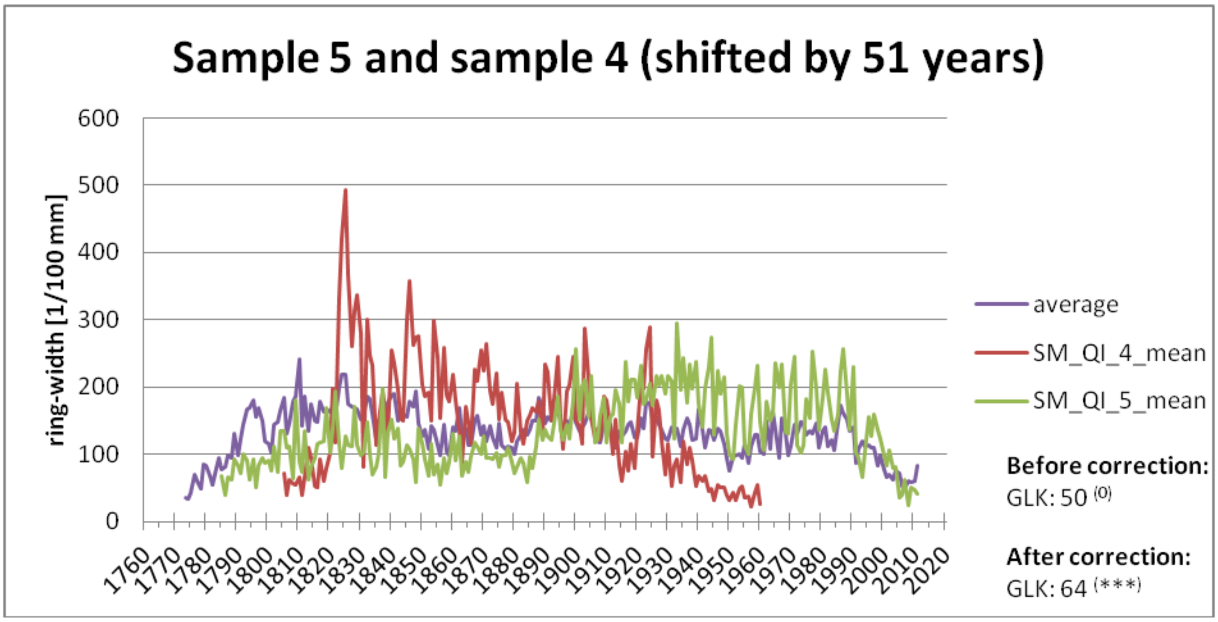


Fig. 3: The shifting of sample n. 4 and the *Gleichläufigkeit* before and afterwards.

A similar correlation was found for SM_QI_1_mean and SM_QI_2_mean by shifting the latter by one year and inserting an additional year. Again, the *Gleichläufigkeits*-value was too high to ignore it Fig. 4.

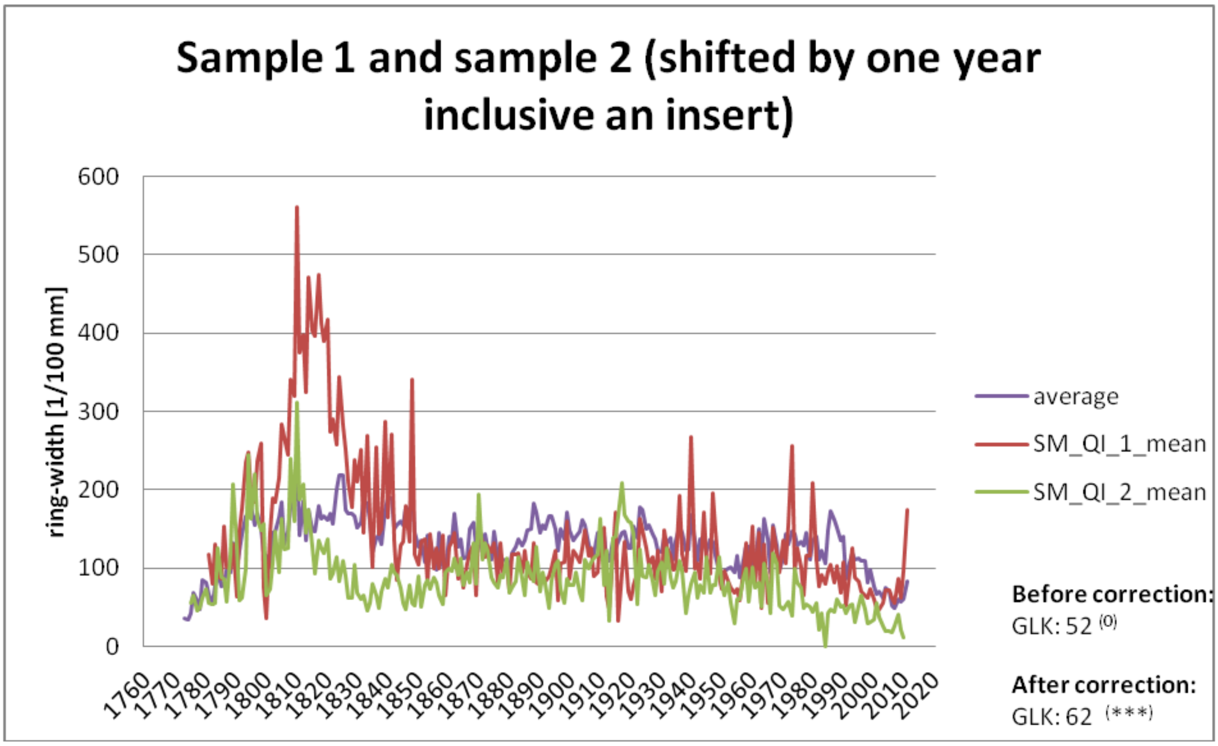


Fig. 4: Shift adaptation, indicating *Gleichläufigkeit* before and afterwards.

From the final crossdated curves, a mean was built. The overall mean of the six crossdates was named “mean_of_6_samples”, which is the mean chronology or overall average. This mean was chosen to be used for further comparisons with the climate data.

3.3 Data analysis

During the crossdating, the data were pre analyzed with the Gleichläufigkeit-values, t-values, t-values Baillie-Pilcher and CDI. Usually, in statistic t-values over 3.5 are significant. However, it is common to have higher t-values of around 4 and 5. Therefore, in dendrochronology t-values higher than 5 are desirable (Baillie and Pilchner 1973). Ring-with chronologies were checked for normality with a Kolmogorov-Smirnov test in R Studio.. Eventough Pearson correlation test were performed, since the samples resulted non normal, the Spearman test was used, and the results compared. Correlation tests were calculated using the “nortest” package (R Core Team, 2013). This was done to see how well the crossdated means of each of the six samples fitted to the average.

3.3.1 *Basal area increment*

Ring-widths are not only influenced by their environment but also by the age of the tree (Biondi and Qeadan, 2008). When working with tree-rings it should always be taken into account that ring-widths an age trend. Age trend or biological growth is intended as the decreasing ring-width size with the increasing diameter of the tree (Biondi and Qeadan, 2008). To avoid the effect of increasing diameter size, the basal area increment (BAI) is calculated. Caution has to be taken as environmental and age trend might correspond and the environmental signal is also removed (Biondi, 1999).

The BAI is calculated to make comparisons between the tree productivity in different regions, or to compare different tree species. As a result the basal area increment of each year was obtained. It was calculated in Excel as followed:

$$\boxed{[(RW_{(t)} + RW_{(t-1)})^2 \text{ x } \pi]_{(t-1)}} - \boxed{[(RW_{(t)} + RW_{(t-1)})^2 \text{ x } \pi]_{(t)}} = BAI_t \qquad \textbf{(}\text{RW: Ring-width)}$$

$$[\text{area of previous year(s) }] – [\text{ area of year t}] \qquad (5)$$

3.3.2 *Pointer years*

A particularly tree-ring, which is very narrow or very wide compared to its surrounding rings is named an event year. If an event year appears in most of the trees of the same species, it can be assumed, that the whole site is reacting to a specific influence. If the event year is detectable in several crossdated chronologies it is called a pointer year (Schweingruber et al. 1990). Pointer years are an acknowledged method to show tree growth reactions due to environmental changes (Neuwirth et al. 2007). They are generally found for a specific species in a specific area but they can also be found for wide spread areas as climatic events (Schweingruber et al. 1990). The calculations were performed with R Studio using the “dplR” package (R Core Team, 2013). Results were obtained with the mean of the 6 samples. The pointer years were plotted with climate diagrams to find trends (see Appendix 2). As in normal practice, the previous 4 years from the pointer year were considered, and if there was an apparent growth change over 40% in at least 75% of all the samples, it was considered a pointer year (Becker, 1994; Mérian, 2011). Using a 75% break means that at least 5 out of the six samples should show a peak in the same year and percentage by this low sample size is equal to 83.3%.

3.4 Climatic data

Monthly precipitation and monthly average in daily maximum, mean and minimum temperatures were downloaded from the CRU database since 1900 (Climate Research Unit, University of East Anglia, Norwich, UK). No snow data were obtained. It can only be said that 2011 must have been a year rich in snow, because this was said to be the reason why the sampled trees fell.

The data has been processed in Excel®. Different outputs had been calculated. Although DENDROCLIM2002 (explained in next chapter) correlates all the monthly climate data separately with the ring-widths, single month diagrams have been produced (see Appendix 3). With the single month diagrams it became easier to access and find an interpretation for climatic signals. Furthermore, the climate data was plotted in seasonal averages (see Appendix 3). This was done to find parallels between pointer years and climate data. Moreover, the monthly and seasonal climate diagrams can also help to interpret the pointer years.

3.5 DENDROCLIM2002

A well-adapted method in dendroclimatology and dendroecology is to analyze the connection between climate data and ring-width growth with a response function (Fritts et al. 1971; Fritts 1976). For this reason the DENDROCLIM2002 (Biondi and Waikul, 2004) analysis program was used to find a match between temperature, precipitation and ring-widths on monthly basis. It’s also possible to run the program with BAI data. DENDROCLIM2002 only shows the significant values ($p < 0.05$). Non-significant values are not shown to improve legibility.

In contrast to a normal correlation function analysis, DENDROCLIM2002 produces a response function analysis, which takes into consideration that climate data (temperature and precipitation) naturally correlate to each other. Correlation functions results are considered equal to the Pearson correlation, while, the response function uses a regression model. With the bootstrapped response and correlation function the significance of changes in growth is detected. This way DENDROCLIM2002 allowed to find a connection between ring-width and climate data, even tough, a tree-ring is limited to the vegetative period (Biondi and Waikul, 2004).

4 Results

4.1 Ring-width chronologies

All the crossdated ring-widths curves are shown in the Appendix 1. Table 1 shows the crossdated chronologies and the relative statistical results. The highest *Gleichläufigkeit*-values were 75% and the lowest, 65% all within the highest GSL. As mentioned, sample n. 3 could not be crossdated and sample n. 6 only partly. This can be seen in the only 124 overlapping years. Sample n. 4 had a shorter overlapping sequence because the sample had a small size and contains fewer rings. Not only the *Gleichläufigkeit*-values were high, but also the TV, the TVBP and the CDI were strong.

Table 1: Curve a and b of each sample after crossdating. Sample n. 3 had only one chronology.

Sample	Reference	Overlap	GSL	GLK	TV	TVBP	CDI
SAR01a	SAR01b	231	***	66	19.5	6.3	36
SAR02a	SAR02b	224	***	65	10.7	6.8	39
SAR03a	SAR03b	-	-	-	-	-	-
SAR04a	SAR04b	151	***	75	7.3	5.0	42
SAR05aa	SAR5bb	217	***	73	11.5	8.9	65
SAR06a	SAR06b	124	***	70	6.9	5.7	38
SAR07a	SAR07b	221	***	75	4.2	9.4	73

The overall mean was intercorrelated with the single chronologies as shown in Table 2. Especially, chronologies from sample n.1 and n.7 showed a nice fit with the mean_of_6_samples. Chronologies from sample n. 4 and n.2, on the other hand had the lowest values. In sample n. 6, chronology "*a*" provides a *Gleichläufigkeits*-value of 61% with GSL*** whereas "*b*" showed a low one. Chronologies measured from the same sample, however, did not always have the same age, probably due to wedging rings (see Fig. 5). It is believed that wedging rings are the result of changing light saturation or stress due to competition, which is not constant during the vegetative period and therefore produces fluctuations in the cell lumen size (Worbes, 2002).

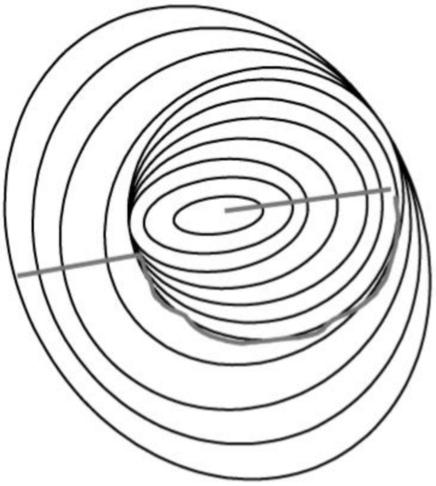


Fig. 5: Broken radius concept and wedging rings: To be able to measure the rings, the solution is to follow a ring until a section is reached where measurement is possible again. Great care must be taken not to switch rings while following a ring.

In Table 3 the mean_of_6_samples was faced with the crossdated means of each of the six the samples. The plotted version is visualized in Fig. 6. Sample n. 5 had a unexpected high *Gleichläufigkeits*-value compared to the low t-values and the CDI. Sample n. 2 achieved much higher values as the two chronologies out of which it was obtained.

Table 2: All the single crossdated chronologies compared with the overall mean. Note: chronology "SAR03b" is only listed but was not used to calculate the mean_of_6_samples

Sample	Reference	Overlap	GSL	GLK	TV	TVBP	CDI
SAR01a	mean_of_6_samples	228	***	69	10	6.8	39
SAR01b	mean_of_6_samples	225	***	65	11.6	7.4	43
SAR02a	mean_of_6_samples	225	**	58	5.4	4.5	26
SAR02b	mean_of_6_samples	238	**	58	6.9	4.3	23
SAR03b	mean_of_6_samples	207	-	45	6.2	0.9	3
SAR04a	mean_of_6_samples	156	**	60	5.1	5.4	31
SAR04b	mean_of_6_samples	151	*	58	6.6	1.5	9
SAR05a	mean_of_6_samples	217	***	65	2.3	4.3	30
SAR05b	mean_of_6_samples	227	**	58	1.2	2.4	16
SAR06a	mean_of_6_samples	236	***	61	7.6	6.8	40
SAR06b	mean_of_6_samples	127	-	55	7.7	3.1	13
SAR07a	mean_of_6_samples	228	***	66	5.1	9.4	62
SAR07b	mean_of_6_samples	229	***	70	7.8	8	56

Table 3: Crossdated means of the six samples compared with the overall mean

Sample	Reference	Overlap	GSL	GLK	TV	TVBP	CDI
SARmean1	mean_of_6_samples	231	***	68	11.5	9	59
SARmean2	mean_of_6_samples	236	***	61	7.9	5.2	30
SARmean4	mean_of_6_samples	156	**	61	6.4	4.7	28
SARmean5	mean_of_6_samples	227	***	65	3.3	4	28
SARmean6	mean_of_6_samples	239	**	59	9.2	6.3	36
SARmean7	mean_of_6_samples	236	***	70	9.1	10.9	75

Table 4 provides a good overview about the oldest ring measured, as well as the age for each sample. The oldest ring was measured in sample n. 6 with an age of 239 years. The youngest was sample n. 4., and was the only outlier. The other five samples were between 227 and 239 years old. To determine the exact age of a tree, the height at which samples are taken has to be considered. It can be assumed, that holm oaks grows 1 m in 2-5 years (Cherubini et al, 2003). However, as trees were not chainsawed at a specific height, it is difficult to say which age they effectively had. First of all, it was not possible to chainsaw at the same height, since some of the trees were not standing and therefore a standard height measurement method could not be implemented. Secondly, security comes first, and therefore, it was at least in one case not possible to chainsaw the closest to the roots. Moreover, a sample got too close to the roots is also not a desirable one, since the structure at this level can interfere with ring-width measurements.

Table 4: Age of each sample and the oldest ring counted.

Sample	oldest ring	age
SM_QI_1_mean	1781	231
SM_QI_2_mean	1775	236
SM_QI_4_mean	1805	156
SM_QI_5_mean	1785	227
SM_QI_6_mean	1773	239
SM_QI_7_mean	1776	236

Spearman and Pearson correlation are shown in the Table 5 and Table 6. Since the results are similar with both methods it was chosen to use the Pearson correlation values, although the data was not normally distributed because not detrended chronologies generally have a skewness.

Table 5: Matrix of crossdated means of all samples correlated to each other with Pearson correlation.

samples	1	2	4	5	6	7
1	1	0.19	0.10	-0.17	-0.09	0.18
2	0.19	1	-0.23	-0.02	-0.13	-0.10
4	0.10	-0.23	1	-0.23	-0.20	0.33
5	-0.17	-0.02	-0.23	1	0.32	-0.31
6	-0.09	-0.13	-0.20	0.32	1	-0.09
7	0.18	-0.10	0.33	-0.31	-0.09	1

Spearman and Pearson correlation tests were verified among the six samples, and a matrix was obtained for each one. Most of the values were around zero or even negative, which means that there was no correlation between the samples. Only samples, which had acceptable correlation values were sample n. 1 and n. 2, (0.19 Spearman / 0.48 Pearson), n. 4 and n. 7 (0.33 Spearman / 0.28 Pearson) and n. 5 and n. 6 (0.32 Spearman / 0.28 Pearson)

Table 6: Matrix of crossdated means of all samples correlated to each other with Pearson correlation.

samples	1	2	4	5	6	7
1	1	0.48	0.03	-0.16	0.01	0.13
2	0.48	1	0.04	-0.08	0.14	-0.02
4	0.03	0.04	1	-0.25	-0.15	0.28
5	-0.16	-0.08	-0.25	1	0.28	-0.14
6	0.01	0.14	-0.15	0.28	1	0.01
7	0.13	-0.02	0.28	-0.14	0.01	1

Furthermore a Pearson correlation was calculated to assess the correlation of the crossdated samples with the mean_of_6_samples, shown in Table 7. Sample n. 1 had the best correlation value (0.6) with the average of all 6 samples. Sample n. 5 had the lowest value (0.21). Remembering the values from the crossdating, only *Gleichläufigkeit* was high for sample n. 5.

Table 7: Pearson correlations are shown as followed. In the second column the average of the six means is shown with the corresponding sample mean.

Pearson	Average_1	0.60
	Average_2	0.46
	Average_4	0.46
	Average_5	0.21
	Average_6	0.51
	Average_7	0.51

All samples had approximately the same age as is shown in Fig. 7 with the sample depth. This leads to the assumption that something must have happened around the year 1770, that led to a creation of an even aged stand. Fig. 8 shows the mean chronology and the standard deviation, which are considerably high.

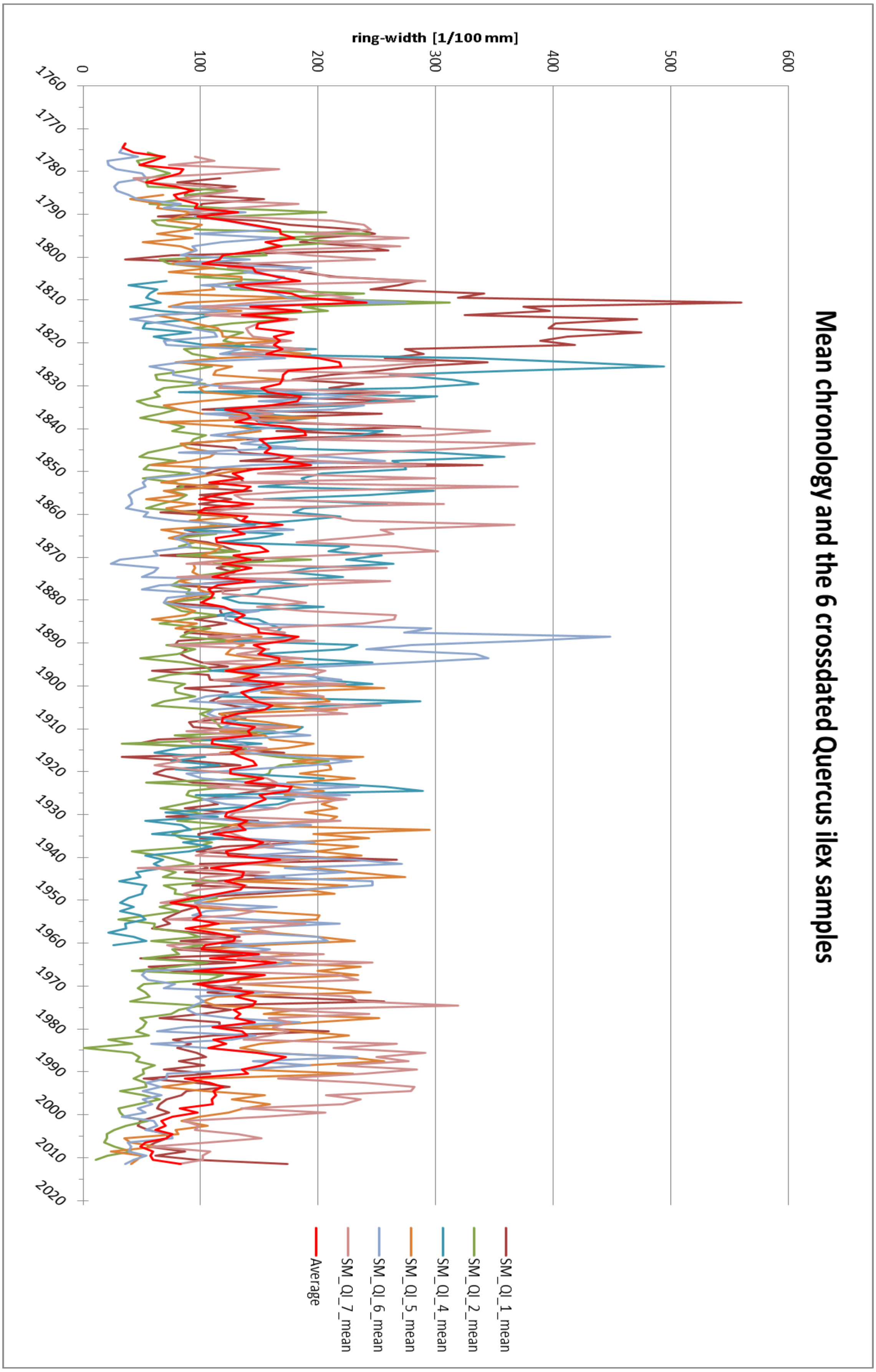


Fig. 6: Mean chronology and the six crossdated samples mean.

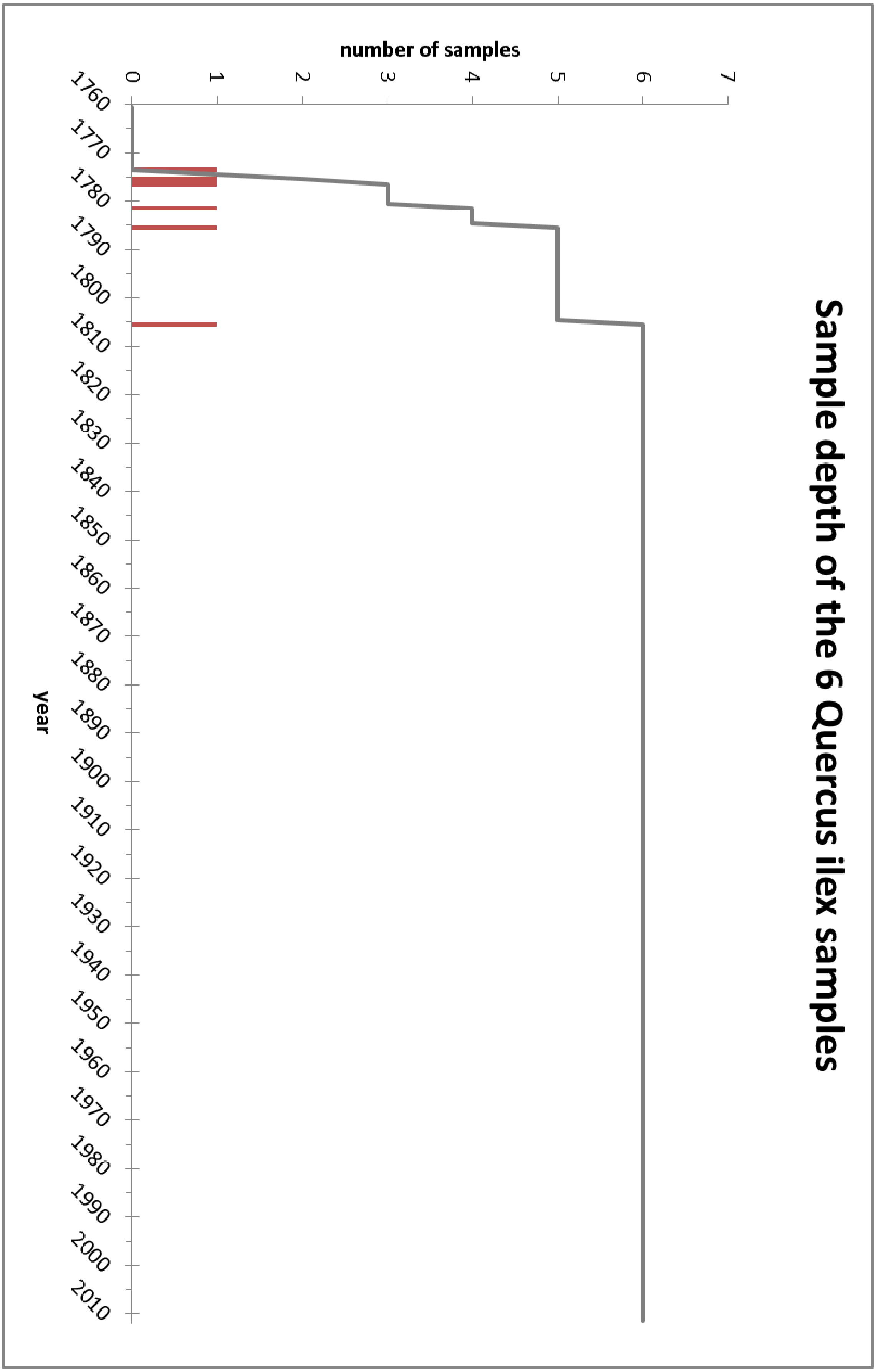


Fig. 7: Sample depth of the six holm oak samples.

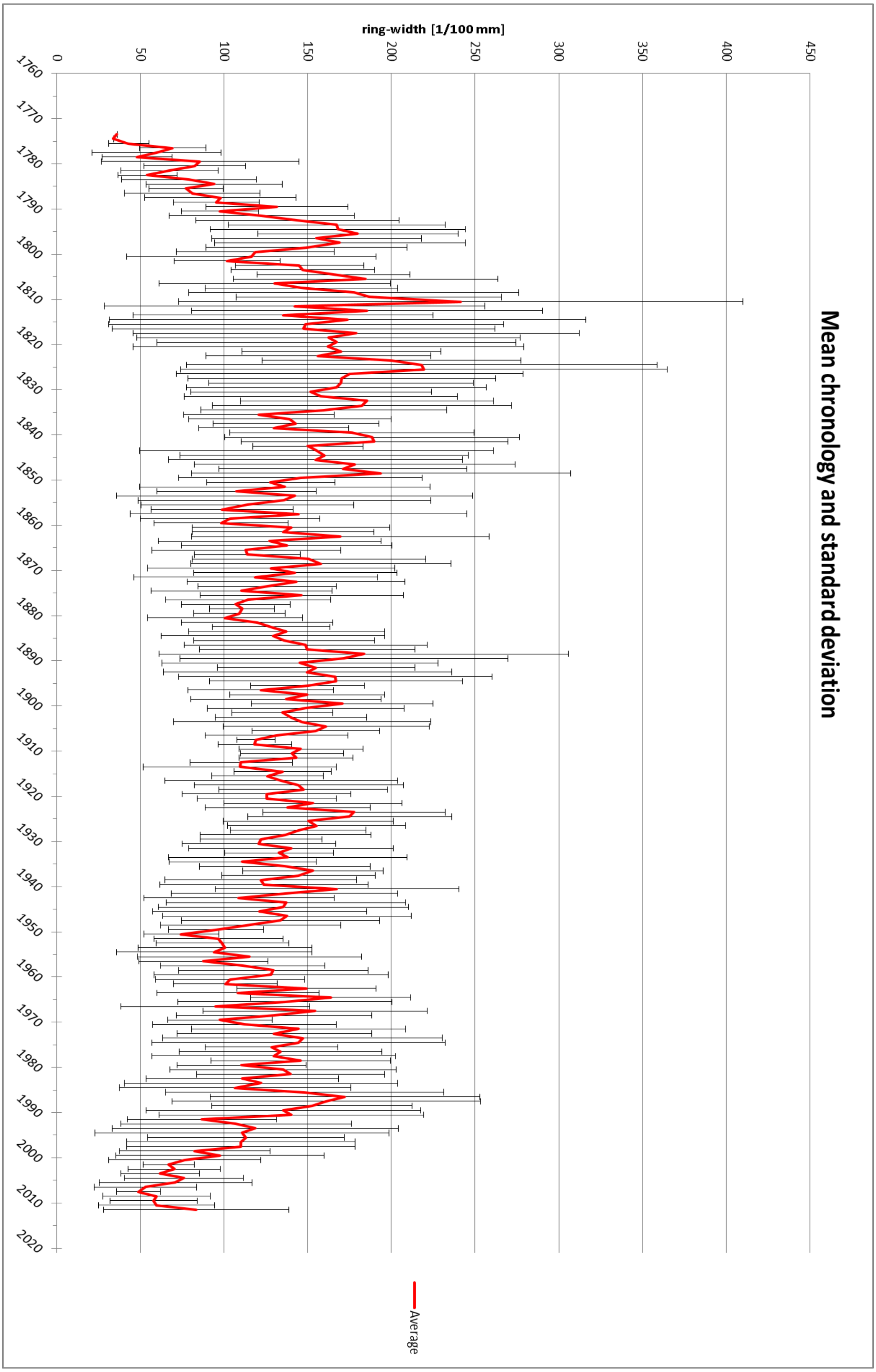


Fig. 8: Mean chronology and the standard deviation.

Each of the six samples was crossdated successfully, and statistical variables (*Gleichläufigkeit*, TV, TVBP, CDI) were calculated. All of them showed acceptably reliable values. However, it is common knowledge that, the higher the sample size, the higher the statistical reliability. This is the reason, why it was decided to work with the mean of the six chronologies. There was the option to use only the three best chronologies, but only three samples were too few.

4.2 Precipitation – drought periods

As drought is considered to be the most limiting factor in tree growth for this region (Cherubini et al., 2003), special attention is given to extreme drought events. For this, the data was divided into different time scales.

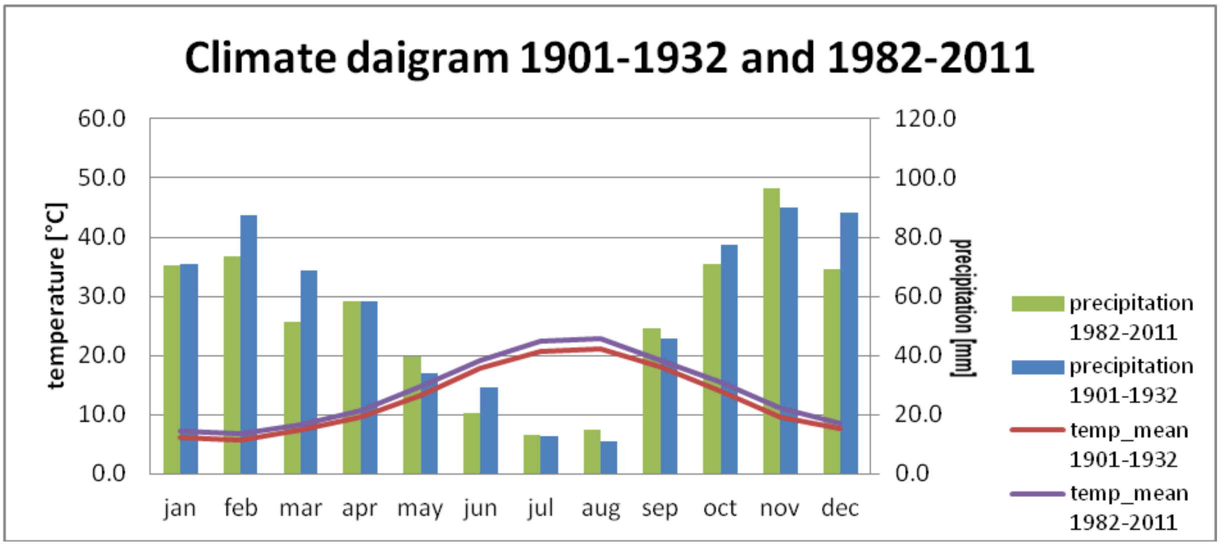


Fig. 9: Two climate diagrams from Nuoro. Blue and red from 1901-1932, green and purple from 1982-2011.

Comparing the climate diagrams form early and late 20th century an increase in temperature could be recognized (see Fig. 9). Precipitation had most changed in the months of February, March and December. These three months showed a decrease in precipitation of together 45.5 mm. Comparing the two periods in a total decrease in precipitation of 58.7 mm was measured. Temperature had increased by 1.1 °C in average with a peak in July (1.7 °C) and August (1.6 °C) as is shown in the Table 8.

It had to be taken into account that Nuoro lies in an altitude of 533 m a.s.l., which is about 420 m lower than the Supramonte. Temperatures in Supramonte are thus lower. Taking into account the +100 m in altitude = -1° C rule of thumb, temperatures are about 4° C lower at

Supramonte. This fact could have led to distortions in the result, but since it was an overall shift of the temperature it should not have affected the calculations in DENDROCLIM2002.

Table 8: Values for Precipitation and mean temperature as shown in Fig. 9 and averages.

	jan	feb	mar	apr	may	jun	jul	aug	sep	oct	nov	dec		
precipitation **1982-2011**	70.5	73.4	51.5	58.2	39.5	20.6	13.2	15.0	49.0	70.9	96.5	69.0	**sum**	627.3
temp_mean **1982-2011**	7.3	6.9	8.3	10.6	14.8	19.1	22.5	22.8	19.2	15.4	11.2	8.5	**average**	13.9
precipitation **1901-1932**	80.9	84.2	65.7	59.8	39.2	23.5	9.8	16.5	45.8	83.2	88.1	89.5	**sum**	686.0
temp_mean **1901-1932**	6.4	6.1	7.7	9.7	13.3	17.9	20.7	21.2	18.3	14.0	10.0	7.6	**average**	12.8

4.3 Basal area increment

The most problematic chronology sections that needed to be detrended were at the beginning of the tree's life, however, as there was no climate records for this period, this section was not used in the further analyses, therefore there was no need for detrending. The BAI was calculated to see if other or better results could be achieved with climate data run with the DENDROCLIM2002 program. The results from the ring-widths were more precise than the ones with the BAI. Nevertheless, the data was calculated and could be used.

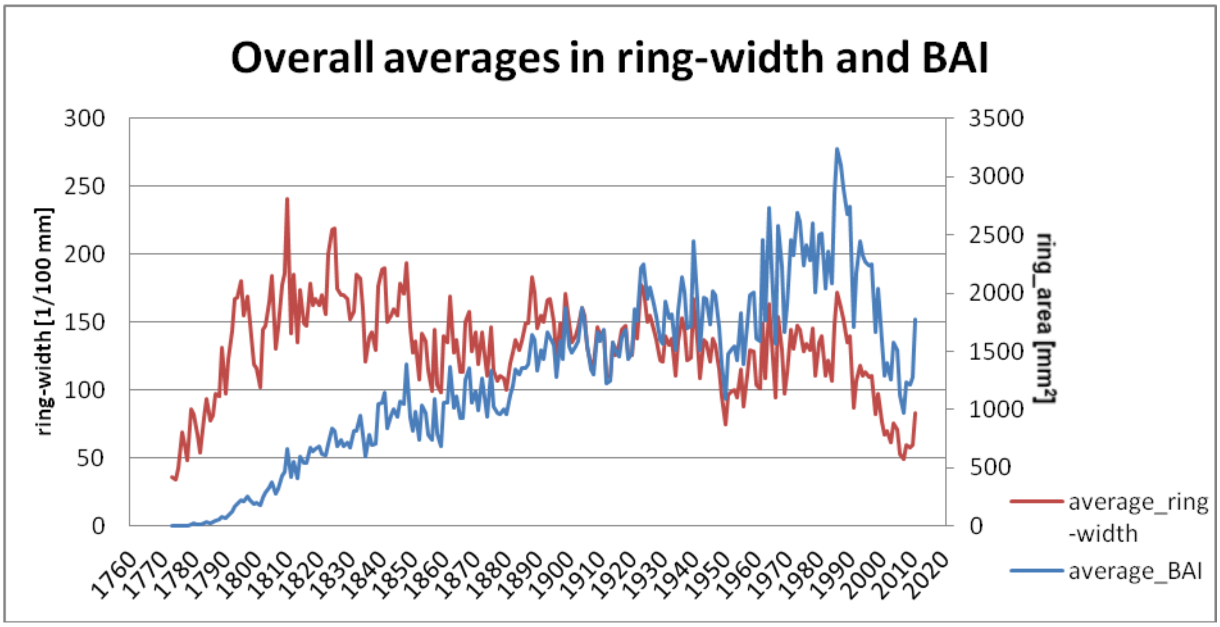


Fig. 10: The mean of the 6 crossdated samples in ring-widths and basal area increments.

Both curves were similar. This was expected as the BAI is calculated on the ring-widths. What could be shown is the diagram was a well overlapping section in the middle, although this is dependent on the scale of the axis. As the diameter of a shoot is small it is not possible to obtain a large basal area increment. This is why the BAI in the first years of the living tree was low. The BAI showed an increase from 0 mm^2 in 1773 to 3245 mm^2 in 1986 which decreased again to 1777 mm^2 in 2011. The ring-width curve looked more like the opposite of the BAI. It had a steep increase in ring-widths from 0.36 mm in 1773 to 2,41 mm in 1810. Between 1811 and 1985 it decreased slowly from 1.86 mm to 1,07 mm. From 1987 to 2011 the decrease was fast form 1.61 mm to 0.83 mm.

4.4 Pointer years

No pointer years were found with a 40% growth change in 75% of the samples. Reducing the growth change parameter to 30%, three pointer years were found, but they are in years not represented by the climate data series measurements at our disposal. A further reduction to 20% resulted in two positive pointer years (1940 and 1980). A positive pointer year means an increase in growth, while a negative pointer year is a decrease in growth. Reducing down to 20% seemed a reasonable decision, since the samples were already averaged curves, built from the average of two chronologies. A further reduction to 15% led to 12 pointer years (see Table 9). However, 15% is not such an interesting growth change. On the other hand, only two pointer years were considered as too few.

Table 9: Pointer years since 1900 with a 15% growth change. 1 are positive and -1 negative pointer years.

Year	Nature
1921	1
1938	-1
1940	1
1950	-1
1963	-1
1965	-1
1966	-1
1967	1
1985	1
1989	-1
1991	-1
2000	-1

At the end, the 12 pointer years were visually compared with the climate data, giving special attention to the two “20%” pointer years (1940 and 1985). Since the main correlation between ring-width and climate data was found with precipitation variable (Campelo et al., 2009; Cartan-Son, 1992; Cherubini et al., 2003; Gea-Izquierdo et al., 2009; Gea-Izquierdo et al.

2011), this factor was considered first. Pointer years were implemented in all monthly and seasonal diagrams (see Appendix 2).

No correlations could be found. The positive pointer years sometimes lay on pronounced precipitation peaks and sometimes in dry seasons. The same was found for the negative pointer years. Unfortunately no trend was recognizable (see Fig. 11). The two marked pointer years with a star show in 1940 a low precipitation peak but in 1985 a low temperature down peak.

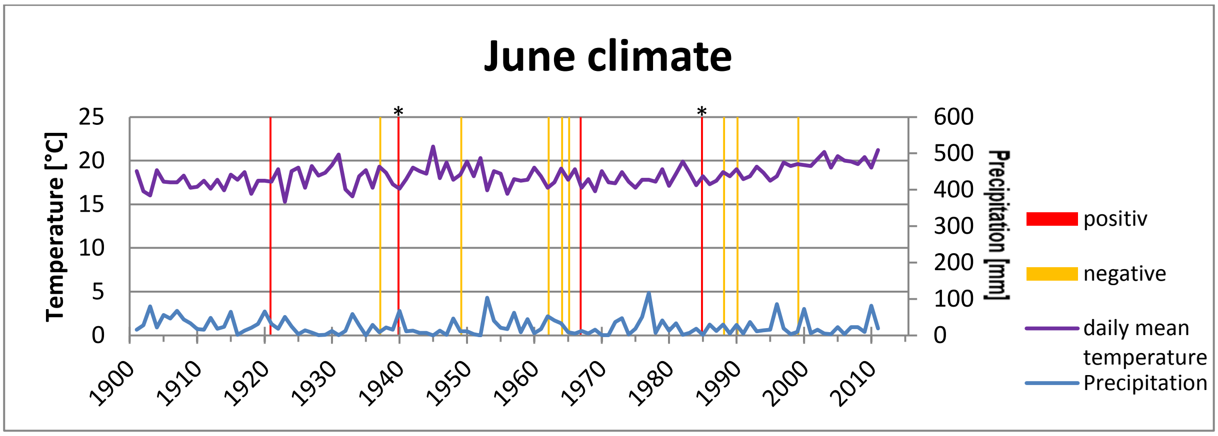


Fig. 11: Precipitation and temperature in June with the 12 positive and negative pointer year. The * indicates the two pointer years with a 20% growth change.

4.5 Tree-ring response to climatic parameters

In each figure of this cahpter, months are indicated with a “T” or a “P” in the end, which stands for temperature and precipitation. Moving interval base length was always set at 72 (2/3 of the number of years in common) as shown in the example of the user manual of DENDROCLIM2002 (Biondi and Waikul, 2004). The higher the base length, the less sensitive the correlation and the least signals are shown. This means that only the values, which strongly differ from the average are going to be significant.

The response function outputs were used in the results, although this signal could lead to confusion due to underestimation of error estimates (Cropper, 1985; Morzukh and Ruark, 1991; Biondi and Waikul, 2004). As the response function considers the natural correlation of temperature and precipitation, the amount of significant values in the output are lower than with the correlation function. Additionally all the calculations were made with the months October to December of the current year. This was done to see, if there is a possible reaction to ring-growth in mild autumns. No significant values were found. Therefore the main focus was set from October of the previous year to September of the current year.

Minimum and maximum temperatures were analyzed. Maximum temperatures were expected to correlate and respond negatively with summer and if minimum temperatures correlate or respond, they were hoped to be found in winter.

4.5.1 RW_mean_of_6_samples results

In the following four figures (Fig. 12 (A),(B) & Fig. 13 (A),(B)) the four possible outputs are shown. These are single interval correlation, single interval response, moving interval correlation and moving interval response. What could be observed was that minimum temperature did show similar signal as maximum temperature. As they both reacted mainly to the summer months, it was believed that the actual signal belongs to the maximum temperature.

Minimum temperature

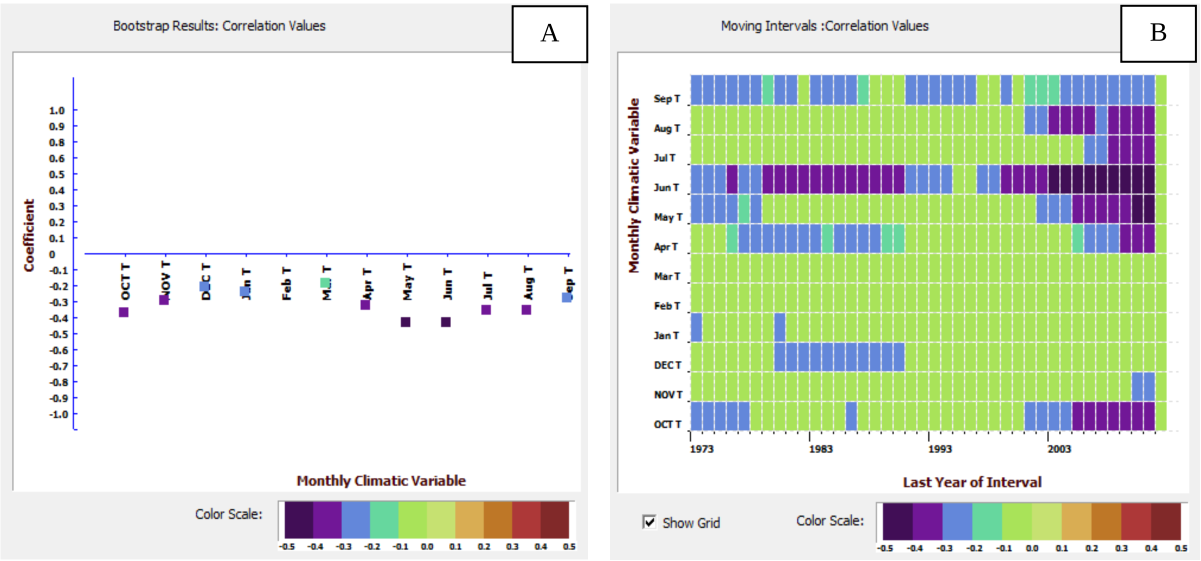


Fig. 12: (A) RW_mean_of_6_samples, t_min, single interval correlation values. **(B)** RW_mean_of_6_samples, t_min, single interval response values.

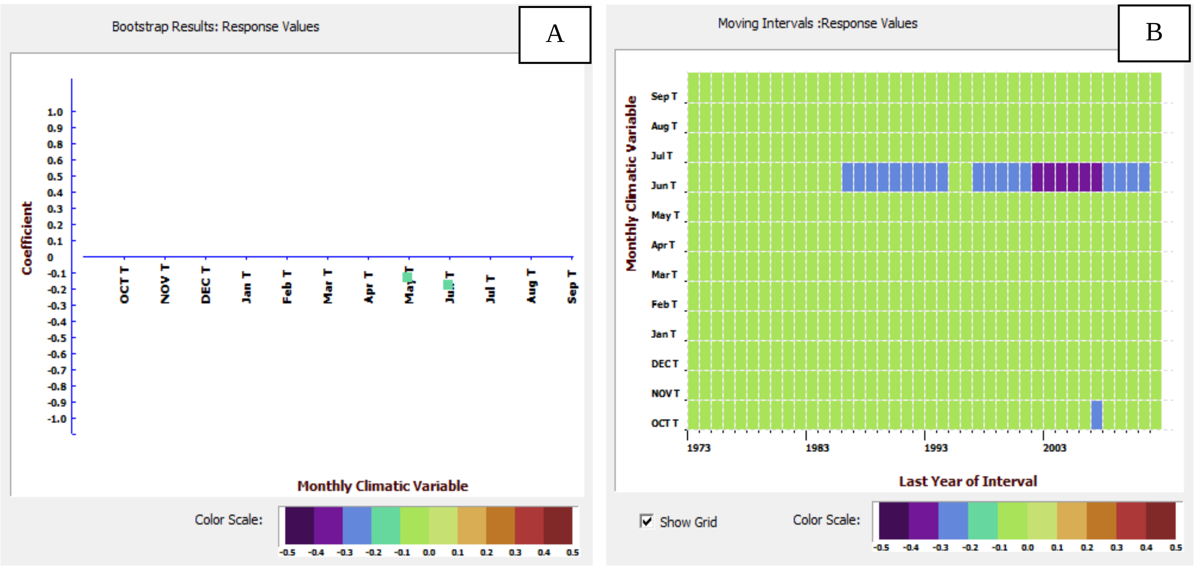


Fig. 13: (A) RW_mean_of_6_samples, t_min, moving interval correlation values. (B) RW_mean_of_6_samples, t_min, moving interval response values.

Only negative correlations and responses could be found with minimum temperature in RW_mean_of_6_samples. Mainly in the last 7 years of the living trees from April to September with a clear peak in June (1999-2011). Other high correlations were visible in October from the previous year (2001). The only response found was negative for June (1986-2011). Further analysis were therefore performed on this month.

Maximum temperature

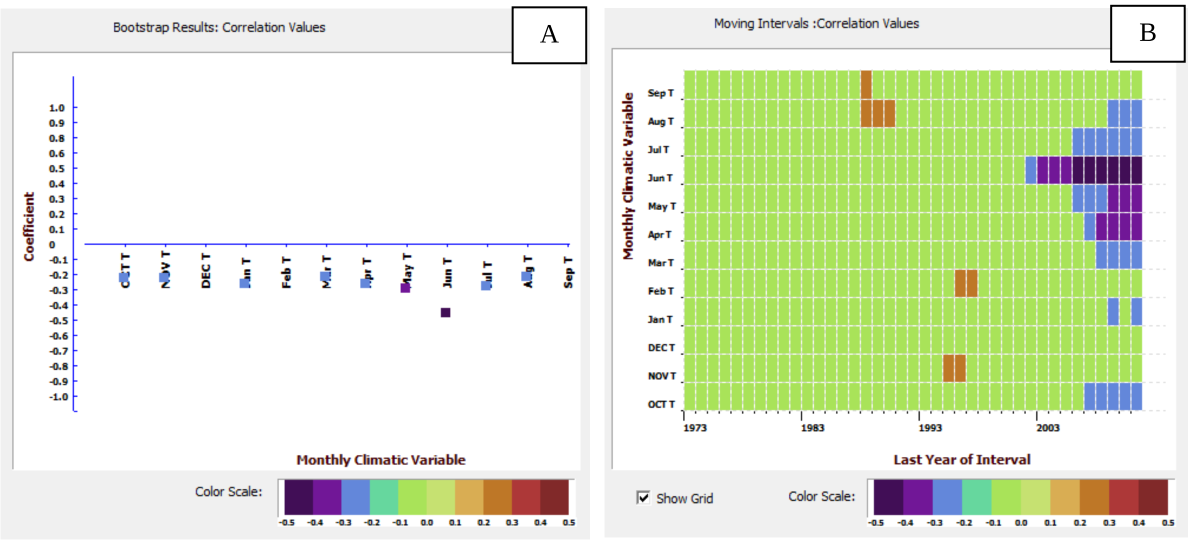


Fig. 14: (A) RW_mean_of_6_samples, t-max, single interval correlation values. (B) RW_mean_of_6_samples, t-max, moving interval correlation values.

Maximum temperature showed no significant response valuses. For this reason they are not shown. The main correlation was comparable to minimum temperature. Negative correlation could be oserved from March until July with a clear peack in June (2002-2011). A positive correlation in RW_mean_of_6_samples was found but not mentionable due to rarity and lower signal. Both temperature profiles (minimum and maximum temperature) showed high negative correlations and low responsens in summer months especially in June. But there were higher negative correlations and responses from RW_mean_of_6_samples with minimum temperature than with maximum temprature.

Precipitation

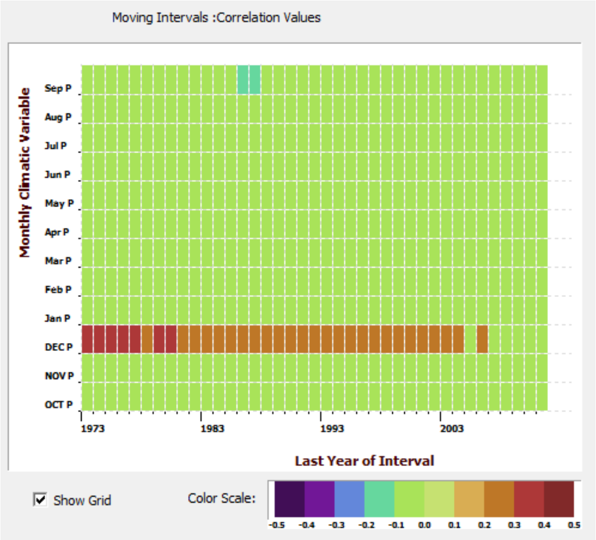


Fig. 15: RW_mean_of_6_samples, precipitation, moving interval correlation values.

With precipitation as a variable, the response and correlation outputs looked the same for single as well as for moving intervals. The moving interval correlation results can be seen in Fig. 15, where the RW_mean_of_6_samples correlated and responded to precipitation in December 1973-2004 of the previous year. Highest correlation values were achieved from 1973-1980.

4.5.2 RW_1 results

Minimum temperature

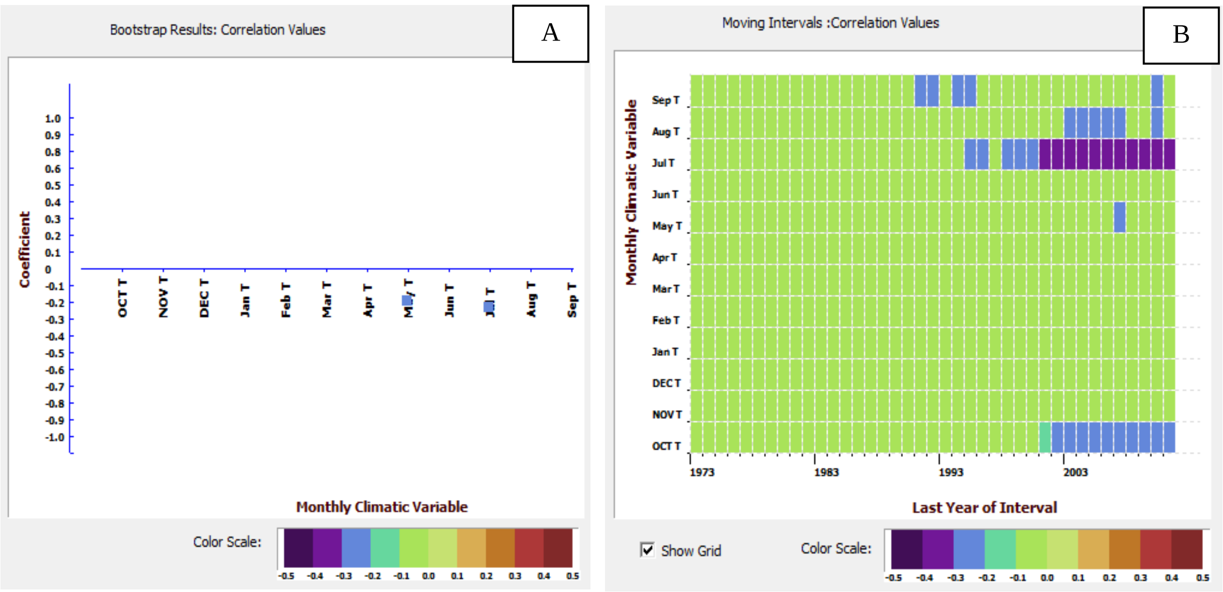


Fig. 16: (A) RW_1_mean, t-min, single interval correlation values. (B) RW_1_mean, t-min, moving interval correlation values.

RW_1_mean showed only negative correlations. No significant response values in single or moving interval analysis were obtained. July showed the highest significant correlation values from 1995 to 2011. Correlation found was only negative. A more decent negative correlation was found in October (2001-2011). Since the single interval analysis correlation showed no significant values for October, the main focus was set on July.

Maximum temperature

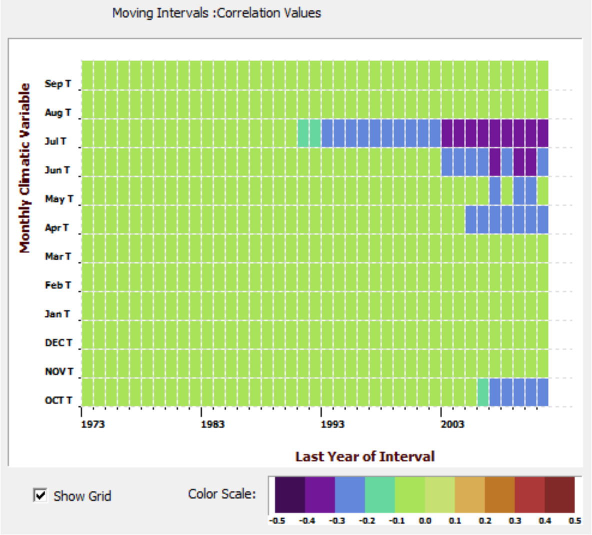


Fig. 17: RW_1_mean, t-max, moving interval correlation values.

Only negative correlations and respond was seen in minimum and maximum temperature mainly in the last 7 years in April, June and July. Highest signals were detected in July starting in 1991 in single and moving interval correlation analysis. Response signals were obtained only in the moving interval in July (1992-2011). October was left aside for the same reasons as in minimum temperatures. Therefore, the main attention was set on July.

Precipitation

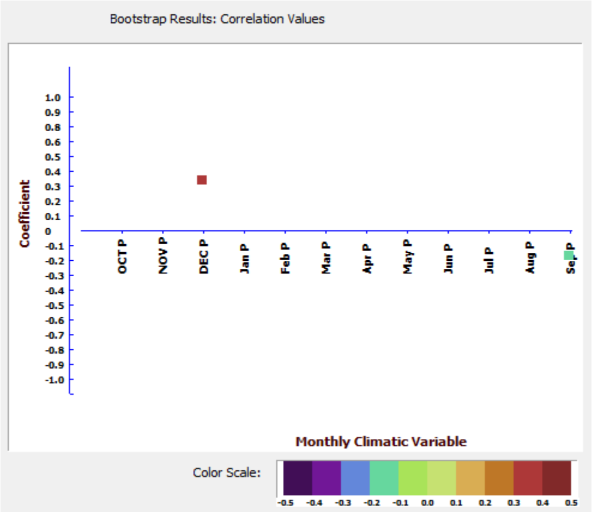


Fig. 18: RW_1_mean, precipitation, single interval response values.

A high positive correlation and response in single and moving interval analysis was found in December. A bit lower negative correlation and response in single and moving interval analysis were found in September. As both showed the signal from 1973 to 2011 the single interval analysis is shown Fig. 18.

4.5.3 RW_7 results

Minimum temperature

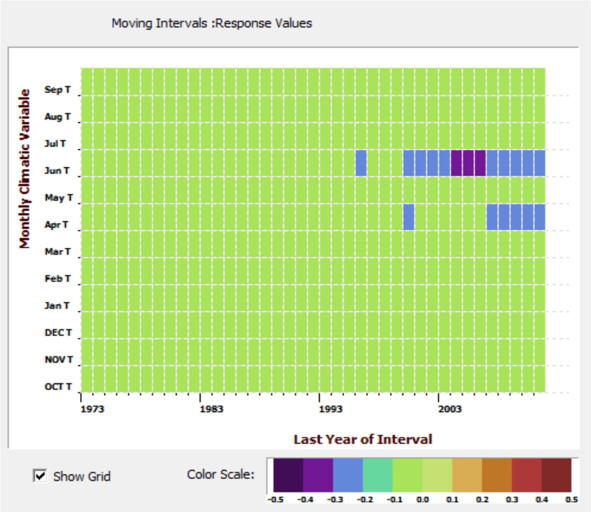


Fig. 19: RW_7_mean, t-min, moving interval response values.

In correlation and response single interval analysis, no significant values were found. Only negative correlations and resposes in moving interval analysis were obtained. July (2000-2011) and April (2007-2011) showed significant values although July values were higher. This is shown in Fig. 19 with the response values.

Maximum temperature

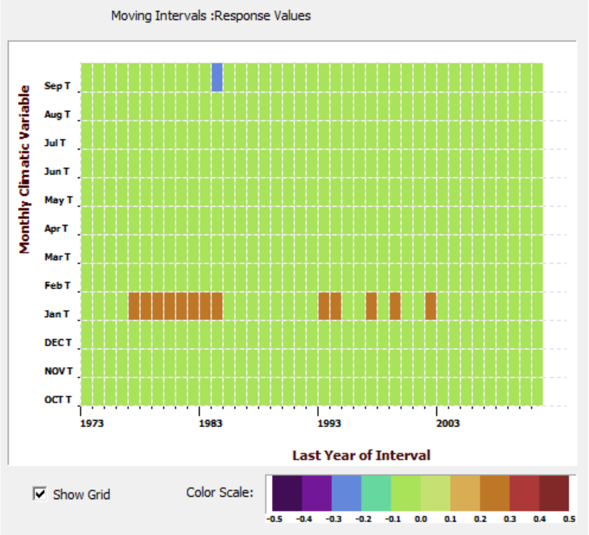


Fig. 20: RW_7_mean, t-max, moving interval response values.

In correlation and response single interval analysis, no significant values were obtaind. Except for a few single negative values only positive values were found in correlation and response moving interval analysis. The main significant values were given in January (1973-2007) on which was set the focus. Correlation values were higher than response values. Other positive correlation values were detected in November, December and February between 1989 and 2000 but only detached. Therefore, they are not going to be disscussed.

Precipitation

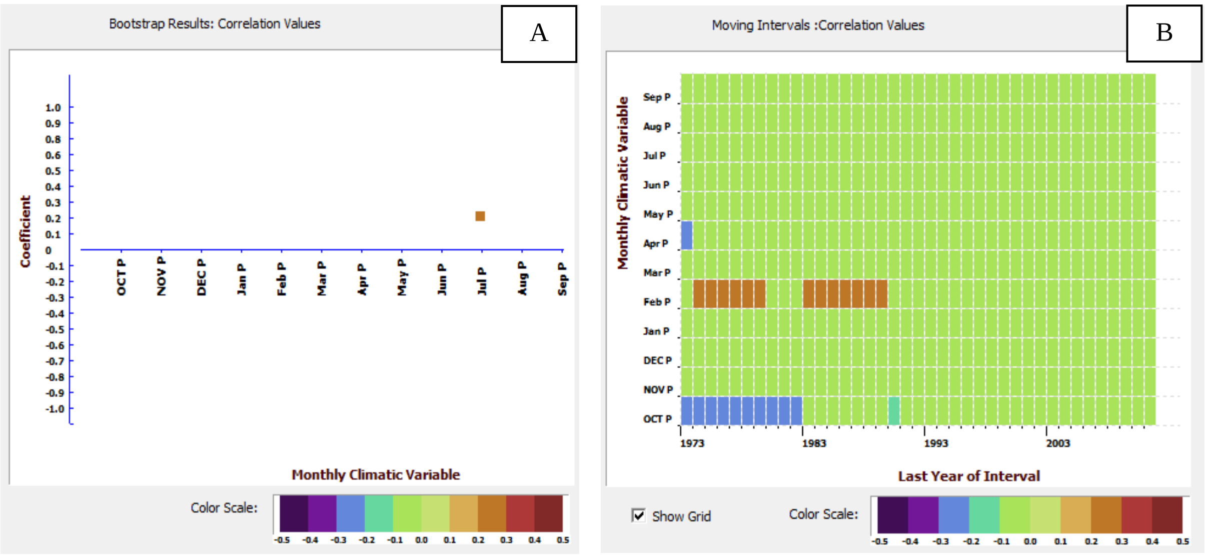


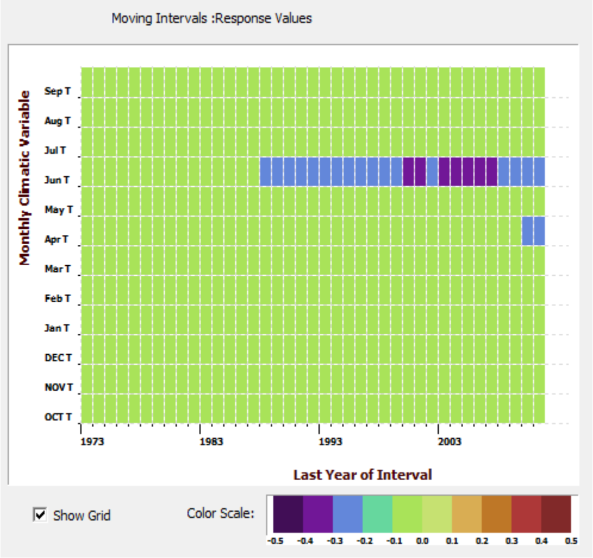
Fig. 21: (A) RW_1_mean, precipitation, single interval correlation values. (B) RW_1_mean, precipitation, moving interval correlation values.

No significant response values were obtained at all. From the single interval output only low significant positive correlation values in July were found. From the moving interval output low positive significant values in February (1974-1979 and 1983-1990) and low significant negative values in October from the previous year (1973-1983) were found. Since the single interval outputs and the moving interval outputs did not equal at all, all three named months were inspected further.

4.5.4 BAI_mean results

Comparing minimum and maximum temperature and precipitation with the mean of BAI, it was found that the response significance values are in generally lower than the correlation values.

Minimum temperature

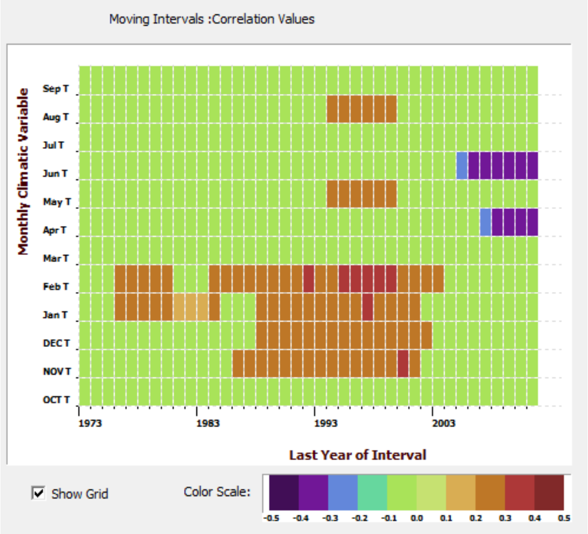


☑ Show Grid

Fig. 22: BAI_mean, t-min, moving interval response values.

In single interval analysis response, no significant values were obtaind. In single interval analysis correlation, low signifiant negative values were found for June. In both moving interval analysis a peak in June was visible. June generated significant values for the timeperiod (1988-2011) (see Fig. 22).

Maximum temperature



☑ Show Grid

Fig. 23: BAI_mean, t-max, moving interval correlation values.

Only scarce reponse values were found in the moving interval analysis, while in the single interval analysis no significance was detected. The same counts for correlation values. That was the reason why only the results of the correlation values of the moving interval analysis are proposed.

Nearly all months showed significant correlation values in some consecutive years except October, March, July and September. Negative significant correlation values were found in April (2007-2011) and June (2005-2011). Positive significant correlation values were visible in November and December from the previous year and January and February from the current year from 1988 to 2002 and in a shorter period in May and August (1994-2000). It was difficult to highlight the important responses, and in the end, November until February from 1988 to 2002 and June and April from 2007 to 2011, were considered.

Precipitation

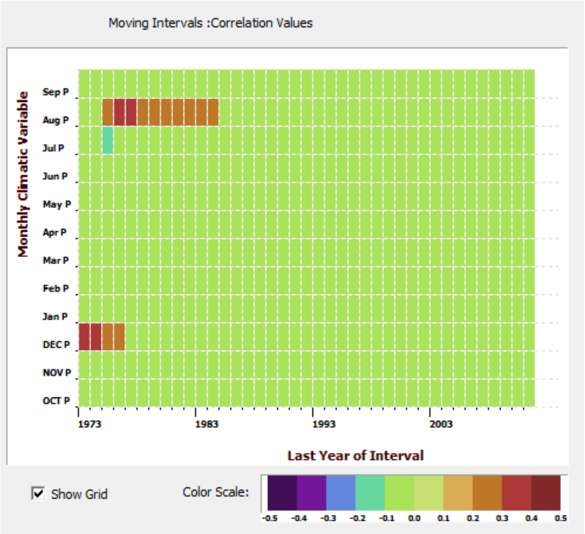


Fig. 24: BAI_mean, precipitation, moving interval correlation values

For precipitation no significant single interval analysis values were obtained. Only some significant moving interval analysis values were generated. There is a positive significant correlation form precipitation in August from 1975 to 1985.

5 Discussion

In traditional dendroclimatology and dendroecology research, a number of six samples would not be satisfying to ensure the representation of the study's outputs, and the same stands for statistical analyses. Speer (2010) stated that 20 trees, which are always measured from two sides, are needed to remove the signal of each individual tree to have a site and species specific chronology. Nevertheless, this were the samples that were able to be collect with the available time and economic resources, and therefore it had to be understood that the results might still be holding noise from single trees trends, and that this was the limit for this thesis.

A problem that arose with a too low sample numbers was for example, shown in Fig. 6, where the year 2011 was increasing in the average. This was mostly due to sample n. 1, which presented a damage on the bark side. Therefore its measurement was difficult and less accurate. The year 2001 did not contain sample n. 2 and n. 4. The other three samples showed a decrease in growth for 2011. The increase of sample n.1 was so high, that the mean was pushed up due to the high growth value of this sample. If more samples would show a common response, single outliers would not have had such a high influence on the mean, and this is where the low sample size is showing its downsides.

The fact that nearly all samples have more or less the same age led to the assumption, that something must have happened back then. In order to find an answer to this question, information about wild fire incidents or logging activities were gathered. However, no significant event record was found. It was also taken into account, that the effective age of the trees is two to five years older than the oldest year found, but this did not change the result. Nevertheless, this was the longest holm oak chronology obtained so far (1773 A.D.).

5.1 Ring-widths

The crossdating was successful as it can be seen by the final crossdated curves, which at a visual comparison appeared to have similar trends (see Table 1). The extra effort to mark each ring that held uncertainties manually resulted to be a good decision, so that a reliable chronology was obtained. However, the results from the Pearson correlations were slightly disconcerting, since many of them returned negative values, and just sample 1 and 2 reported a good positive correlation. A possible explanation to this issue could be found in measurement errors, errors in the crossdating process or other factors, which affected the tree growth and therefore led to irregularities in tree-ring formation.

In fact, in this case, ring measurements could not be done following the classical method, which envisaged a straight line from bark to pith, because of the numerous irregularities of the samples. However, even if stem disks and not cores were used, in order to minimize the effect of wedging rings or at least to have the chance to correct possible uncertain years (Worbes, 2002).This could also be the explanation, why the samples did no correlate among each other because the cumulated amount of mistakes made it impossible to reach a final chronology, which could fit all samples, and due to the small sample size no final decision to rectify single chronologies could be made. Another hypothesis is that samples variation might be a result of concurrence or differences of genetic patterns among samples (Michaud et al., 1992; Worbes, 2002). Nevertheless, the contrast between different years was sufficient to create a chronology, therefore the question whether ring-widths were too homogenous to be counted, can be answered negatively. The only issue that remains to be improved the reliability of the resulting chronology, would be the sample size, which must be expanded, in order to have the chance to minimize the uncertainty of attributing a wedging ring to a year.

5.2 Pointer years

The question whether pointer years could be assigned to the extreme values in temperature or precipitation or both, could not have a direct answer because there were no pattern recognized around the pointer years. Positive pointer years were hoped to be found in precipitation rich years and mild sommer temperatures. In contrast, negative pointer years were hoped to match with low spring and summer precipitation and high summer temperaruter. Both, positive and negative pointer years failed to be matched with the accordingly temperature or precipitation on yearly, seasonal or monthly basis. The low sample size could again be an expanatory factor for this findings. With a higher sample size pointer years could have been calculated in a more reliable way. Another reason why no clear signal could be recognised could be that temperature and precipitation have a more complex influence on holm oak than assumed. It could be therefore, that there was a scale problem, as the data used was an average over a month, intra-monthly peaks got smoothed. Pointer years were laying on local climate data peak values but did not follow a trend and no pointer years were found at climate data extrem peaks (see Fig. 11).

5.3 Tree-ring response to climatic parameters

The outputs from DENDROCLIM2002 showed a very clear correlation and response with different months in precipitation and minimum and maximum temperature. The results of Dendroclim were satisfiying. The base length applied lead to results from only 1973 to 2011 which at first sight might looks like a waste of information. However, these results were more sensitive to the calculations.

In Table 11 a broad overview about the main correlations and responses with climate and the different input chronologies is shown.

Table 10: Main correlations and responses with different climate data. In blue the negative correlation are shown and in red the positive.

	T_min	**T_max**	**Precipitation**
RW_mean	June	June	December
RW_1	July	July	December
RW_7	June	January	several
BAI_mean	June	several	August

Precipitation in any month always showed a positive effect on tree growth. This can be taken as a fact, that precipitation is indeed a limiting factor for holm oak in Supramonte especially in summer. RW_1 showed the clearer and more logical signal than RW_7. Both correlated very well with the mean of the average of the six samples mean. Even though sample n. 1 was considered the more reliable. High temperature had a positive effects to tree growth in winter and a negative effectin summer. In former studies correlations in ring-width growth have been found for precipitation in June and July (Cartan-Son, 1992; Gea-Izquierdo et al., 2009), in February and September (Cherubini et al., 2003) and in previous Autumn and current January and May (Campelo et al., 2009). All of these three studies found higher correlation of ring-growth with precipitation than with temperature. In this study it was found, that temperature had higher significant values than precipitation. Taking into consideration the possibility that since there is a decrease in rain, there is going to be also a decrease in overall cloud coverage. Therefore, less clouds mean more sunny days, which result in higher temperatures. So in the end, the high response to temperature is also due to less precipitation. Summarized it can be said, that there is a reaction from temperature and precipitation visible in holm oak. A more detailed analysis is given in the four following subchaprters (5.3.1-5.3.4).

5.3.1 RW_mean_of_6_samples

In opposition with the results from Cartan-Son (1992), Cherubini et al. (2003), Gea-Izquierdo et al. (2009) and Gea-Izquierdo et al. (2011) it was found that precipitation correlated with December of the “previous year”. This is not exactly what was expected. December is one of the precipitation richest months in Nuoro. In December trees are expected not to have any cambial activity due to low temperature. Although, this assumption could be invalidated in case of mild December temperatures. But this could be an explanation only for sparse events and not for a longer period like DENDROCLIM2002 showed. Holm oak has deep roots and could be able to store precipitation from December until spring (Biondi and Waikul, 2004). In fact, this would be the case when precipitation stayed in from of snow. This is the more plausible solution taking into consideration that the samples were taken from trees, which fell due to the heavy snow in winter 2011. Also in contrary to the before mentioned studies, temperature seems to have a higher impact than precipitation. This all could lay at the specific site of Supramonte compared to the other studies, but here again, with the low sample size it is difficult to get reliable answers.

The negative influence on tree growht due to temperature in June could be explained by the rising temperature in June (see Fig. 6 and Appendix 3). This could be found in both, minimum and maximum temperature. Holm oak produced narrower rings due to temperature risnig in the last 30 years.

5.3.2 RW_1_mean

The results from sample n. 1 gave a clear trend how climate could affect tree growth of holm oak. Minimum and maximum temperatures showed a significant signal in the last two decades. Rising temperatures seemed to limit tree growth especially in July where temperatures were among the highest.

Negative September values in precipitation were also found by Cherubini et al., (2003). For positive December precipitation values the same could be said as for the result of the mean_of_6_samples. Sample n. 1 gave even higher correlation and response values for December precipitation than the mean_of_6_samples. It was believed that this occurred through snow accumulation. It would have been very interesting to have data on snow amount. Because, subtracting the estimated 4° C for the height difference from Nuoro to Supramonte, average temperature for winter is still around 3.5° C nowadays. This does not mean, that it could not snow in winter, but the signal for precipitation would be expected to at least lower since the last 30 years in the DENDROCLIM2002 output. Furthermore, the 4° C are estimated with a rule of thumb. It could be more than 4° C. In conclusion RW_1_mean showed very plausible outcomes for the climate variables.

5.3.3 RW_7_mean

July belongs to the hottest months like June, in fact sample n. 7 showed significant values for minimum temperature in July. This could be explained with an increase in July's temperatures. The significant response values counted the last ten years and the last twenty years for significant correlation values. Even thought it could be expected that the significant time period could have been longer, especially for the response values, because the climatic trend was already showing a change in the '80s.

Maximum temperature did not show significant values in summer months as expected, but seemed to influence tree growth in January positively. First this sounded reasonable but looking at the years (1973-2007) in which the significant values were obtained, no apparent explanation could be given. If the values would have been found from 1980 to 2011 it could have been explained with the higher temperature values in this period, but it appeared to be the opposite. As there were no significant single interval analysis values, which normally is the case when finding significant values in the moving interval analysis, the moving interval results had to be regarded with caution.

Precipitation showed debatable values. As already presented, no response was found in the results, and single interval correlation values differ from moving interval correlation. The only significant values that could be explained were the ones from the single interval correlation. With higher precipitation in July, tree growth is influenced positively. The July climate diagram (see Appendix 3), in fact showed some precipitation richer years (1976-2002) compared to the average from 1901-2011. The positive influence from February precipitation could not be explained, as no signs for higher amount of precipitation could be found. No explanation for the negative influence on precipitation in October was found. Precipitation values for the proposed years by DENDROCLIM2002 were not too high (flood) or too low (drought), neither was there snow (taking the temperature into account). In conclusion, the present analysis of tree-rings and climate relationships, is not giving an exhaustive explanation to understand the tree-ring outcome of sample n 7.

5.3.4 BAI_mean

Minimum temperature showed a nice correlation and response with June for the last two decades. This was found as well in RW_mean_of_6 and RW_1_mean and could be explained with the same reason. Maximum temperature shows a more diffuse output. The positive correlated period from 1988 to 2002 from November to February could not be explained. Maximum temperature showed no variation for these months, but having warmer winter temperatures would be an explanation because than tree growth could start earlier and build area richer rings.The short negative correlated period could be explained by the steep increase of maximum temperature in April and in June although the time period could have been expected to be longer as the increasing in temperature was already visible 30 years ago (see Appendix 3). From 1975 to 1985 there was a ten year sequence with more pronounced precipitation than in average. As August still could be counted to the dryer months, a positive correlation seems reasonable. In conclusion it could be said that temperature and precipitation gave logical results but the positive values from maximum temperature could not be explained.

5.4 Ring-widths or BAIs

Looking at the final outcomes, both datasets gave results about possible correlations and responses. Some results came out as expected others less. As it was difficult to say what was the true factor, which provokes a significant signal in the DENDROCLIM2002 output, both could be right. To prove whether DENDROCLIM2002 ran more reliable with ring-widths or with BAIs further research is required. From the current point of view ring-width chronologies would be preferred, as they gave more reliable outputs especially with maximum temperature. Another criteria, which emphasized choosing ring-widths, was the overall higher output level of significant values especially in the single moving interval analysis. If the samples would be younger, it could possibly be that BAIs were preferred, due to the age trend equalization.

5.5 Climate variability effect on ring-with pattern

The main variability found was by DENDROCLIM2002. Unfortunately the pointer years did not match with temperature neither with precipitation. Especially in the 30 most recent years it was very difficult to identify ring borders because they were too narrow and homogenous. What could be observed was that in general correlations started at the beginning of the output data (1973) and ended at arround 1986 or the opposite happened. Correlations started at mid 80ties until 2011. This led to the assumtion that something changed arround that time. This is most probably due to climate change, because since the eighties, temperatures are rising (see Appendix 3). The point is, that since then also a decrease of both ring-widths and BAIs was detectable. It was difficult to say whether the climate played a role in the falling down of the trees or if it was, as by the local foresters told, due to the haevy snow. Most probably it was a combination. Trees were already suffering from stress and could not withstand the weight of the snow. It would be interesting to analysis stem disk of living trees to see if they also show this decrease since the last 30 years. Another option, which had to be taken into acount was a infestation,of *Phytophthora quercina* for example, althought holm oak possesses hard wood, which has a protecting function (Robin et al., 1998). Nevertheless, as pointer years failed to be assingned to specific temperature or precipitation peaks, no reconsturction of past climate condition was able to be done.

6 Conclusions and Outlook

In order to produce a reliable chronology for holm oak whole stem disks need to be collected. Coring *Quercus ilex* is too time consuming and might even be impossible as its wood is too dense and the analysis of tree-rings might be misled by wood irregularities. To avoid irregularities it is important to choose high altitude situated research fields, or more in general sites with rigid winters, so rings are more likely to be visible. Even though difficulties such as wedging rings can lead to measure mistakes. Having stem disks makes it possible to follow wedging rings but still is difficult. Thanks to stem disks IADFs are easier detected. With cores this would not be an option and measure errors would be too high.

Unfortunately the pointer year assignment to climate was not possible. The main findings of this study, therefore, were the negative significant correlation between June and July temperature and the positive significant correlation between December and precipitation associated with tree growth. But in this case it has to be considered, that June and July temperature are also dependent from the precipitation in the same months. Less precipitation means less clouds, which leads to more sunny days and this results in higher temperatures. Therefore it is difficult to say whether temperature or precipitation has the higher influence on tree growth. Furthermore, ring-width chronologies are chosen prior to basal area increment chronologies to be run with DENDROCLIM2002.

Comparing the climate diagrams with the two periods there is an increase in temperature. If this process will continue and precipitation stays about the same the three drought period could become longer. It is difficult make a prognosis, especially as precipitation can vary locally but this surly will have an impact on holm oak growth. It might not particularly affect the Supramonte stand, as it is a more wet location, but it certainly will affect the warmer stands as Gea-Izquierdo et al. (2011) predicted. As was shown, the rings already started to get narrower over the past 30 years. To be sure that this was due to climate change, living holm oaks should be sampled. To better understand the consequences for holm oak and to obtain more significant results, further studies with enough sample numbers are required. Nevertheless, it was possible to provide the longest chronology ever measured for holm oak. With a bigger sample size it is hoped to be able to achieve higher correlation between the samples in order to assign pointer years to climate.

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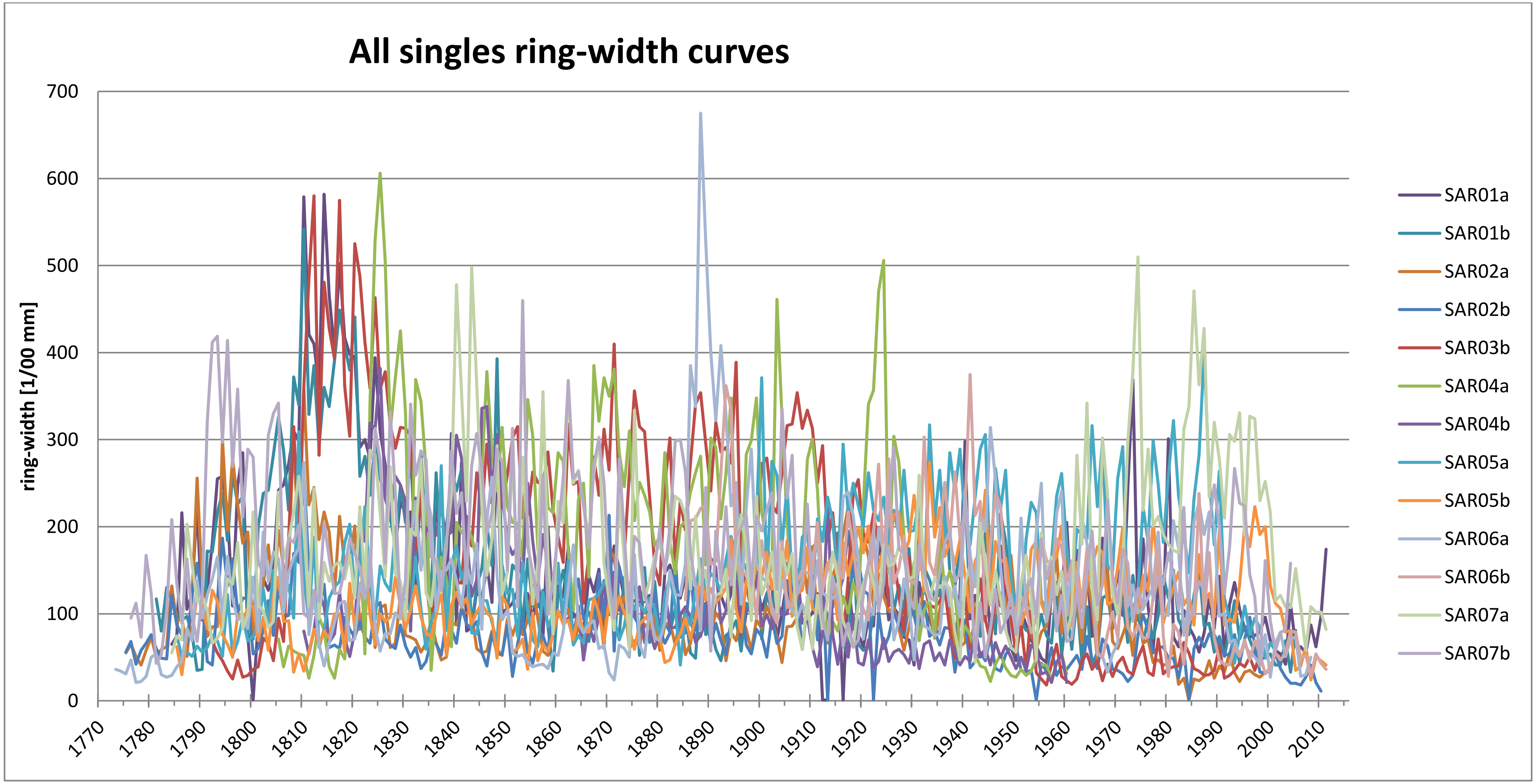
Climate and holm oak distribution data

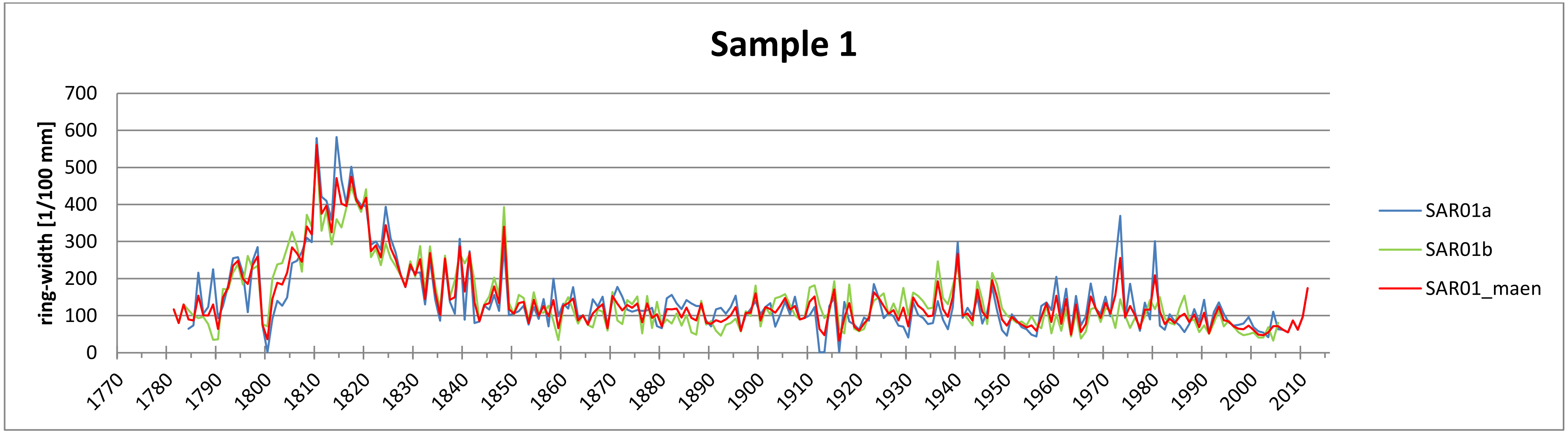
Climate data for Nuoro (1901-2011). CRU database (Climate Research Unit, University of East Anglia, Norwich, UK)

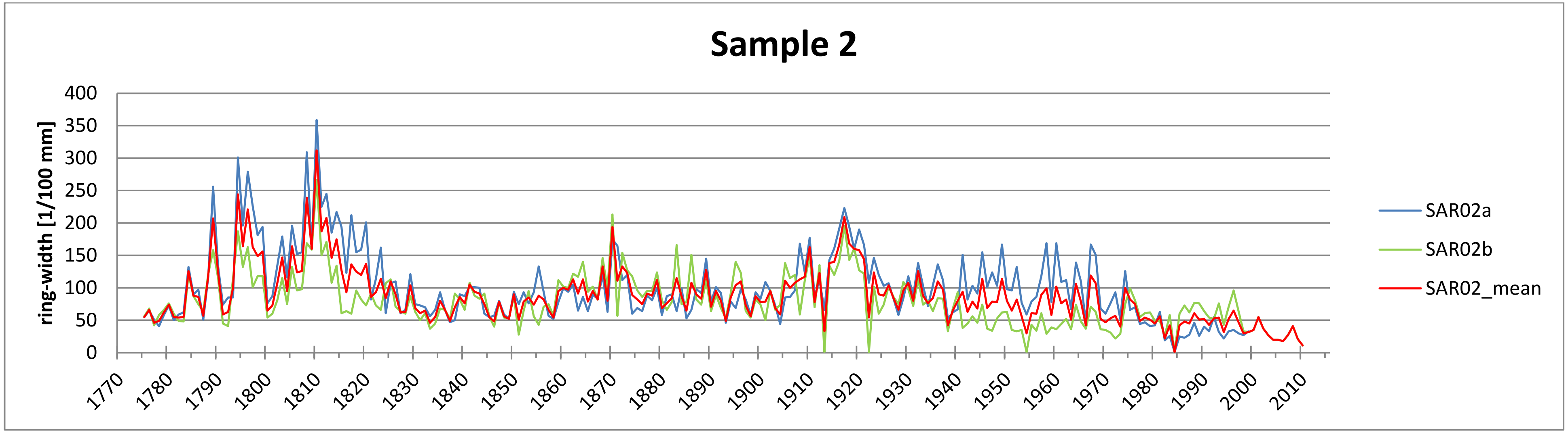
Distribution data for holm oak, which was used by Delzon et al. (2013) for map visualization. http://inventaire-forestier.ign.fr/edb/query/show-query-form#consultation_panel, (last access: 30th August 2014)

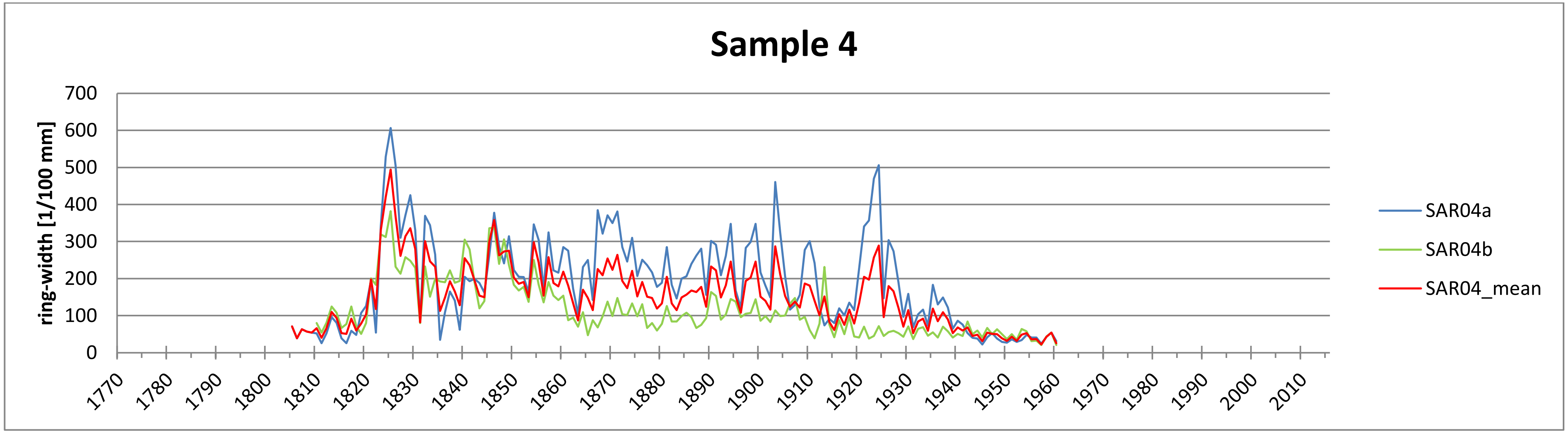
Appendix

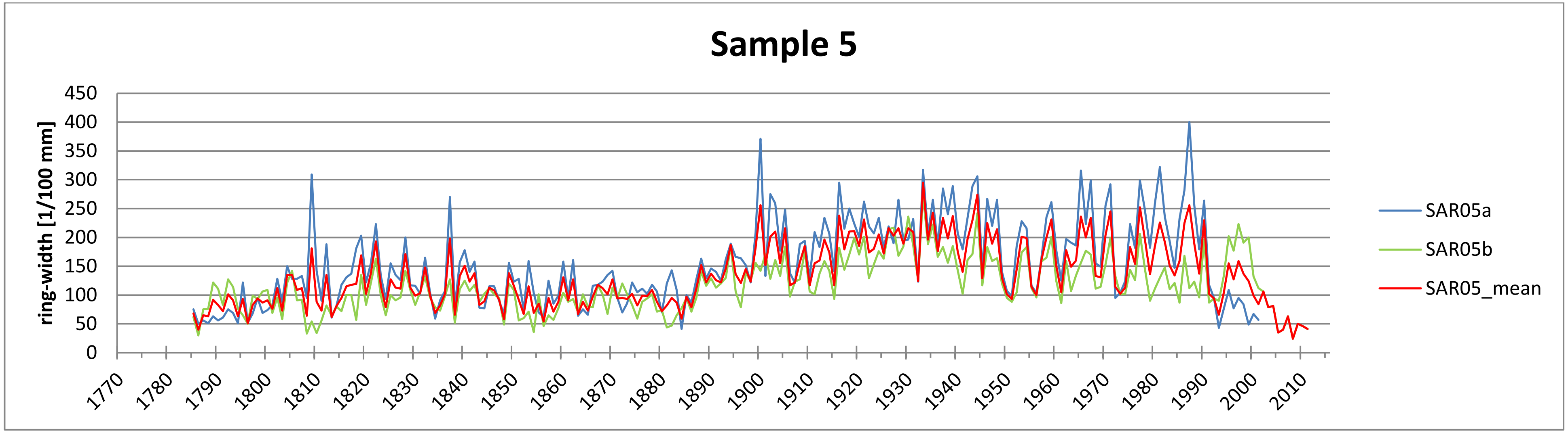
Appendix 1: Chronologies

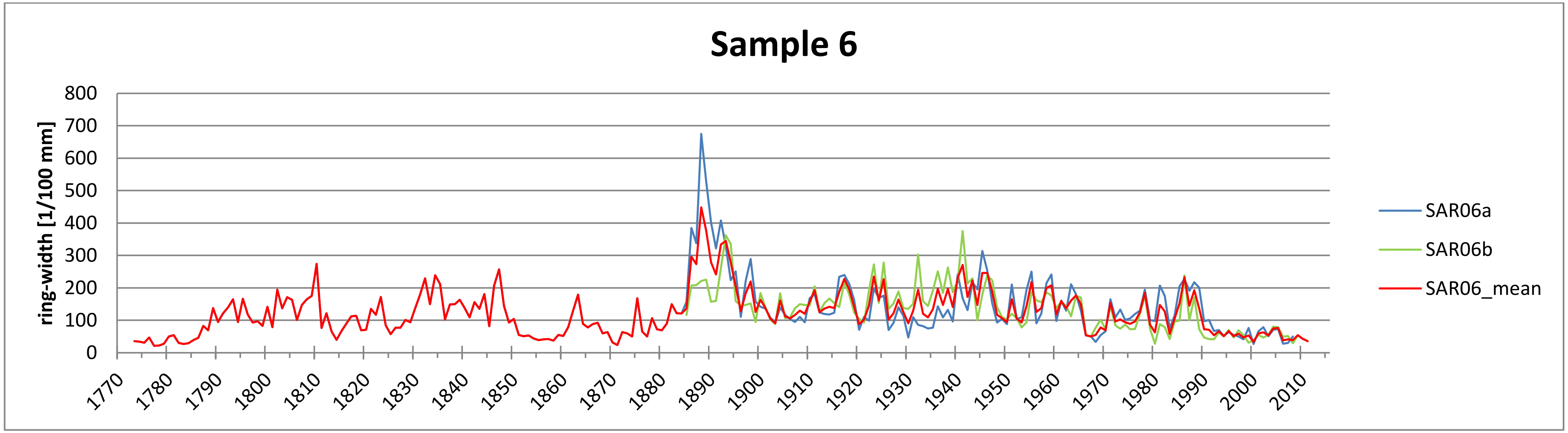


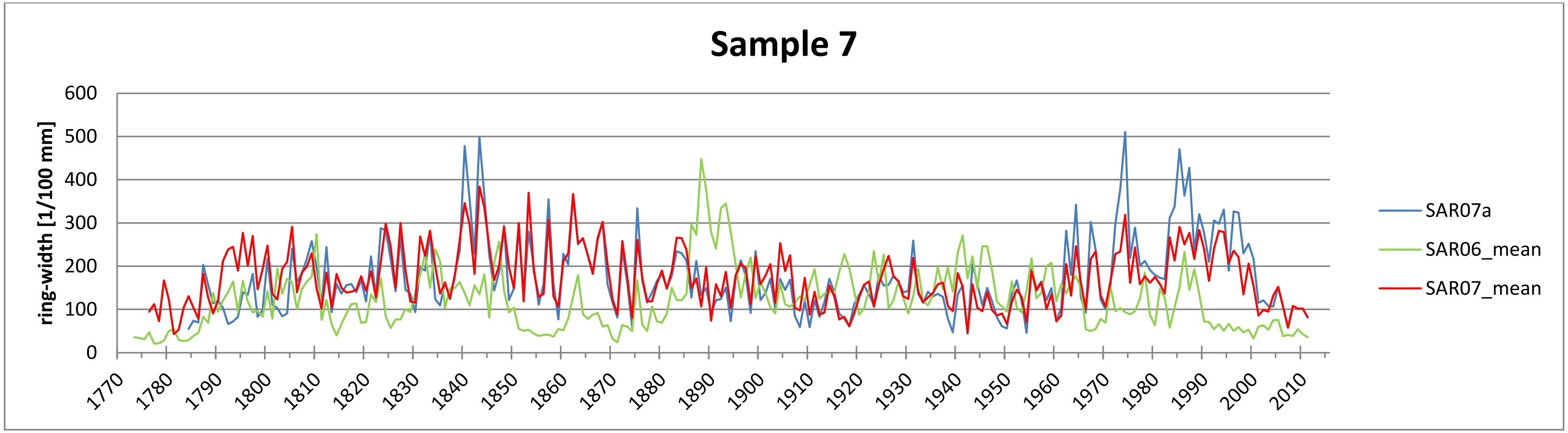

Sample 1
ring-width [1/100 mm]
700
600
500
400
300
200
100
0
1770
1780
1790
1800
1810
1820
1830
1840
1850
1860
1870
1880
1890
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
SAR01a
SAR01b
SAR01_maen


Sample 2
ring-width [1/100 mm]
400
350
300
250
200
150
100
50
0
1770
1780
1790
1800
1810
1820
1830
1840
1850
1860
1870
1880
1890
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
SAR02a
SAR02b
SAR02_mean


Sample 4
ring-width [1/100 mm]
700
600
500
400
300
200
100
0
1770
1780
1790
1800
1810
1820
1830
1840
1850
1860
1870
1880
1890
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
SAR04a
SAR04b
SAR04_mean

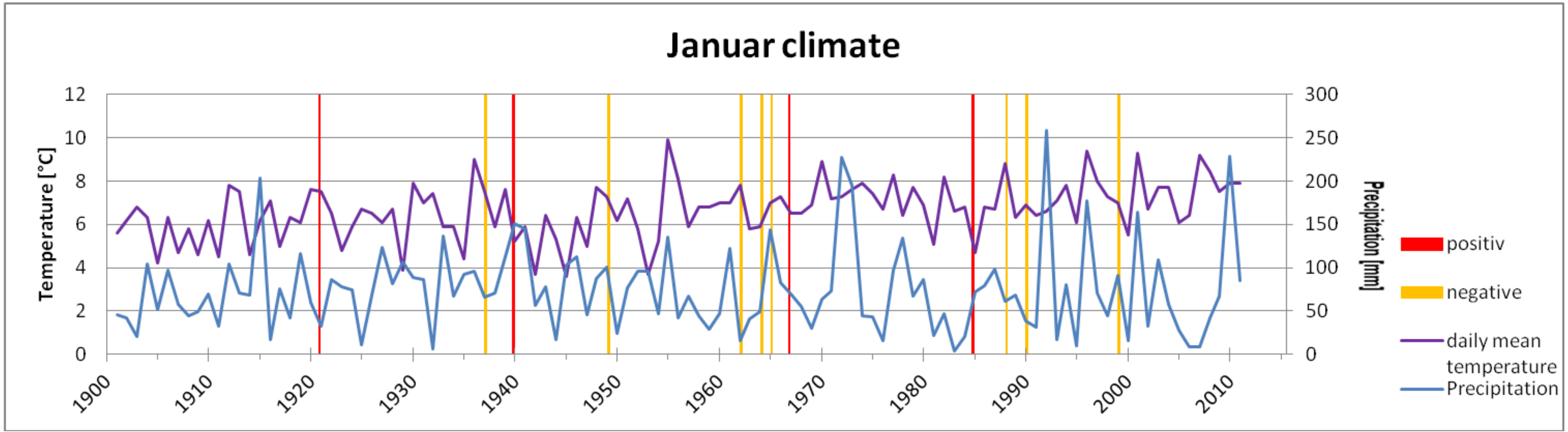

Sample 5
ring-width [1/100 mm]
450
400
350
300
250
200
150
100
50
0
1770
1780
1790
1800
1810
1820
1830
1840
1850
1860
1870
1880
1890
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
SAR05a
SAR05b
SAR05_mean

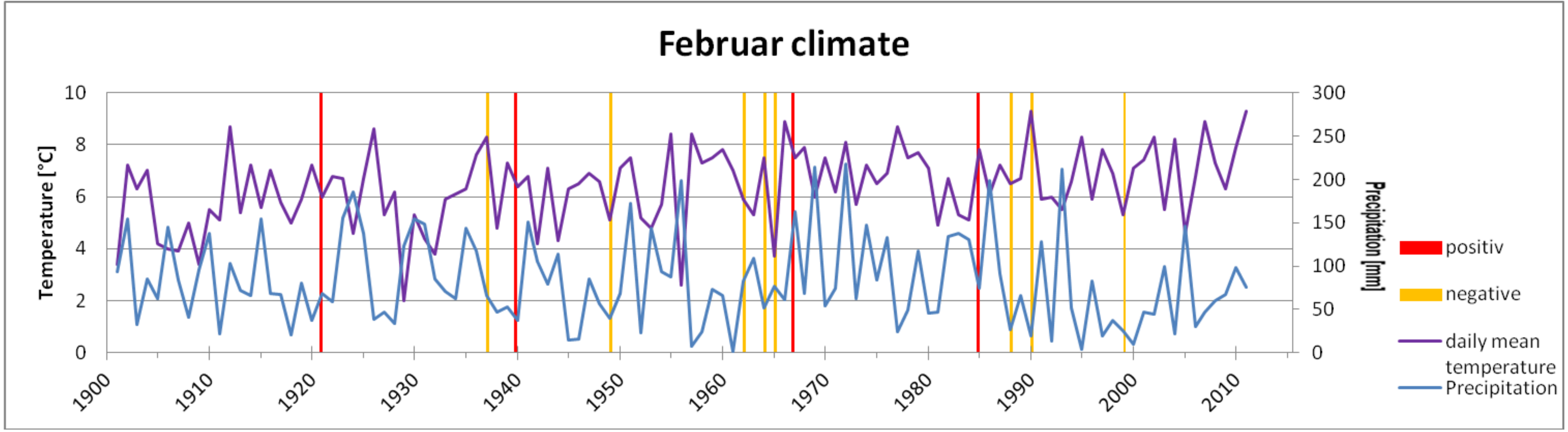

Sample 6
ring-width [1/100 mm]
800
700
600
500
400
300
200
100
0
1770
1780
1790
1800
1810
1820
1830
1840
1850
1860
1870
1880
1890
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
SAR06a
SAR06b
SAR06_mean

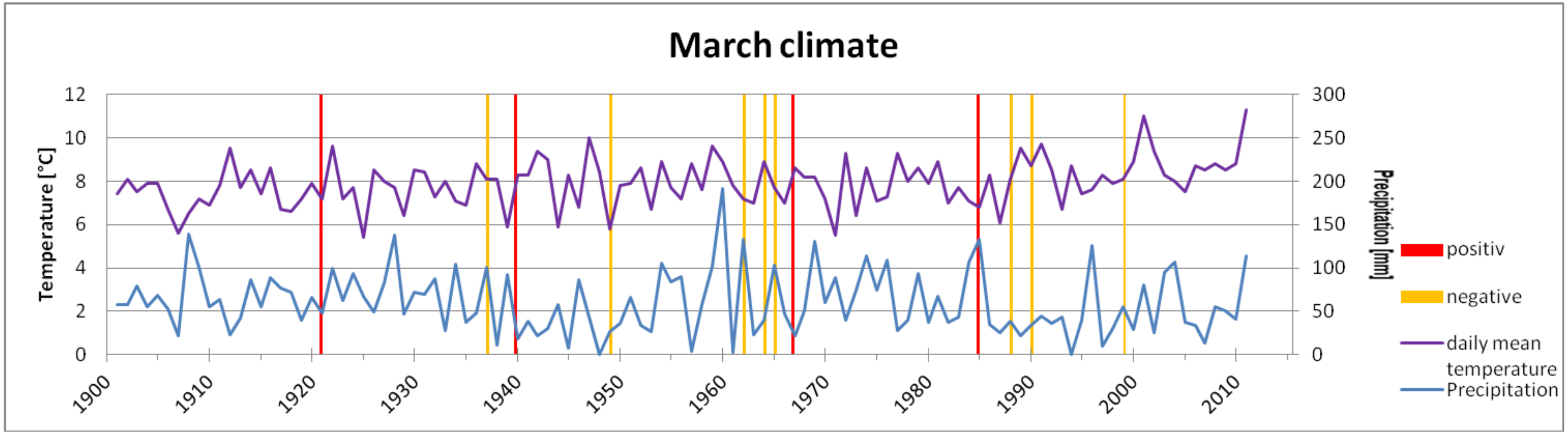

Sample 7
ring-width [1/100 mm]
600
500
400
300
200
100
0
1770
1780
1790
1800
1810
1820
1830
1840
1850
1860
1870
1880
1890
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
SAR07a
SAR06_mean
SAR07_mean

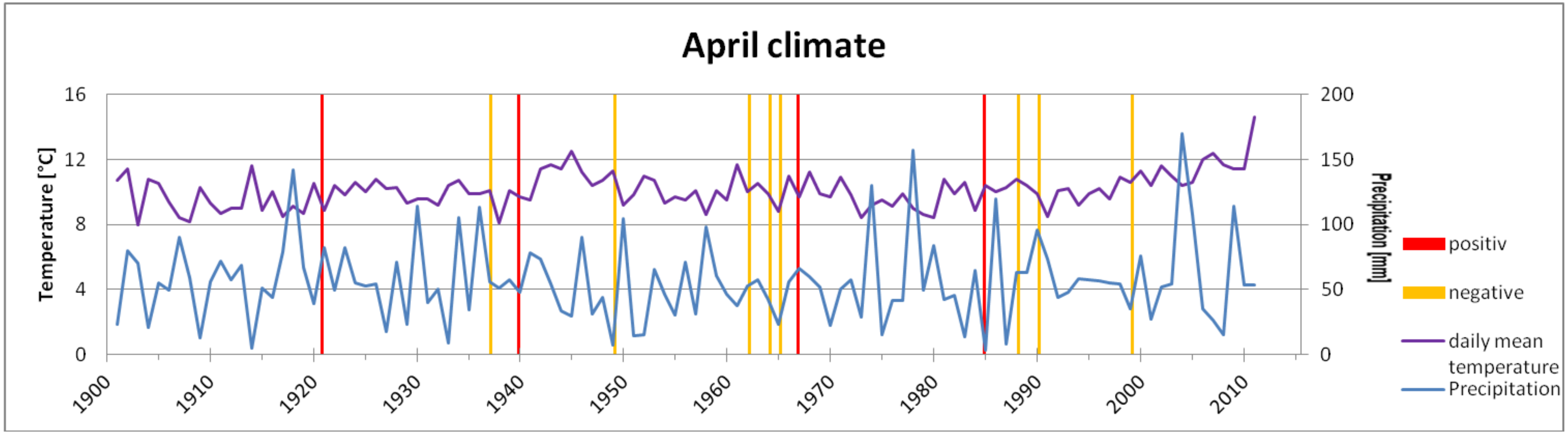
Appendix 2: pointer years

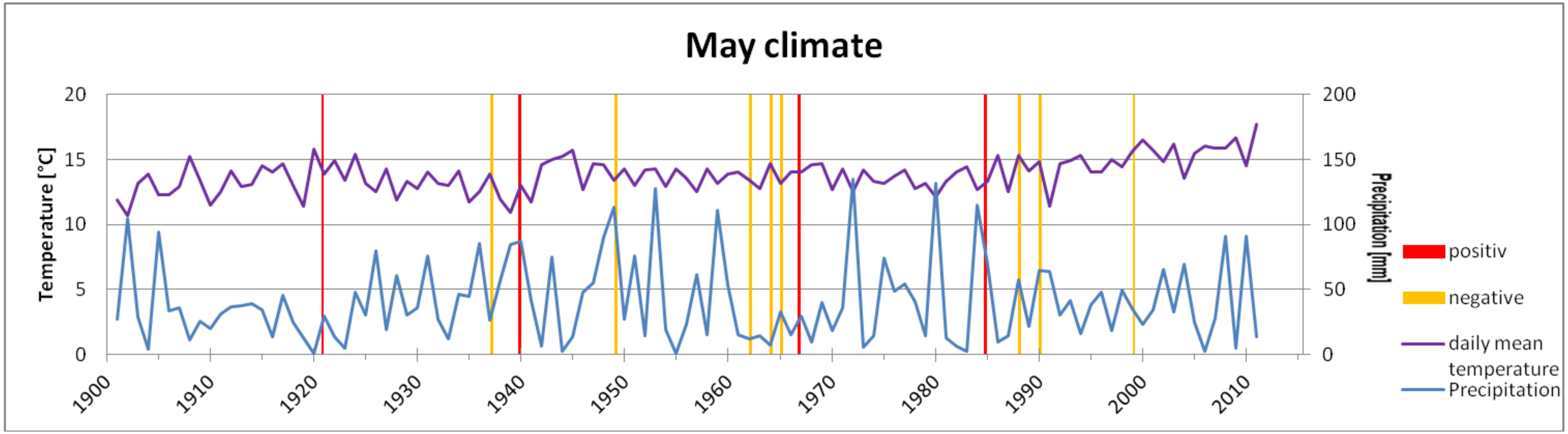
The scale of each of the months are different. This makes it more complicated to compare them. On the other hand the visualization is higher.

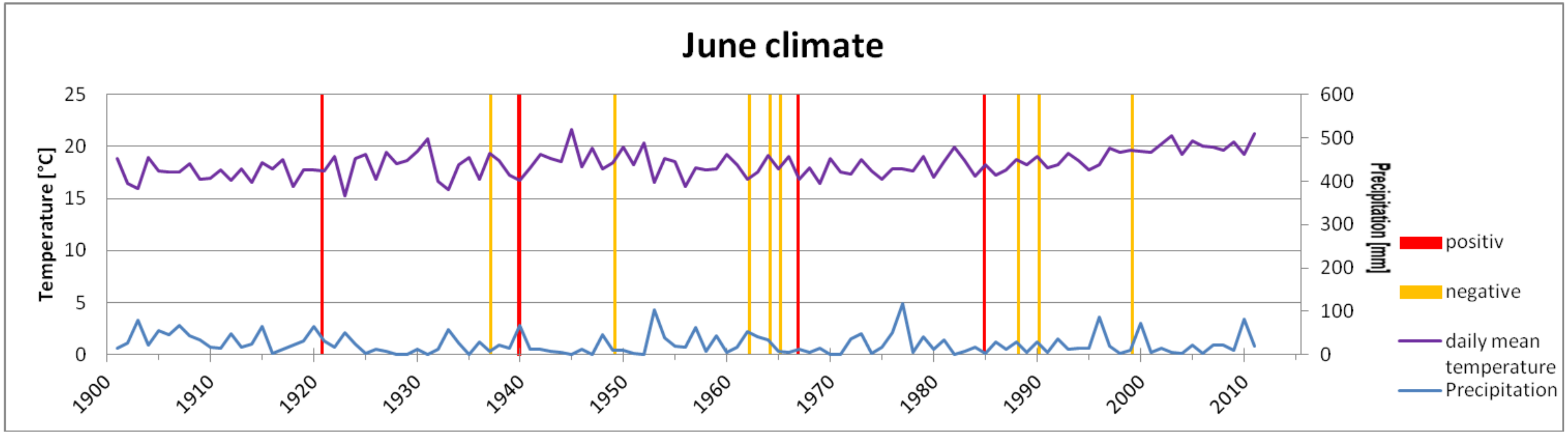


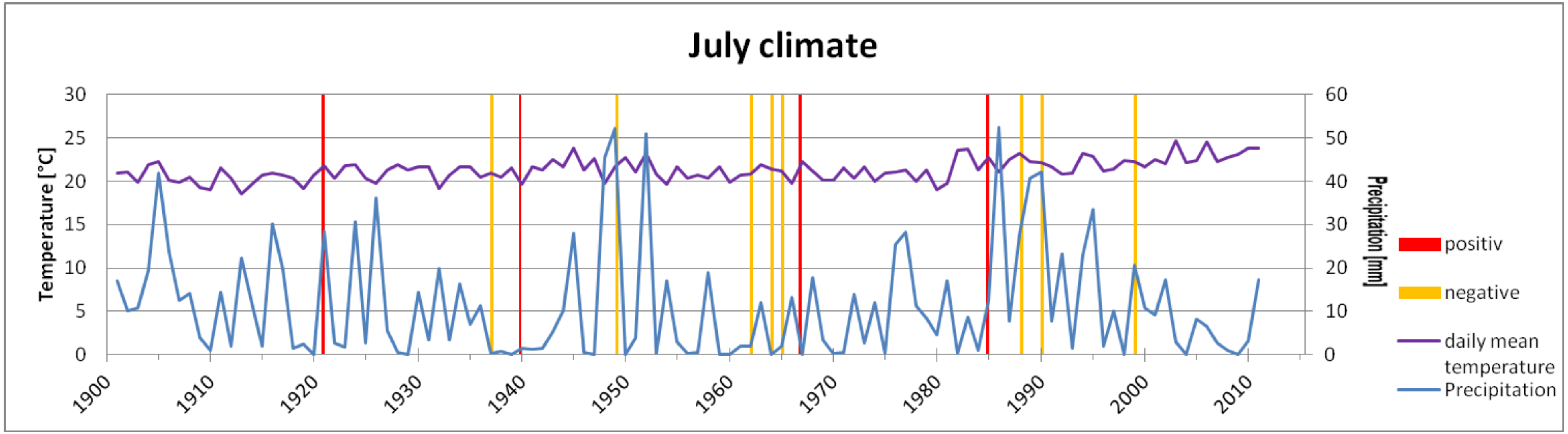


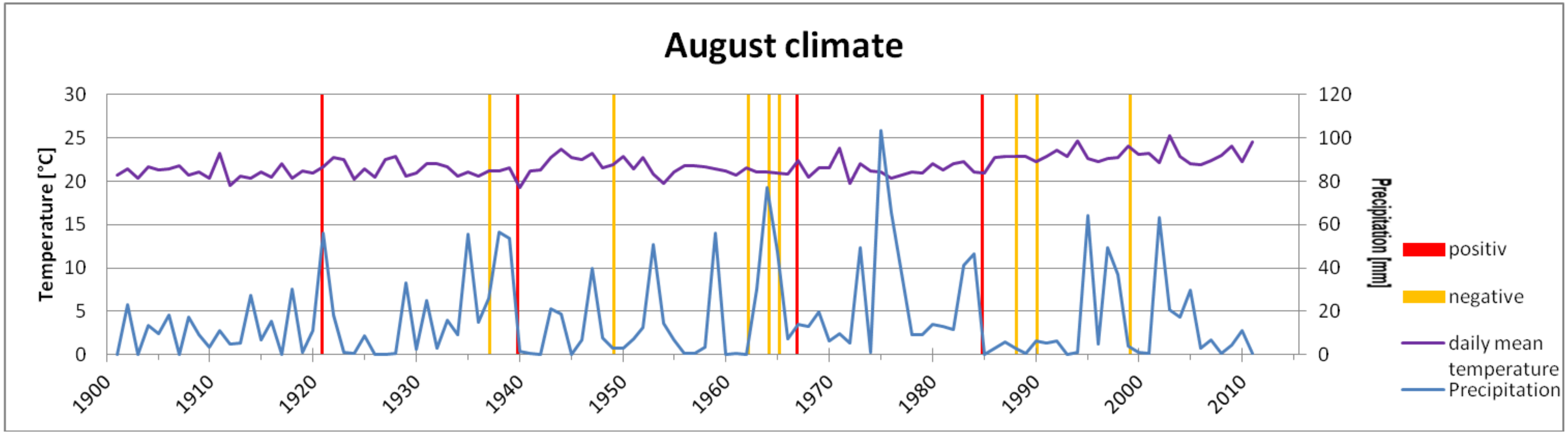

March climate
Temperature [°C]
0
2
4
6
8
10
12
Precipitation [mm]
0
50
100
150
200
250
300
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
positiv
negative
daily mean temperature
Precipitation

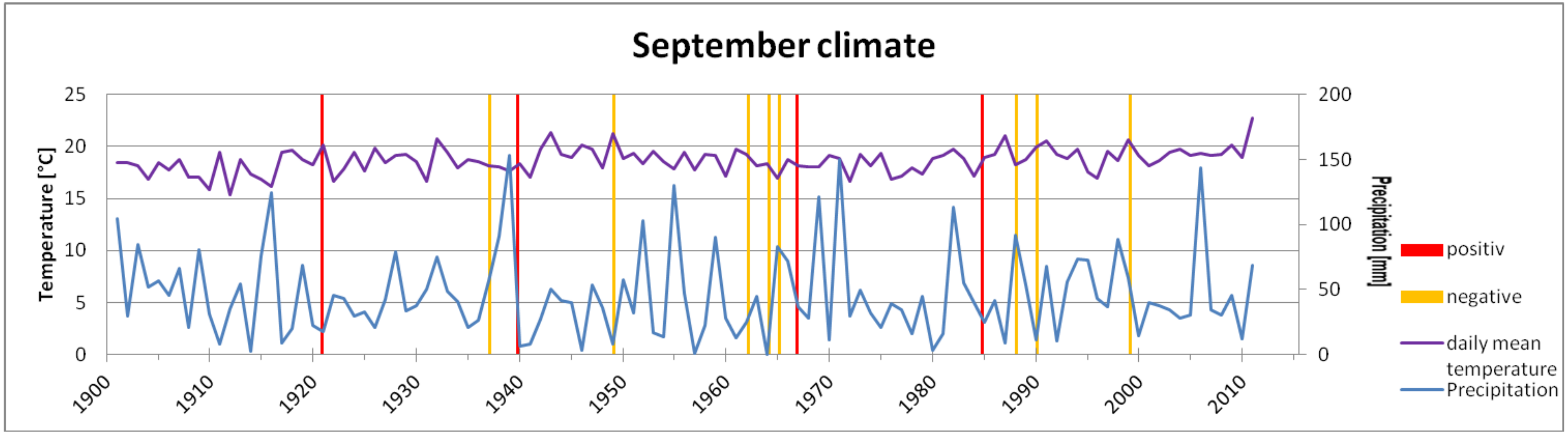

April climate
Temperature [°C]
0
4
8
12
16
Precipitation [mm]
0
50
100
150
200
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
positiv
negative
daily mean temperature
Precipitation

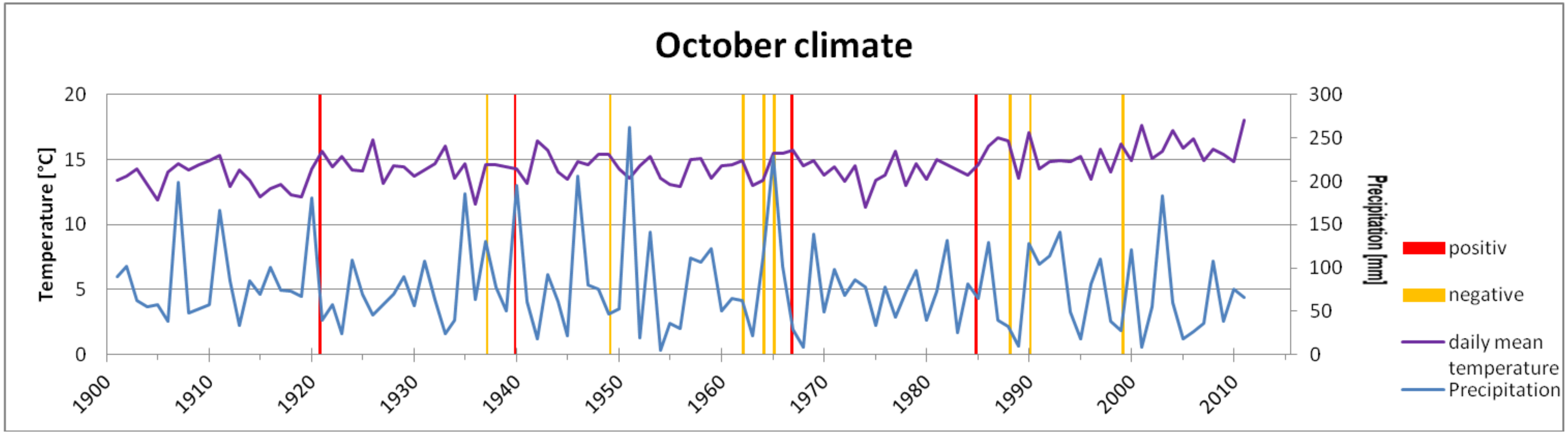

May climate
Temperature [°C]
0
5
10
15
20
Precipitation [mm]
0
50
100
150
200
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
positiv
negative
daily mean temperature
Precipitation

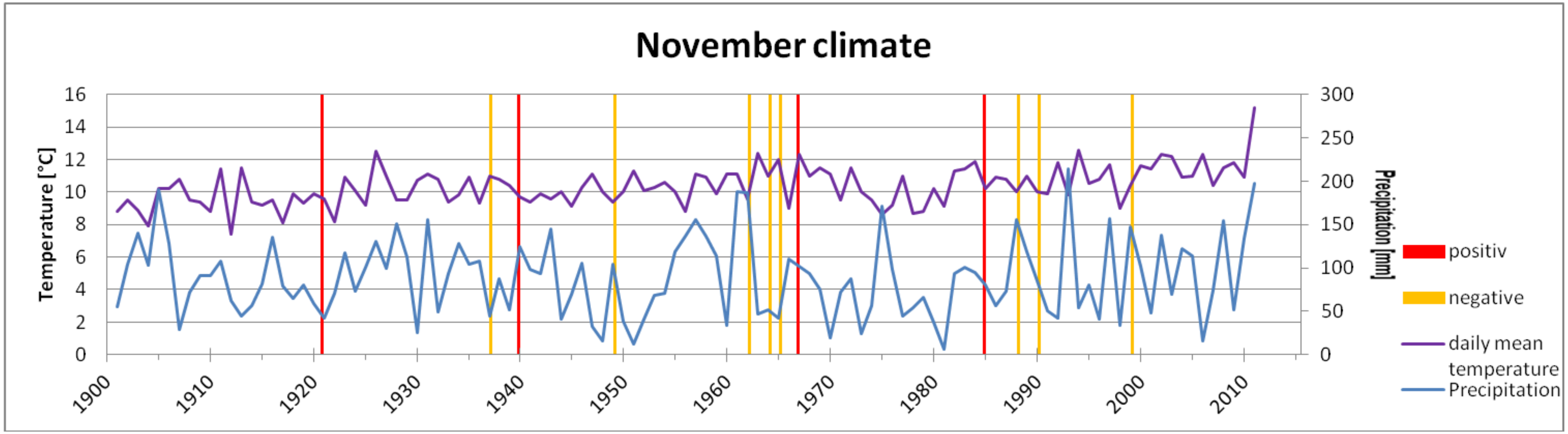

June climate
Temperature [°C]
0
5
10
15
20
25
Precipitation [mm]
0
100
200
300
400
500
600
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
positiv
negative
daily mean temperature
Precipitation

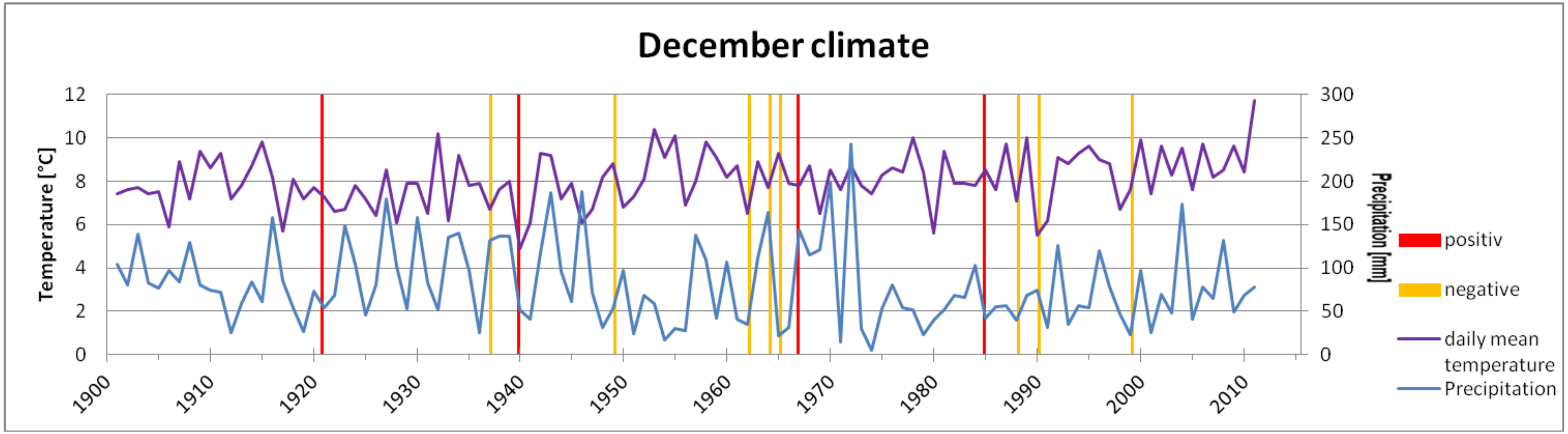

July climate
Temperature [°C]
30
25
20
15
10
5
0
Precipitation [mm]
60
50
40
30
20
10
0
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
positiv
negative
daily mean temperature
Precipitation

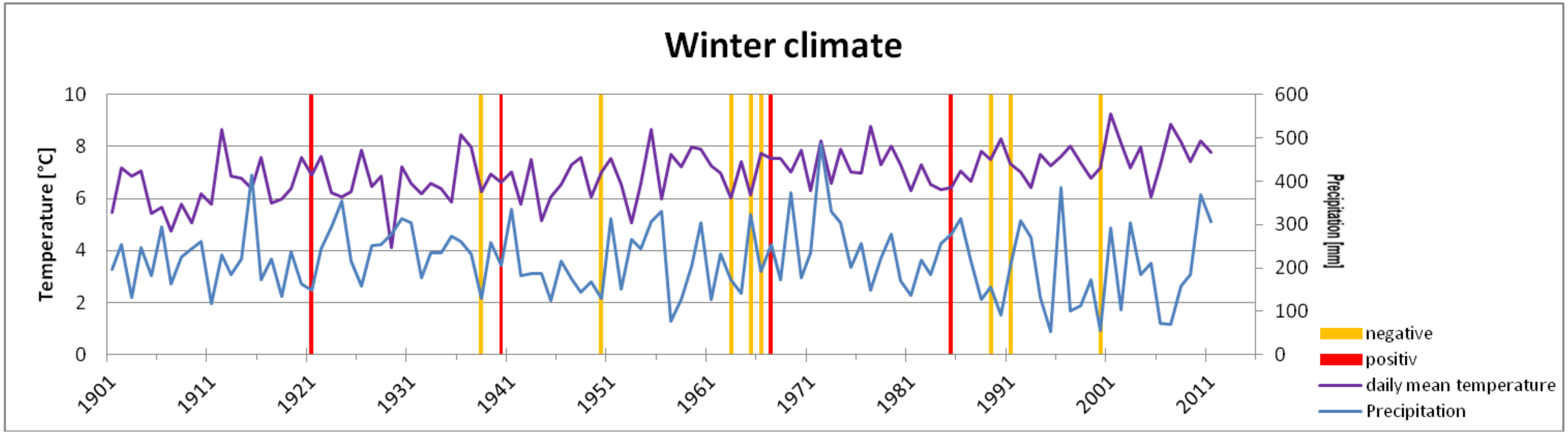

August climate
Temperature [°C]
30
25
20
15
10
5
0
Precipitation [mm]
120
100
80
60
40
20
0
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
positiv
negative
daily mean temperature
Precipitation

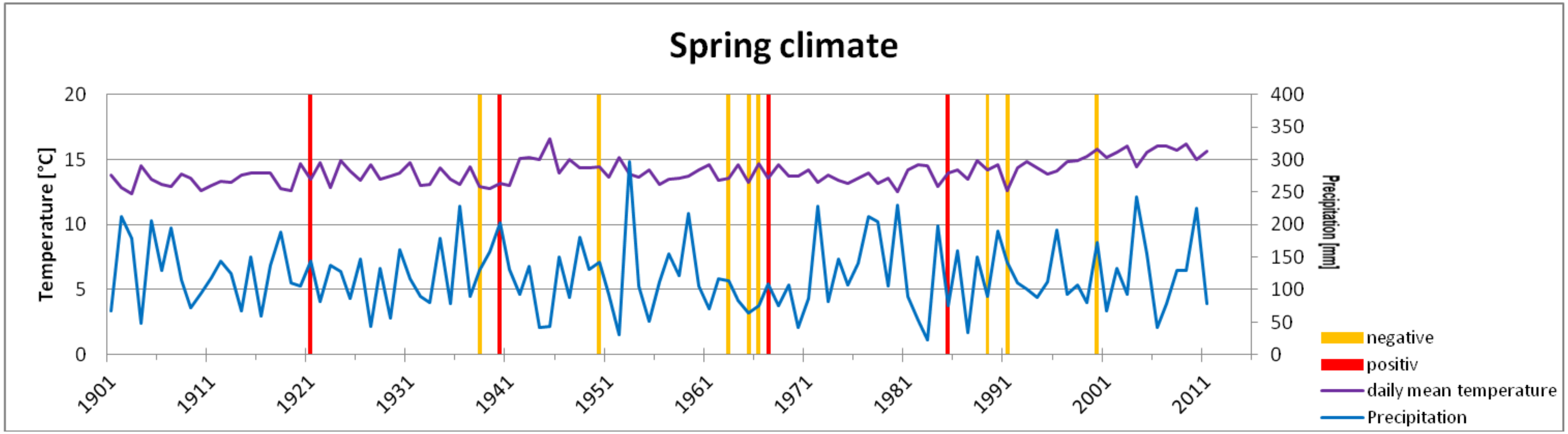

September climate
Temperature [°C]
25
20
15
10
5
0
Precipitation [mm]
200
150
100
50
0
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
positiv
negative
daily mean temperature
Precipitation

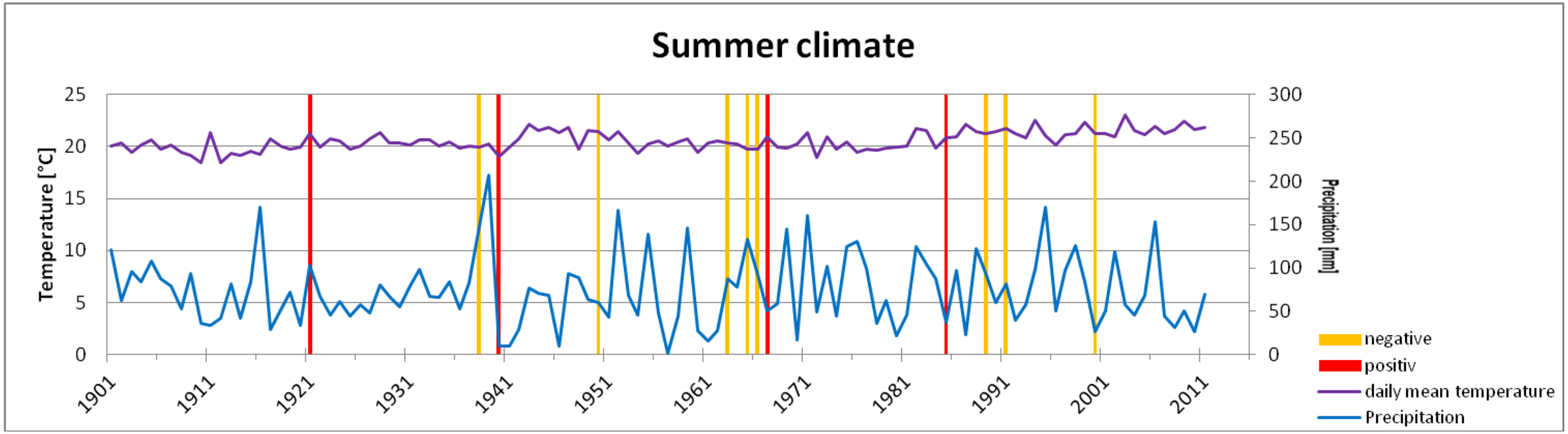

October climate
Temperature [°C]
20
15
10
5
0
Precipitation [mm]
300
250
200
150
100
50
0
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
positiv
negative
daily mean temperature
Precipitation

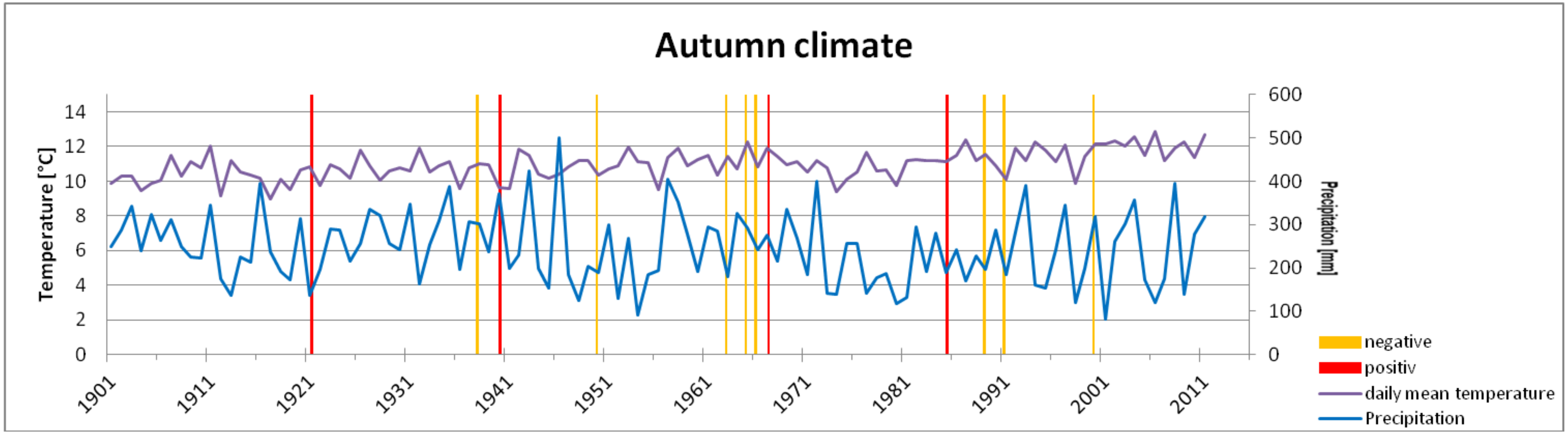

November climate
Temperature [°C]
16
14
12
10
8
6
4
2
0
Precipitation [mm]
300
250
200
150
100
50
0
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
positiv
negative
daily mean temperature
Precipitation

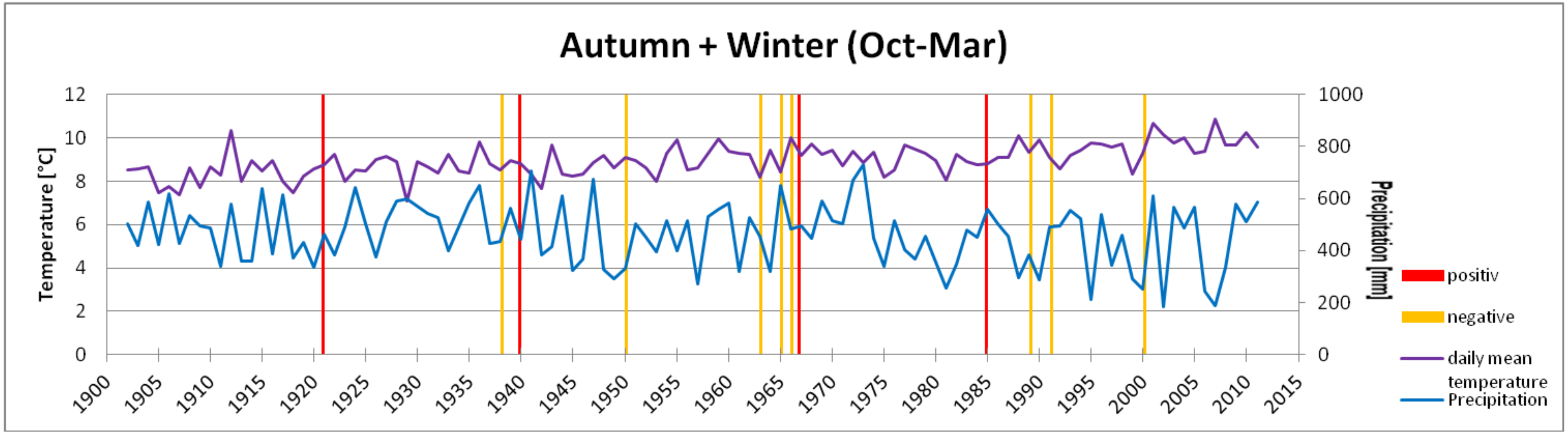

December climate
Temperature [°C]
12
10
8
6
4
2
0
Precipitation [mm]
300
250
200
150
100
50
0
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
positiv
negative
daily mean temperature
Precipitation

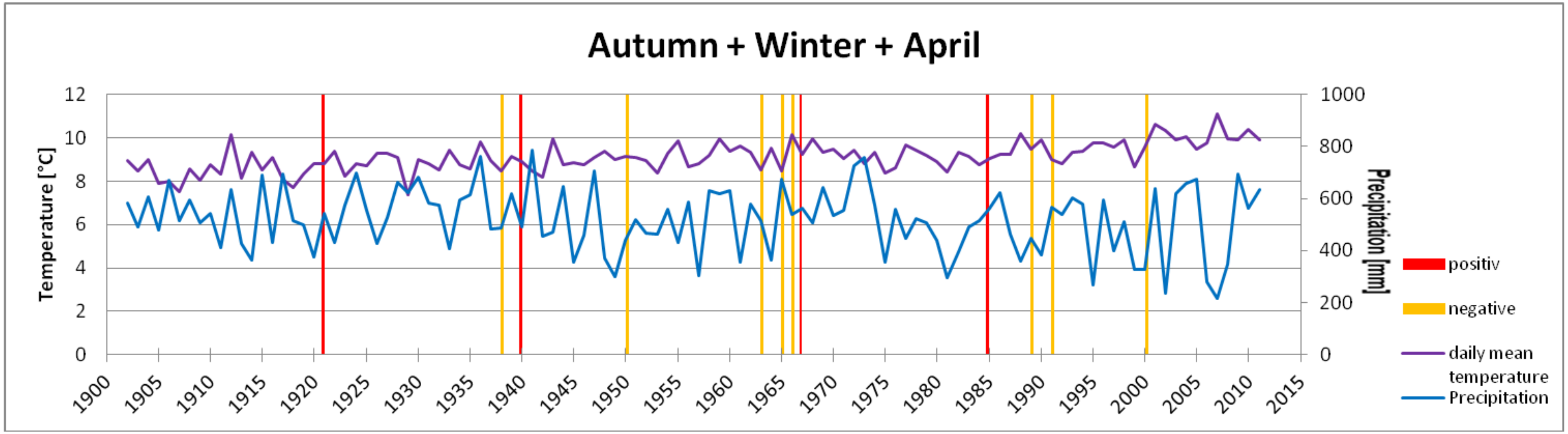

Winter climate
Temperature [°C]
0
2
4
6
8
10
Precipitation [mm]
0
100
200
300
400
500
600
1901
1911
1921
1931
1941
1951
1961
1971
1981
1991
2001
2011
negative
positiv
daily mean temperature
Precipitation

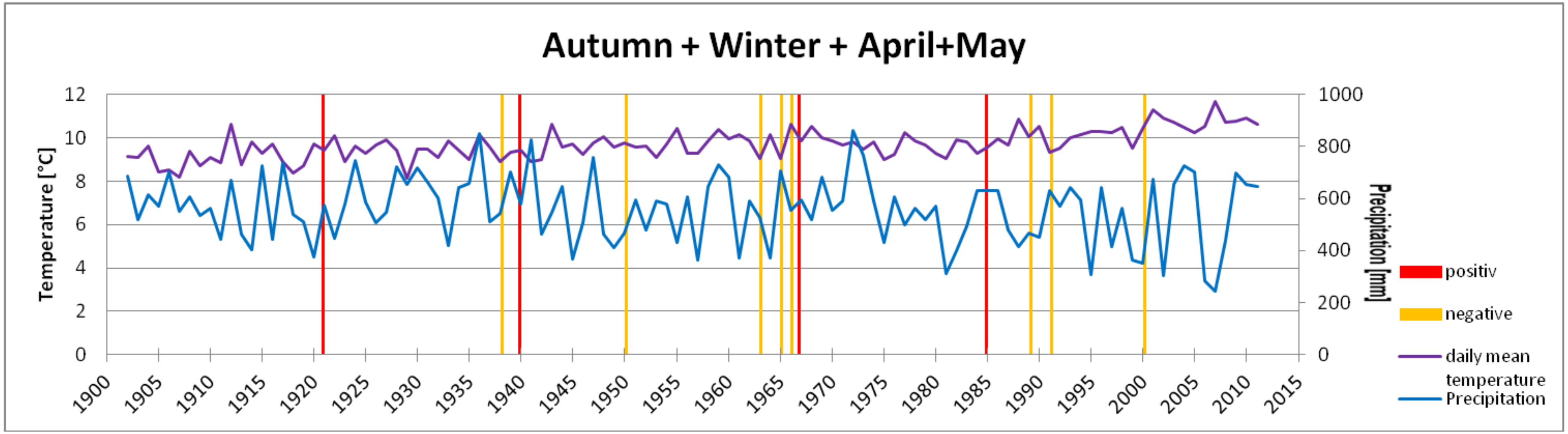

Spring climate
Temperature [°C]
0
5
10
15
20
Precipitation [mm]
0
50
100
150
200
250
300
350
400
1901
1911
1921
1931
1941
1951
1961
1971
1981
1991
2001
2011
negative
positiv
daily mean temperature
Precipitation

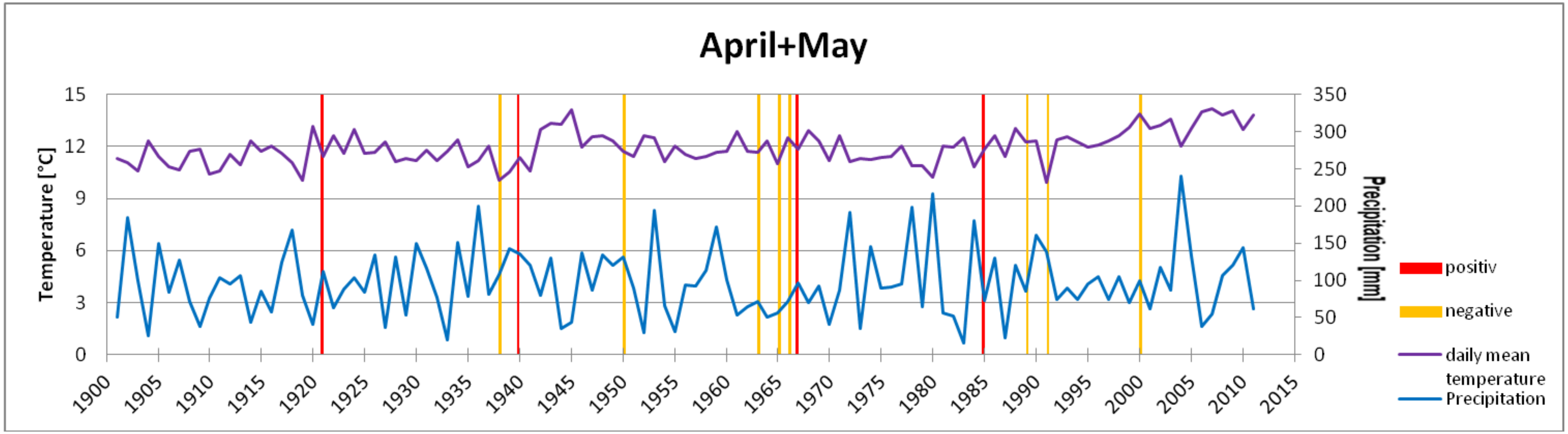

Summer climate
Temperature [°C]
0
5
10
15
20
25
Precipitation [mm]
0
50
100
150
200
250
300
1901
1911
1921
1931
1941
1951
1961
1971
1981
1991
2001
2011
negative
positiv
daily mean temperature
Precipitation

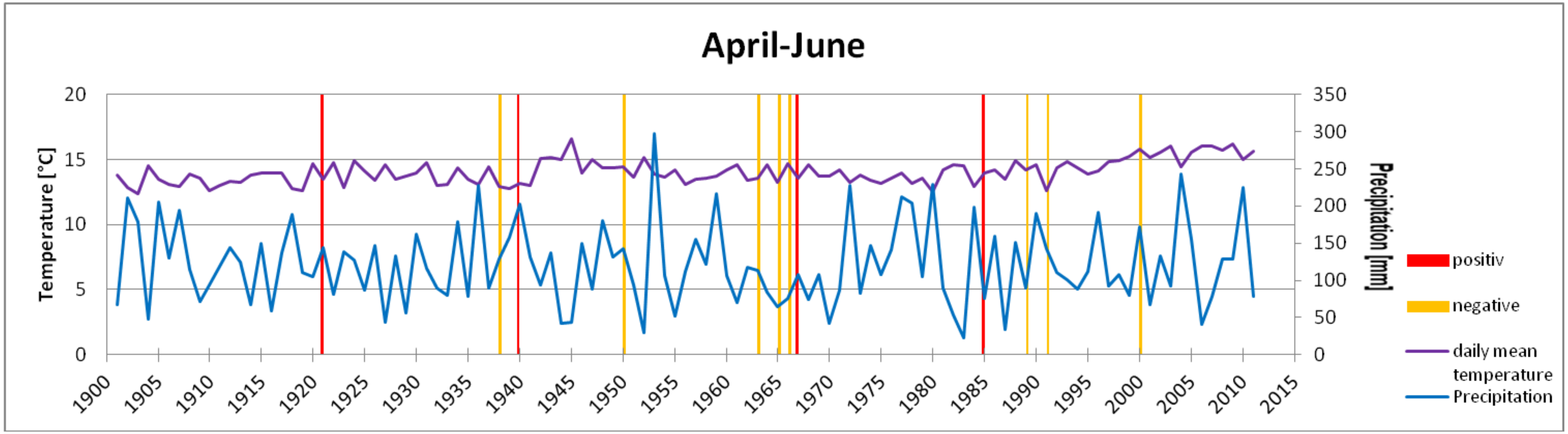

Autumn climate
Temperature [°C]
0
2
4
6
8
10
12
14
Precipitation [mm]
0
100
200
300
400
500
600
1901
1911
1921
1931
1941
1951
1961
1971
1981
1991
2001
2011
negative
positiv
daily mean temperature
Precipitation

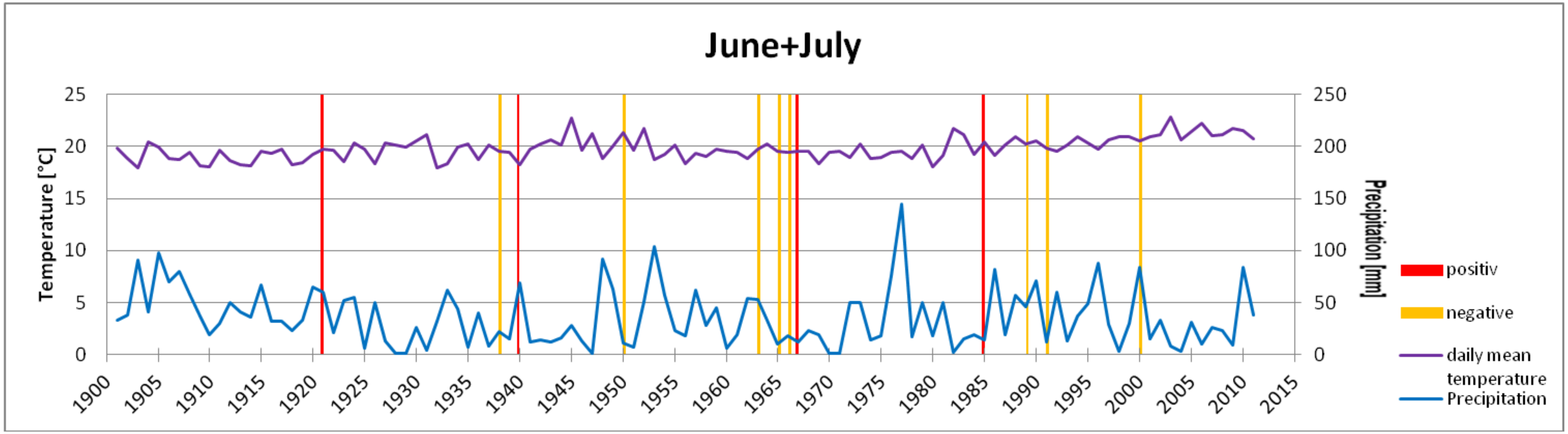

Autumn + Winter (Oct-Mar)
Temperature [°C]
0
2
4
6
8
10
12
Precipitation [mm]
0
200
400
600
800
1000
1900
1905
1910
1915
1920
1925
1930
1935
1940
1945
1950
1955
1960
1965
1970
1975
1980
1985
1990
1995
2000
2005
2010
2015
positiv
negative
daily mean temperature
Precipitation

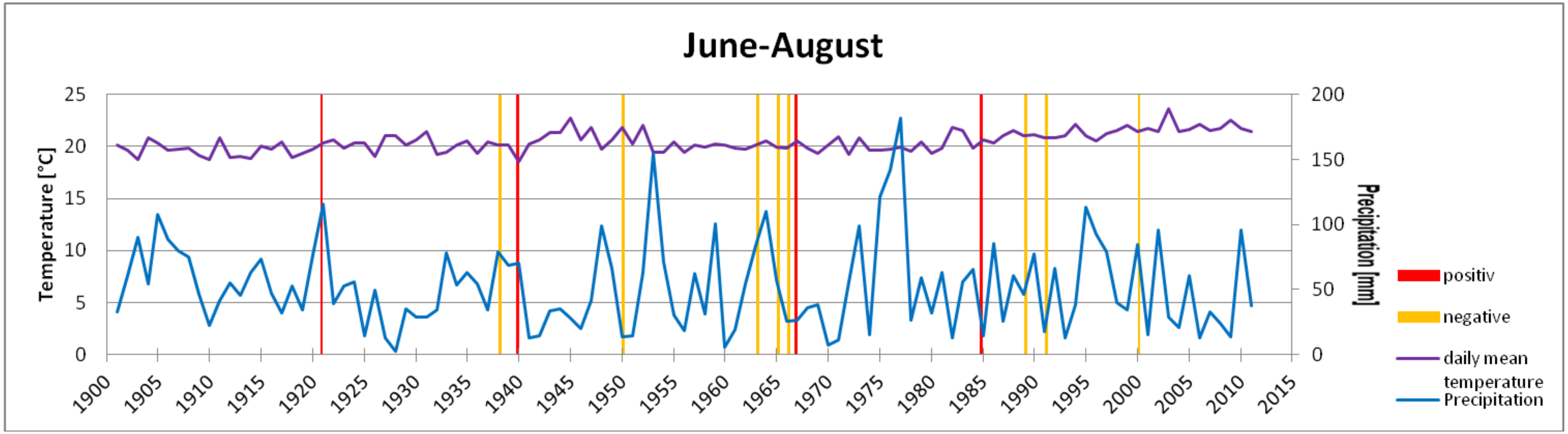

Autumn + Winter + April
Temperature [°C]
0
2
4
6
8
10
12
Precipitation [mm]
0
200
400
600
800
1000
1900
1905
1910
1915
1920
1925
1930
1935
1940
1945
1950
1955
1960
1965
1970
1975
1980
1985
1990
1995
2000
2005
2010
2015
positiv
negative
daily mean temperature
Precipitation

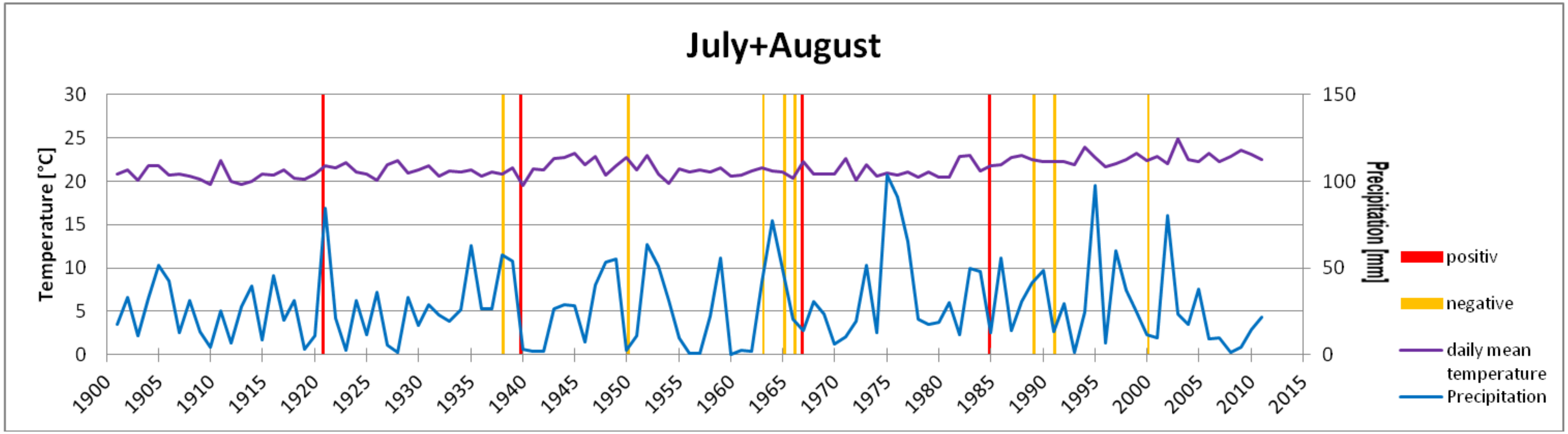

Autumn + Winter + April+May
Temperature [°C]
0
2
4
6
8
10
12
Precipitation [mm]
0
200
400
600
800
1000
1900
1905
1910
1915
1920
1925
1930
1935
1940
1945
1950
1955
1960
1965
1970
1975
1980
1985
1990
1995
2000
2005
2010
2015
positiv
negative
daily mean temperature
Precipitation

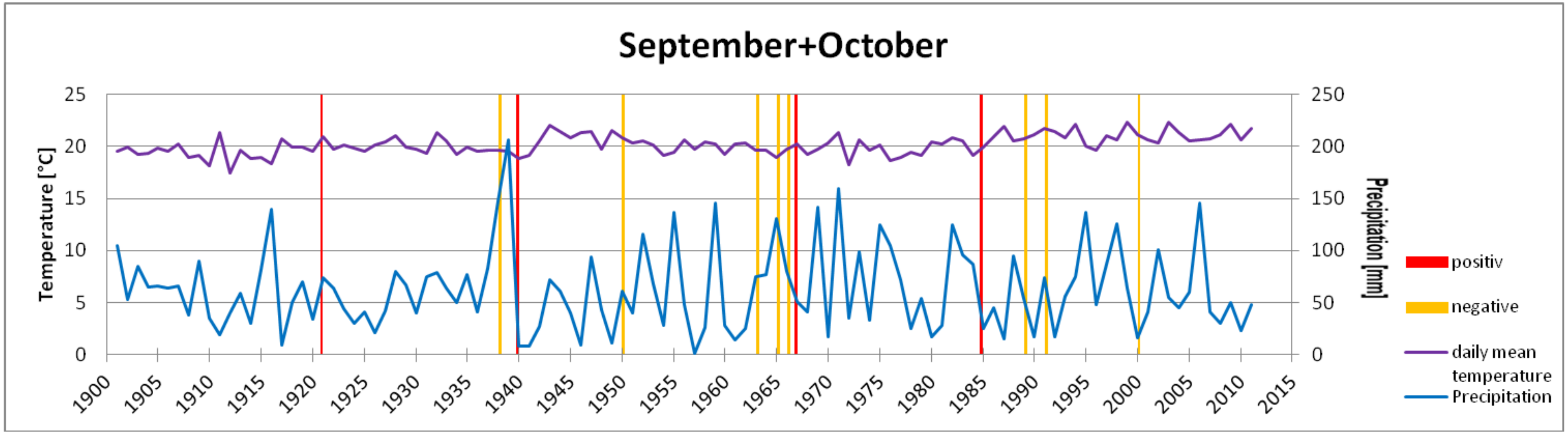

April+May
Temperature [°C]
0
3
6
9
12
15
Precipitation [mm]
0
50
100
150
200
250
300
350
1900
1905
1910
1915
1920
1925
1930
1935
1940
1945
1950
1955
1960
1965
1970
1975
1980
1985
1990
1995
2000
2005
2010
2015
positiv
negative
daily mean temperature
Precipitation


April-June
Temperature [°C]
20
15
10
5
0
Precipitation [mm]
350
300
250
200
150
100
50
0
1900
1905
1910
1915
1920
1925
1930
1935
1940
1945
1950
1955
1960
1965
1970
1975
1980
1985
1990
1995
2000
2005
2010
2015
positiv
negative
daily mean temperature
Precipitation


June+July
Temperature [°C]
25
20
15
10
5
0
Precipitation [mm]
250
200
150
100
50
0
1900
1905
1910
1915
1920
1925
1930
1935
1940
1945
1950
1955
1960
1965
1970
1975
1980
1985
1990
1995
2000
2005
2010
2015
positiv
negative
daily mean temperature
Precipitation

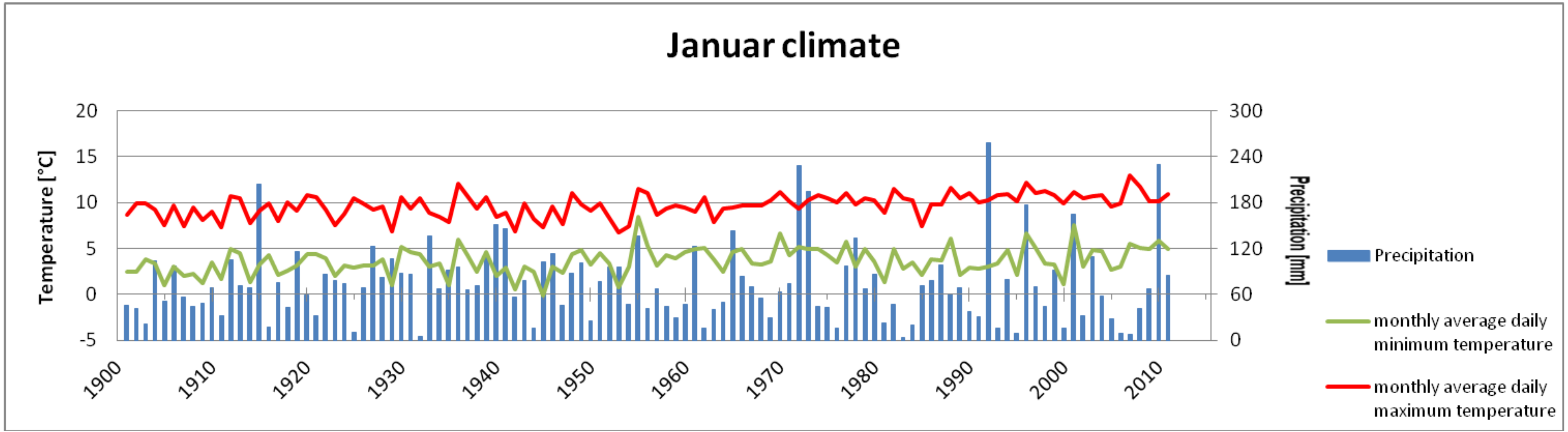

June-August
Temperature [°C]
0
5
10
15
20
25
Precipitation [mm]
0
50
100
150
200
1900
1905
1910
1915
1920
1925
1930
1935
1940
1945
1950
1955
1960
1965
1970
1975
1980
1985
1990
1995
2000
2005
2010
2015
positiv
negative
daily mean temperature
Precipitation

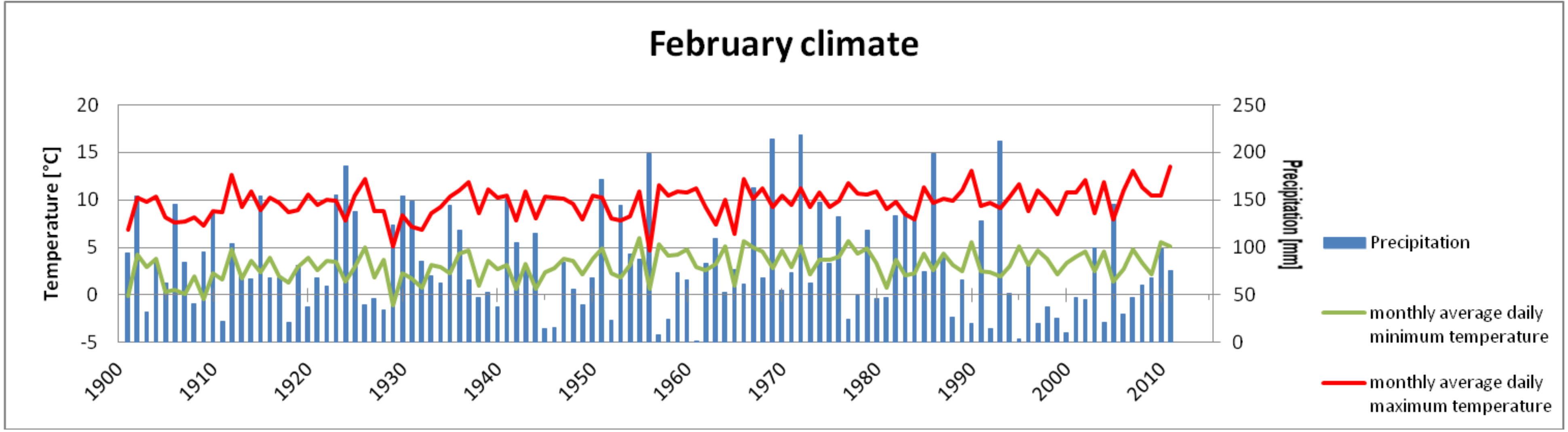

July+August
Temperature [°C]
0
5
10
15
20
25
30
Precipitation [mm]
0
50
100
150
1900
1905
1910
1915
1920
1925
1930
1935
1940
1945
1950
1955
1960
1965
1970
1975
1980
1985
1990
1995
2000
2005
2010
2015
positiv
negative
daily mean temperature
Precipitation

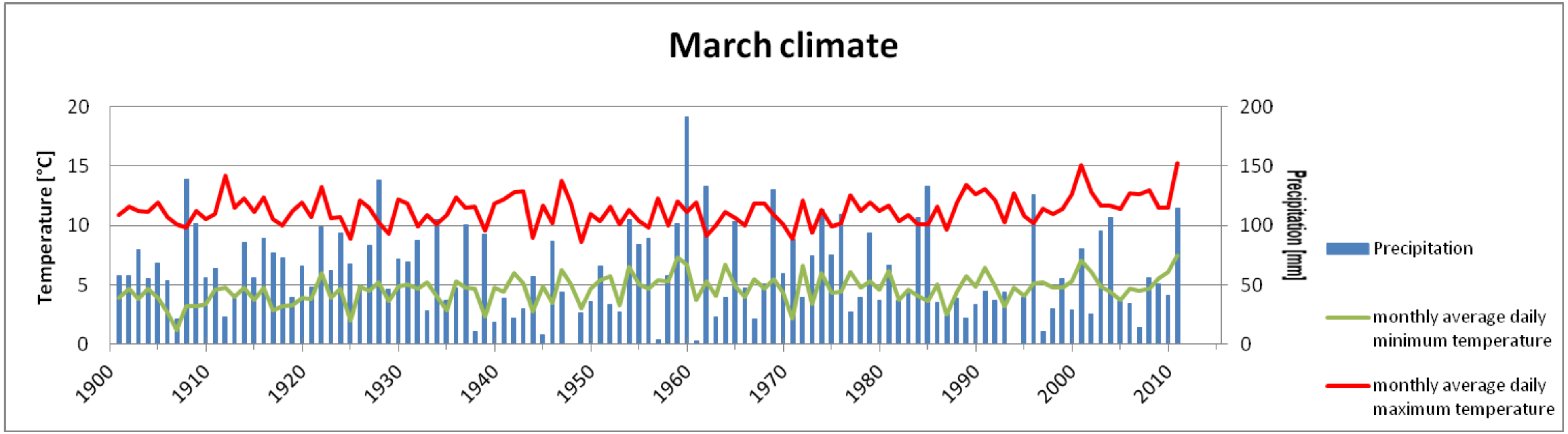

September+October
Temperature [°C]
25
20
15
10
5
0
Precipitation [mm]
250
200
150
100
50
0
1900
1905
1910
1915
1920
1925
1930
1935
1940
1945
1950
1955
1960
1965
1970
1975
1980
1985
1990
1995
2000
2005
2010
2015
positiv
negative
daily mean temperature
Precipitation

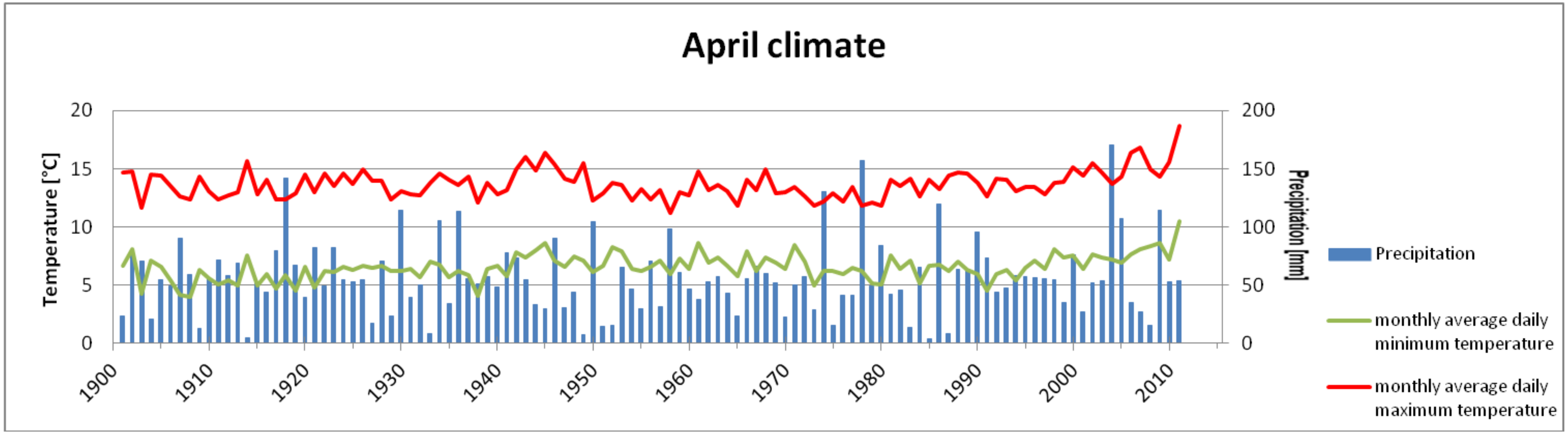
Appendix 3: Climate data for DendroClima2002

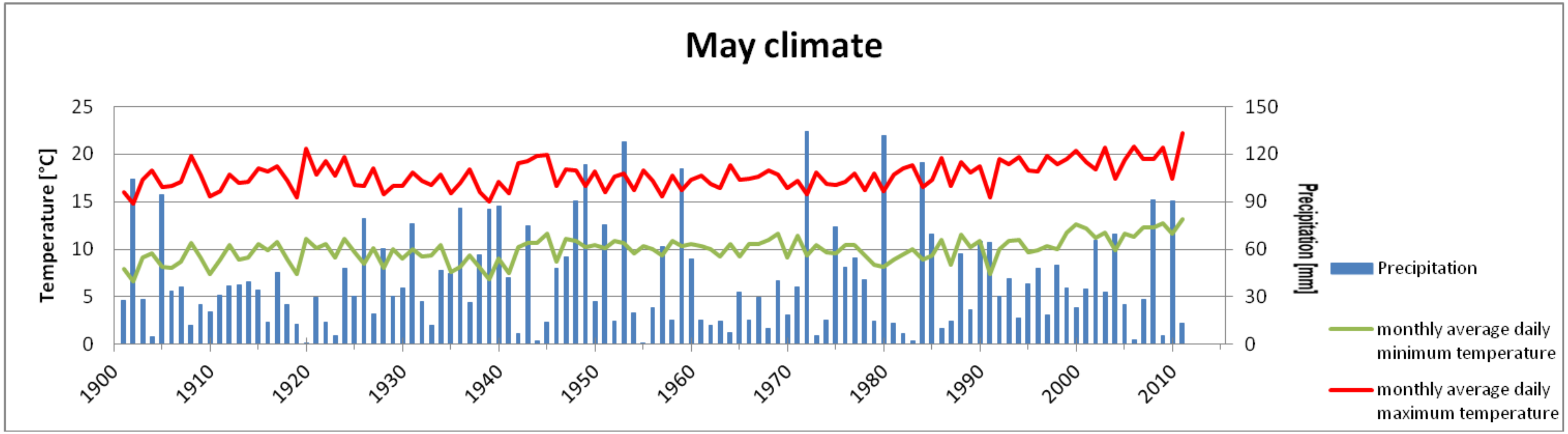
The scale of each of the months are different. This makes it more complicated to compare them. On the other hand the visualization is higher.

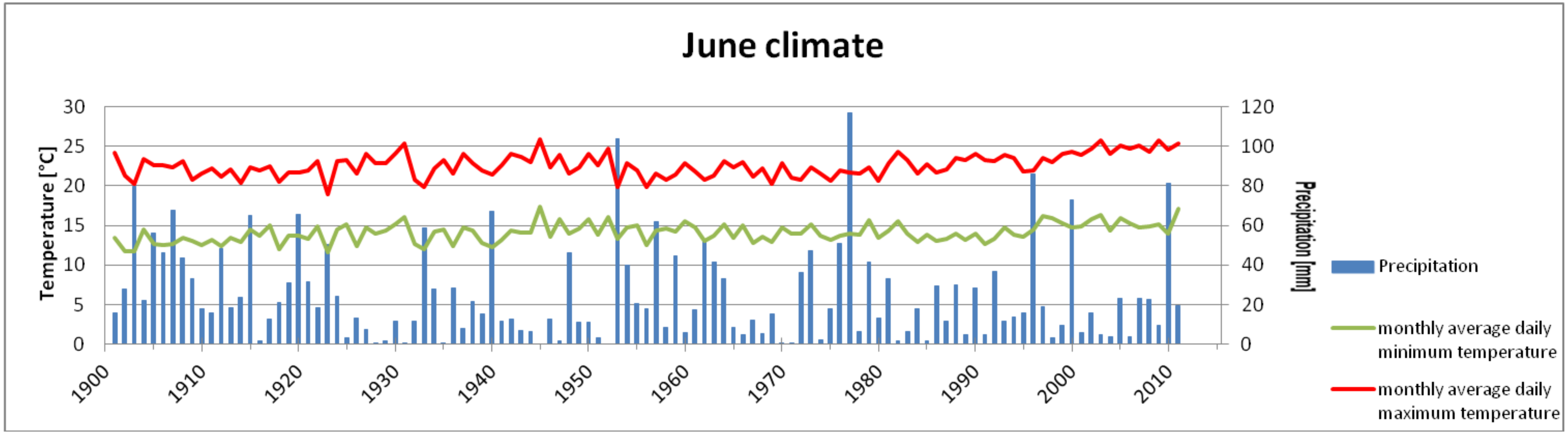


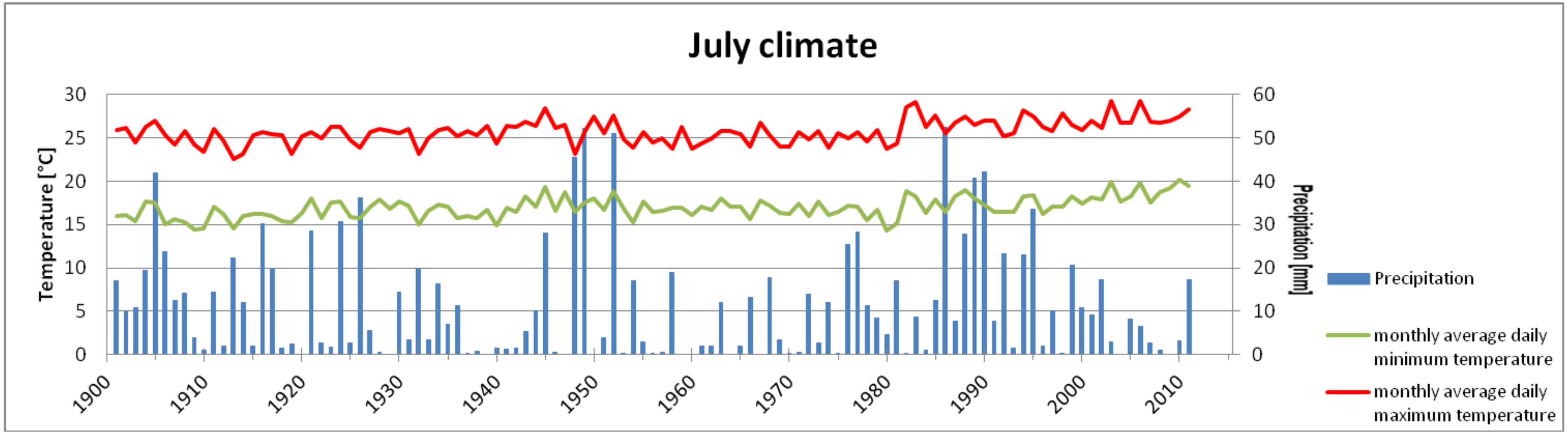


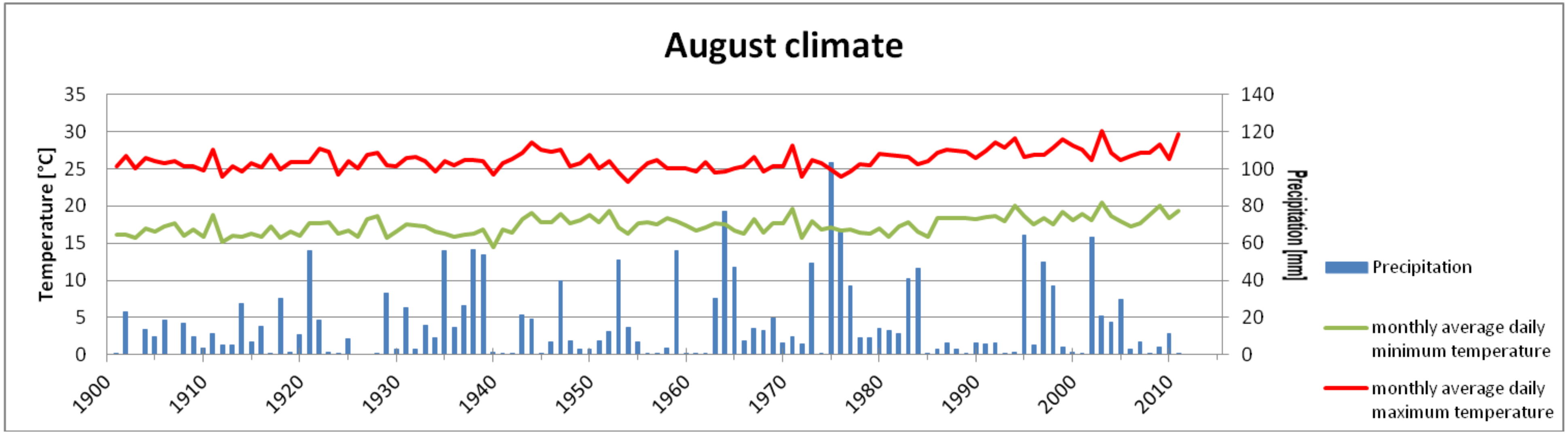

March climate
Temperature [°C]
0
5
10
15
20
Precipitation [mm]
0
50
100
150
200
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
Precipitation
monthly average daily minimum temperature
monthly average daily maximum temperature

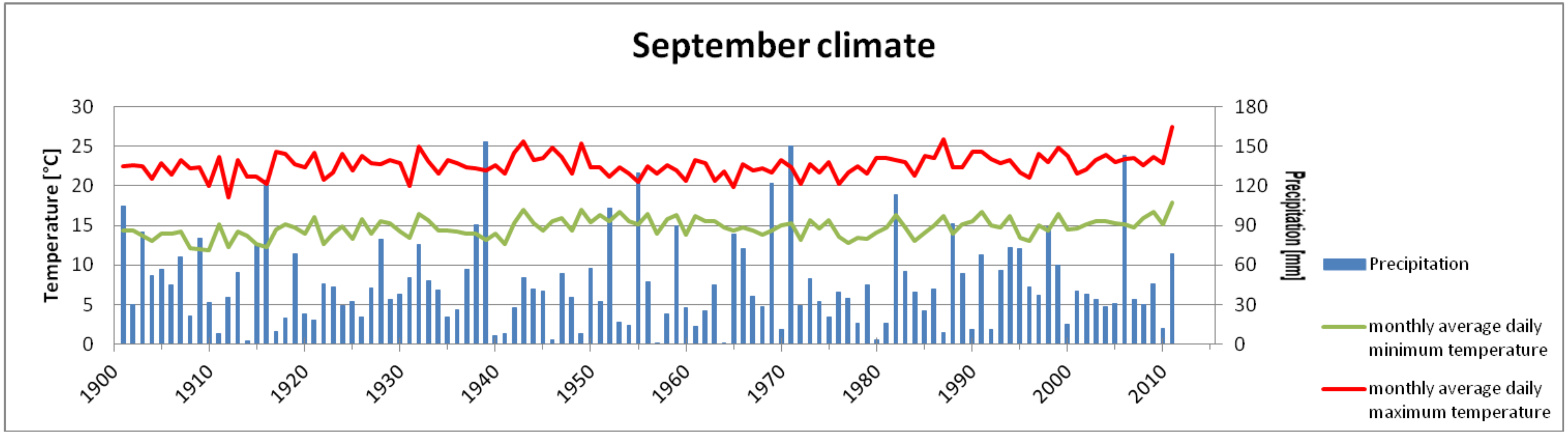

April climate
Temperature [°C]
0
5
10
15
20
Precipitation [mm]
0
50
100
150
200
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
Precipitation
monthly average daily minimum temperature
monthly average daily maximum temperature

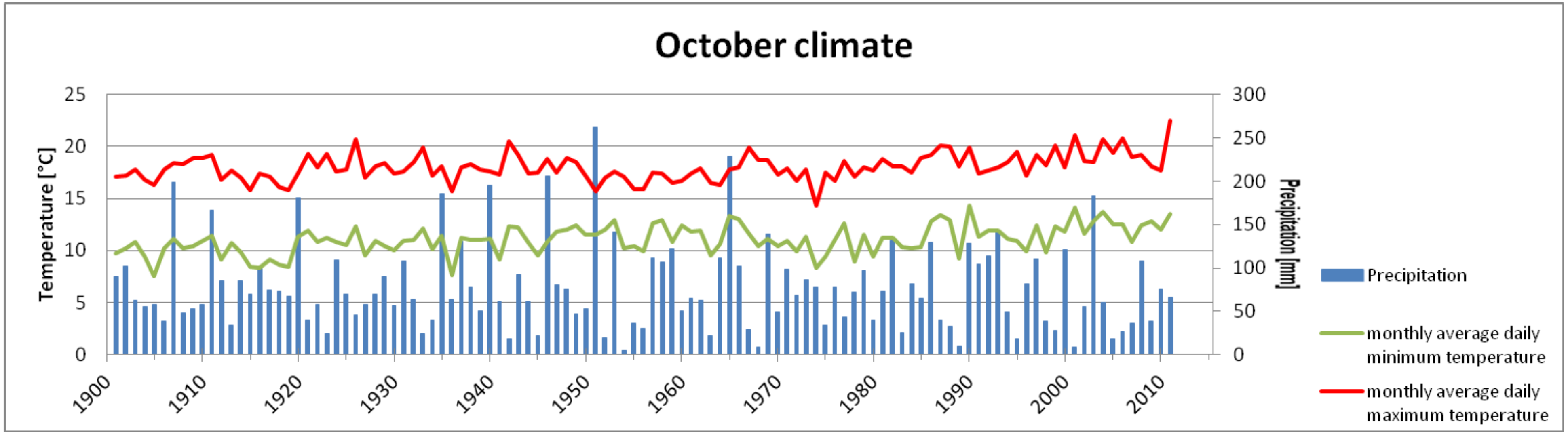

May climate
Temperature [°C]
25
20
15
10
5
0
150
120
90
60
30
0
Precipitation [mm]
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
Precipitation
monthly average daily minimum temperature
monthly average daily maximum temperature

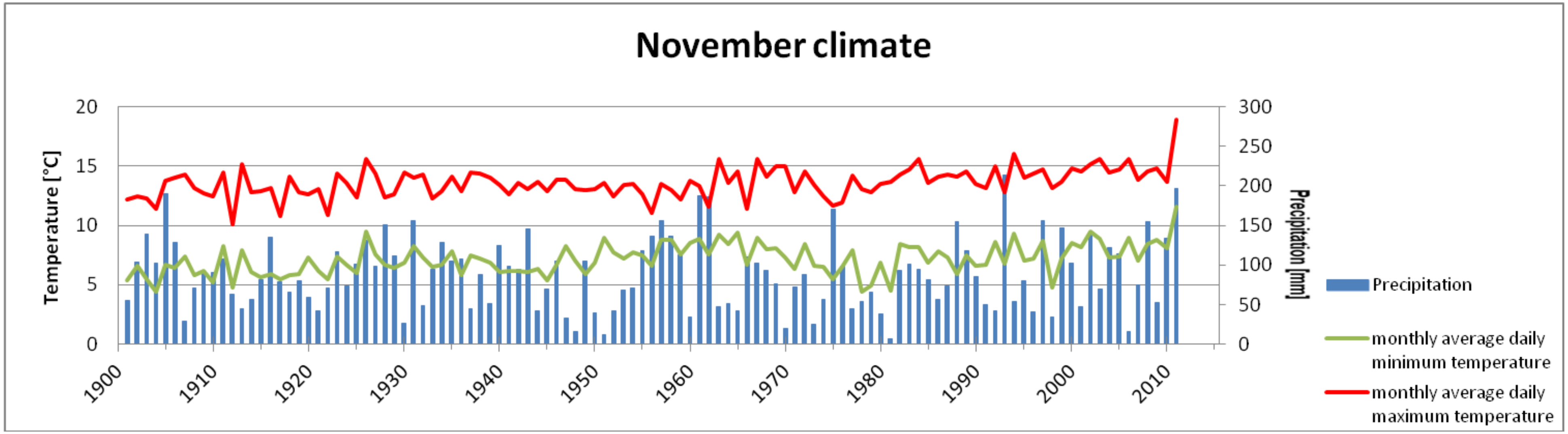

June climate
Temperature [°C]
30
25
20
15
10
5
0
120
100
80
60
40
20
0
Precipitation [mm]
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
Precipitation
monthly average daily minimum temperature
monthly average daily maximum temperature

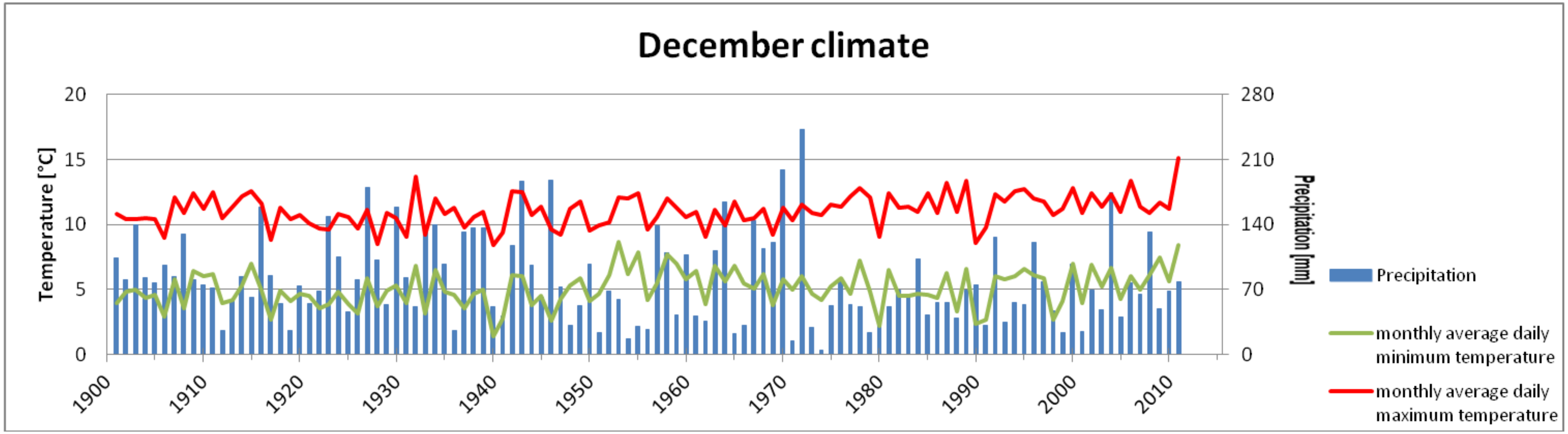

July climate
Temperature [°C]
30
25
20
15
10
5
0
60
50
40
30
20
10
0
Precipitation [mm]
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
Precipitation
monthly average daily minimum temperature
monthly average daily maximum temperature

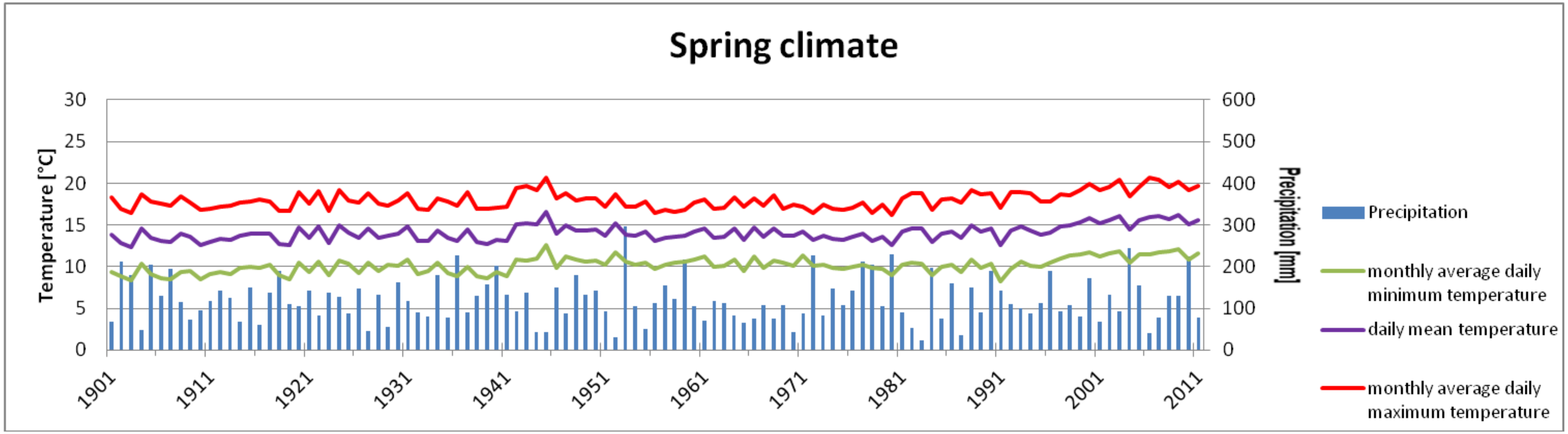

August climate
Temperature [°C]
35
30
25
20
15
10
5
0
140
120
100
80
60
40
20
0
Precipitation [mm]
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
Precipitation
monthly average daily minimum temperature
monthly average daily maximum temperature

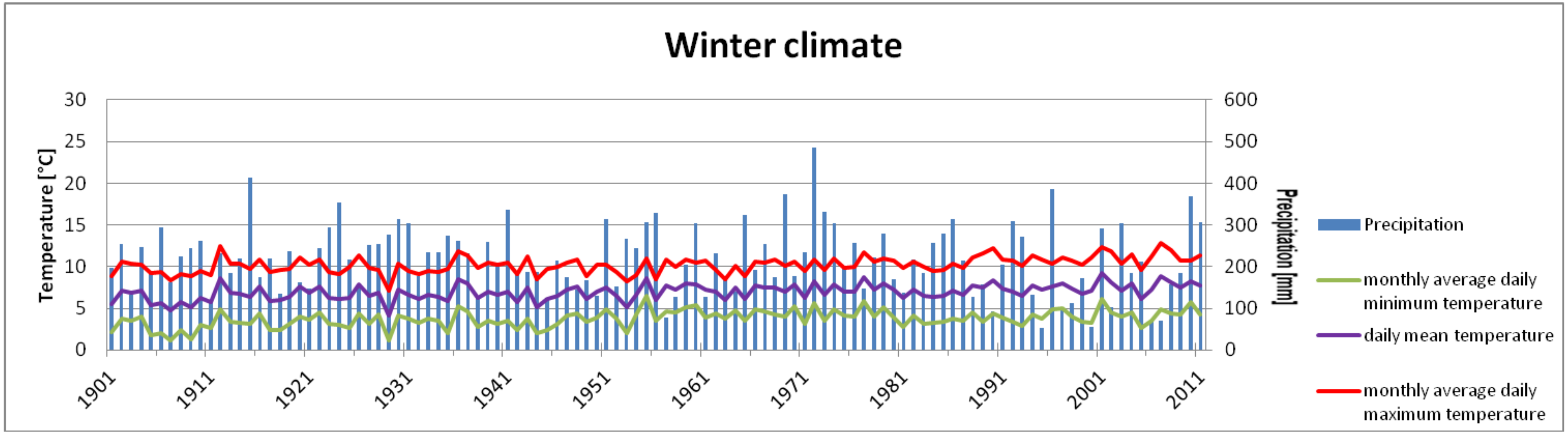

September climate
Temperature [°C]
0
5
10
15
20
25
30
Precipitation [mm]
0
30
60
90
120
150
180
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
Precipitation
monthly average daily minimum temperature
monthly average daily maximum temperature

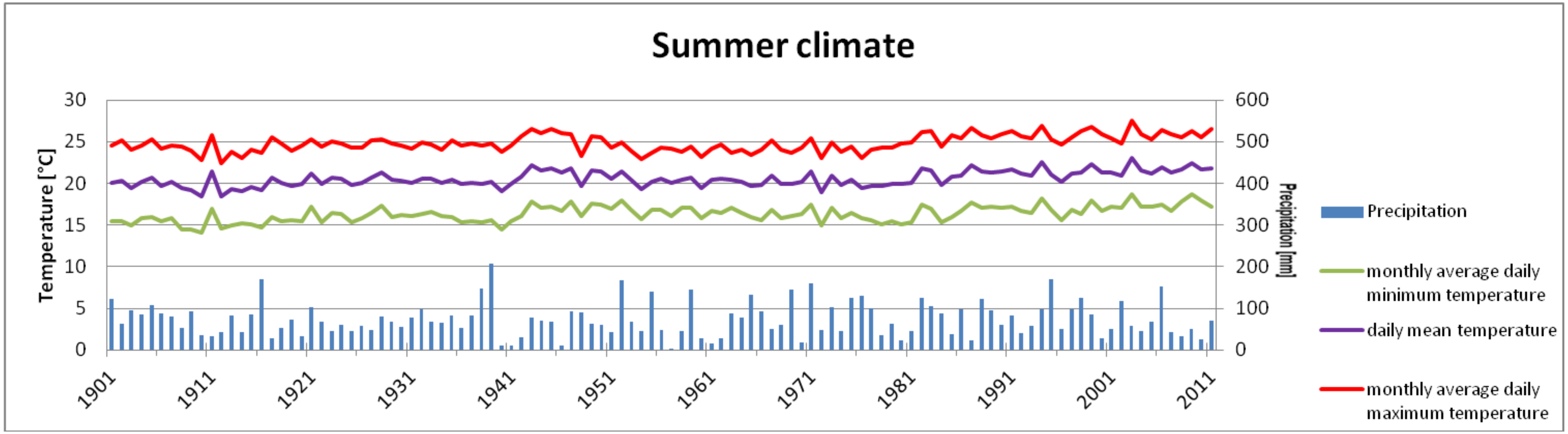

October climate
Temperature [°C]
0
5
10
15
20
25
Precipitation [mm]
0
50
100
150
200
250
300
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
Precipitation
monthly average daily minimum temperature
monthly average daily maximum temperature

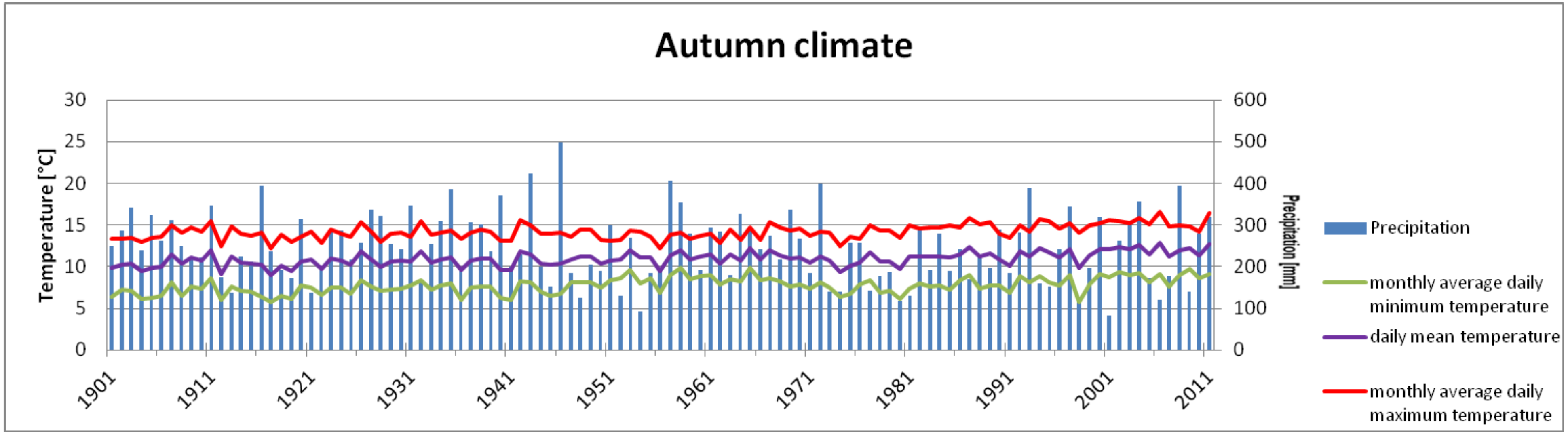

November climate
Temperature [°C]
20
15
10
5
0
300
250
200
150
100
50
0
Precipitation [mm]
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
Precipitation
monthly average daily minimum temperature
monthly average daily maximum temperature


December climate
Temperature [°C]
20
15
10
5
0
280
210
140
70
0
Precipitation [mm]
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
Precipitation
monthly average daily minimum temperature
monthly average daily maximum temperature


Spring climate
Temperature [°C]
0
5
10
15
20
25
30
Precipitation [mm]
0
100
200
300
400
500
600
1901
1911
1921
1931
1941
1951
1961
1971
1981
1991
2001
2011
Precipitation
monthly average daily minimum temperature
daily mean temperature
monthly average daily maximum temperature


Winter climate
Temperature [°C]
0
5
10
15
20
25
30
Precipitation [mm]
0
100
200
300
400
500
600
1901
1911
1921
1931
1941
1951
1961
1971
1981
1991
2001
2011
Precipitation
monthly average daily minimum temperature
daily mean temperature
monthly average daily maximum temperature


Summer climate
Temperature [°C]
30
25
20
15
10
5
0
Precipitation [mm]
600
500
400
300
200
100
0
1901
1911
1921
1931
1941
1951
1961
1971
1981
1991
2001
2011
Precipitation
monthly average daily minimum temperature
daily mean temperature
monthly average daily maximum temperature


Autumn climate
Temperature [°C]
30
25
20
15
10
5
0
Precipitation [mm]
600
500
400
300
200
100
0
1901
1911
1921
1931
1941
1951
1961
1971
1981
1991
2001
2011
Precipitation
monthly average daily minimum temperature
daily mean temperature
monthly average daily maximum temperature

Personal Declaration

I hereby declare that the submitted thesis is the result of my own, independent, work. All external sources are explicitly acknowledged in the thesis.

Andreas Good

Zürich, 29th September 2014