CHARLES UNIVERSITY IN PRAGUE

FACULTY OF SCIENCE

DEPARTMENT OF PHYSICAL GEOGRAPHY AND GEOECOLOGY

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KLIMATICKÝ SIGNÁL V LETOKRUHOVÝCH CHRONOLOGIÍCH BOROVICE KLEČE

CLIMATE SIGNAL IN TREE RING SERIES OF MOUNTAIN PINE

Master`s thesis

Supervisor: Mgr. Václav Treml, PhD.

Prague 2014

Zadání diplomové práce

Téma práce: Dendroklimatická rekonstrukce na příkladu borovice kleče (*Pinus mugo*)

Cíle práce

1. Vytvořit co nejdelší letokruhové chronologie borovice kleče z Krkonoš;

2. Posoudit variabilitu v růstu mezi různými stanovišti;

3. Na základě letokruhových indexů rekonstruovat teplotní poměry v minulosti;

Použité pracovní metody, zájmové území, datové zdroje

Studované území: Krkonoše, dvě plochy lišící se nadmořskou výškou.

Metody: (1) odběr vzorků – odebrat výseče větví ze dvou ploch; (2) výseče křížově datovat; (3) vytvořit stanovištní chronologie:

- chronologie porovnat z hlediska jejich základních statistických charakteristik;
- indexované chronologie porovnat s chronologií smrku z Krkonoš;
- na základě delší indexované chronologie rekonstruovat teploty v Krkonoších (kalibrační data ze stanice Sněžka);
- rekonstruované teploty srovnat s jinými rekonstrukcemi teploty (historické záznamy, jiné dendrochronologické rekonstrukce);

Datum zadání: 15.6. 2012

Jméno studenta: Alina Samusevich

Podpis studenta:....................................

Jméno vedoucího práce: Václav Treml

Podpis vedoucího práce: …..............................

I declare that I worked out the presented thesis independently and I quoted all used sources of information in accordance with Methodical instructions about ethical principles for writing academic thesis.

Prague, August 15, 2014 **……………………………..**

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Abstract

Pinus mugo Turra (sensu lato) is a prostrate shrub growing above the alpine timberline in the mountain ranges of Southern, Central and Eastern Europe. It is well adapted to the harsh alpine environment creating different mechanisms for survival. The research was carried out in Krkonoše Mountains on base of *Pinus mugo* individuals compared with *Picea abies* trees. Samples from shrubs were gathered using serial sectioning from four sites in different elevations located on Sněžka Mountain and Smogornia Ridge. Further analysis of the sampled material was made with the help of different detrending methods to see which method will return the best growth response to climate parameters. RCS detrending and detrending via simple averaging reflected the best climate signal contained in dwarf pine chronologies. The advantage of these methods is based on their ability to reflect growth conditions of the particular site. Upper sites showed significant correlations with temperatures of the growing season, while on lower sites the signal was quite unclear. The amount of precipitation plays the significant role on shrub growth during the vegetation period (especially July month) and early spring when water is very important for growth initiation. Upper *Pinus mugo* sites showed high sensitivity to droughts, especially during vegetation period. Climate signal at lower pine sites was weaker and more diverse. Comparison with spruce sites showed, that growth response of upper shrub sites and spruce sites follows the similar trend. However climate signal in *Pinus mugo* was shown to be weaker than in spruce individuals, which is mainly explained by different positions of two species according to their environmental limits.

Key words: mountain pine, dwarf pine, Pinus mugo, *Picea abies,* climate signal, PDSI, RCS detrending, spline detrending, detrending by average.

Abstrakt

Borovice kleč (Pinus mugo Turra (sensu lato)) je keřem rostoucím nad hranicí lesa v pohořích jižní, střední a východní Evropy. Kleč je dobře přizpůsobená na extrémní horské prostředí a často tvoří výškový vegetační stupeň 250 – 300 m. Diplomová práce byla řešena v Krkonoších na základě letokruhových vzorků borovice kleče, které byly dále porovnané s chronologiemi smrku ztepilého. Vzorky kleče byly odebrány s využitím metody sériových řezů ze čtyř lokalit v různé nadmořské výšce ze Sněžky a Stříbrného hřbetu. Následná analýza vzorků byla provedena s použitím různých standardizačních metod za účelem zjištění nejvhodnější metody pro analýzu odezvy růstu keřů na klimatické proměnné. RCS standardizace a standardizace průměrováním sérií z jedné lokality odrážejí nejsilněji klimatický signál který obsahují chronologie kleče. Přednost těchto metod vyplývá z jejich schopnosti odrážet podmínky růstu na rlzných stanovištích. Výše položené lokality se vyznačují relativně silnou korelací růstu s teplotami vegetačního období, v případě lokalit ležících při horní hranici lesa podobný signál není zřejmý. Množství srážek významně ovlivňuje růst keřů během vegetačního období (obzvlášť v měsíci červenci) i také na jaře kdy je dostatek vody důležitý pro zahájenéí růstu. Na výše položených lokalitách *Pinus mugo* se ukázala silná citlivost keřů k obdobím sucha, obzvlášť během léta. Klimatický signál na dolních lokalitách byl celkově více smíšený a slabší. Porovnáním s chronologiemi smrku se ukázalo, že klimatický signál keřů z výše položených stanovišť je podobný smrku, ale slabší. Vysvětluji to různou polohou těchto druhů vůči jejich environmentálním limitům.

Klíčová slova: borovice kleč, smrk ztepilý, klimatický signál, palmerův index sucha, RCS standardizace, standardizace pomocí splinových metod, standardizace průměrováním.

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1 Introduction

Wooden shrubs (e.g., *Pinus mugo*, *Pinus pumila*, *Juniperus nana*, *Betula nana*, *Salix arctica*) growing at their environmental limits have become one of the most prospective fields for dendroclimatological and dendroecological research during the past years (Woodcock and Bradley 1994, Wilmking et al. 2004). They are providing scientists with climatic information from regions with short climatologic data coverage. Shrubs, growing at their northern or altitudinal limits, represent a model of perfect adaptation to the severe habitats they are growing in, that is why their growth reactions as well as their functioning mechanisms are of a great potential interest (Bär et al. 2005).

Predicted future warming during the 21^{st} century (IPCC 2007) will lead to the upslope and northward treeline advance (Kullman and Öberg 2009, Öberg and Kullman 2011) thus fundamentally changing the landscape (Holtmeier and Broll 2007). It can influence the global carbon cycle by increasing the terrestrial carbon sink and influence the biodiversity of the ecotone by changing competitive relationship within the ground cover vegetation (Grace et al. 2002).

According to Körner (2012) the main reasons supported the shrub ecotone formation are linked with the difference in aerodynamic properties of shrubs and trees and the duration of the growing season. While trees are exposed to the ambient atmosphere and thermally connected with it, shrubs benefit much from the near-ground heating. Mean duration of the vegetation period for trees must be at least 94 days otherwise it will cause complications for the xylogenesis completion and maturation of evergreen foliage. Shrubs and herbs however are more flexible and can withstand even growing season of 45 days (Körner 2012).

In mountain regions of the Sothern, Central and Eastern Europe, prostrate Dwarf pine (*Pinus mugo* Turra) represents distinct component of ecosystems situated above the alpine timberline (Hamerník and Musil 2007). *Pinus mugo* Turra sensu lato (s.l.) is a complex of polymorphic species of 2 – 3 m high with the montane distribution (Heuertz et al. 2010). It is very difficult to segregate the taxa due to a great variability in growth forms, possible hybridization, needle and cones characteristics (Heuertz et al. 2010). According to Hamerník and Musil (2007) the taxa of *Pinus mugo* Turra (sensu lato) can be divided into ten working groups. Mountain pine from Krkonoše Mountains belongs to "shrub forms" occupied central and eastern parts of the dwarf pine range.

It is suggested that dwarf shrubs have different sensitivity to environmental controls in comparison to trees (García-Cervigón Morales et al. 2012). Though the general trends in growth response to climatic changes at shrubs and trees are similar, the strength of the climate signal is weaker at shrubs than at trees. This is explained first of all by the different position of them in relation to their environmental limits (García-Cervigón Morales et al. 2012). Shrubs are less sensitive to frost events and pollution (Souček et al. 2001, Rixen et al. 2012, Vacek et al. 2012), quicker react on warm spring temperatures (García-Cervigón Morales et al. 2012) and are positively influenced by the duration of vegetation season and availability of water during summer (García-Cervigón Morales et al. 2012).

This thesis is focused on the analyses of climate signal in *Pinus mugo* individuals at Krkonoše Mountains. I aimed to fill particularly following objectives:

1) Creation of long reliable *Pinus mugo* tree-ring (TRW) chronologies from Krkonoše Mountains;
2) Analysis of climate-growth response variability on sites differing in altitude;
3) Comparison of methods for extracting climate signal from prostrate shrubs;
4) Comparison of climate signal between prostrate shrub *P. mugo* and tree *P. abies*;

The aims of this research however differ from the original work assignment. Due to the absence of old enough *P. mugo* sampled series it has been difficult to construct chronologies suitable for climate reconstruction to the past.

Studying of shrubs will help better understand and predict changes in subalpine and alpine landscapes especially in terms of global warming. It will help to understand the feedback mechanisms between land cover changes, carbon cycle, melting of permafrost, changes in albedo, water balance etc.

2 Shrubs at high altitudes

2.1 Shrub and tree life forms in cold environment

Bioclimatic border between trees and shrubs in high altitudes is explained by aerodynamic consequences of being tall (Körner 2012). Körner (2012) defines krummholz zone at high altitudes as a zone of shrub vegetation under 3 m high. According to Holtmeier (2009) the height of 2 m is enough for tree to overcome snow cover and started to be exposed to ambient air circulation.

There is a lot of evidence that temperature around 0°C limit the formation of plant tissues (Körner and Paulsen 2004) at high altitudes. Growth still remains very slow in cambial and apical meristems both above and under the ground between 0°C - 5°C (Rossi et al. 2007).

Stem of tress together with main branches and roots concentrate about 95% of its biomass. Thus to build-up the perennial structure, to mature and to reach robustness against unfavorable conditions, tree needs some period of time. At high altitudes the duration of growing season is important as well as temperatures of growing season. It has been stated by Körner (2012) that minimum length of vegetation period for tree in alpine environment should be 94 days. Shrubs and herbs are more flexible from this point of view. Some species can survive the whole year under the snow cover. Vegetation period of 45 days has been stated to be enough for them to complete seasonal life cycle. Low stature life forms (mostly herbs) benefit from short lived foliage and growth flexibility in comparison with trees (Körner 2012).

Due to its prostrate form shrubs are able to create its own microclimate based on the reduced heat exchange and shelter effect. This ability helps them to experience warmer conditions near the ground. In the opening due to the lack of shelter and occurrence of open ground shrubs can experience colder conditions (Körner 2012). Snow cover protects low stature vegetation from droughts and frost cycles, thus protecting them from embolism (Körner 2012).

Roots of isolated trees can use the advantage of open stands and profit from higher temperatures due to the solar ground warming. However, when forest canopy closes, roots are withstand to the same temperature as atmosphere (Körner 2012).

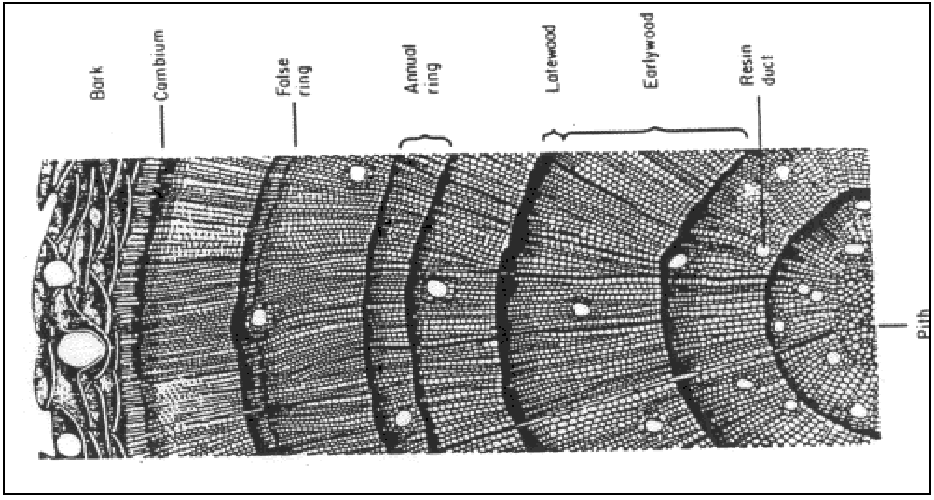
According to Körner (2012) common assumption, that trees exposed to ambient air are more susceptible to frost damage is not true. Tall trees can prevent radiation cooling of leafs below air temperature during cold nights by faster transfer of heat. Low stature vegetation on the opposite can cool below atmospheric temperatures. Frost can affect trees through damaging xylem, or inducing embolism by freeze-thaw cycles. This effect is mostly observed at isolated trees at high altitudes and is not common during the growing season (Körner 2012). A high degree of aerodynamic exposure to the ambient atmosphere enforces convective heat transfer at trees also during the growing season, causing trees to experience climatic conditions close to those registered by climatic stations. Trees thus do not take enough thermal advantage from solar heating in comparison with low stature vegetation (Körner 2012).

Under the condition of limited nutrient availability at high altitudes myccorhizal fungi are very important for both tree and shrub species. The usage of same mycorrhyzal fungi partner sometimes occurs, allowing access of both species to the same pool of nutrients (Wieser and Tausz 2007).

2.2 Structure of tree rings

Wood structure of coniferous trees is shown at Figure 1. Tree-ring consists of early wood (big cells with thin walls) and late wood (small cells with thick walls). The main function of early wood is to transport water and minerals in the beginning of the vegetation period. The function of late wood is to provide support to the whole tree (Stokes and Smiley 1996).

Figure 1: Cross-section of the conifer stem showing the wood structure (Fritts 1976)



The influence of environmental factors on tree growth is well documented in the structure of TRW (Fritts 1976). The influence of some environmental factors (for example, the influence of frost) can have the immediate effect on tree-ring structure, other factors (for example, winter drought) will be observed only in some period of time (Fritts 1976). Competition or shading will cause systematical changes in tree-ring structure; disturbances (fires or breakdowns of insects) will cause a rapid change in TRW (Fritts 1976).

Extreme events can be reflected in the structure of TRW in different ways. For example, frosts during the growing season causes the damage of xylem, thus forming so called frost tree-ring (Gurskaya et al. 2002). Frost tree-rings can reflect early spring, summer or autumn frosts (Gurskaya et al. 2002). According to D`Arrigo et al. (2001) frost rings can be also linked to volcanic eruptions. It is difficult to highlight the exact temperature threshold at which frost rings can be formed (Gurskaya et al. 2002).Temperature however must be lower than 0°C as the intercellular sap freezes at lower degrees due to its salinity (Dvorakovski 1983).

Stöckli and Schweingruber (1996) have observed frost damages in *Pinus mugo* at air temperatures 0°C – 1,5°C which is going in contrast with Dvorakovski (1983). According to Sakai (1983) there are two ways of damaging plant with low temperatures: 1) rapid decrease in temperatures below 0°C and damage of cells membranes by frozen crystals inside of them; 2) graduate cooling leading to dehydration of cells resulting in limitation of metabolic processes. Sometimes frost rings do not form even during the low temperature periods. First of all, it can be explained by low temperatures during the whole vegetation period with the low rate of division of cambium and cell enlargement (Gurskaya et al. 2002). Among other reasons small daily amplitude of temperatures (Stöckli and Schweingruber 1996), dew, winds, clouds (Leuning 1988), differences in the sensitivity of cells (Gurskaya 2014) can be named.

Regarding the age, tree-rings can differently reflect the environmental changes. For example, young and old TRW can have different sensitivity to temperature and precipitation changes, so known CSAE effect – climate signal age effect (Esper et al 2008).

Shrubs are characterized by a big number of missing tree rings, especially at the stem base (Kyncl and Wild 2004, Wilmking et al. 2012). According to Wilmking et al. (2012) it is possible to distinguish three types of them: locally missing rings (LMR), totally missing rings (TMR) and continuously missing outer rings at the stem base (CMORs). CMORs is the most common type of missing rings in woody shrubs (Kolishchuk 1990) either they are angiosperms or gymnosperms (Wilmking et al. 2012). According to Wilmking et al. (2012): "CMORs is a general strategy of woody plants to deal with extreme environmental conditions”. Their research conducted in 6 different types of sites (elevational shrubline, elevational treeline, latitudinal treeline, wet hydrological limit, dry hydrological limit and permafrost influences soils) supports this result. In total 202 individuals have been sampled (92 shrubs and 110 trees). 29% of all samples have shown CMORs. Among the sampled individuals there have been 6 different species of shrubs (*Alnus. crispa, Betula nana, Juniperus nana, Pinus mugo, Salix alaxensis, Salix glauca*) from Alaska, Sweden and Czech Republic. Only *Alnus crispa* and *Betula nana* from Alaska have not shown CMORs, which can be explained by their more erect growth form and younger age. The link between the CMORs amount and shrub age have been also proved by other samples (for *J. nana* from Sweden Spearman correlation was r=0.58, at p<0.001). The same is true for shrub size: the longer the stem of the shrub is, the more CMORs it has (for *P. mugo* from Czech Republic Spearman correlation was r=0.57, P<0.013). Sometimes a great amount of CMORs can be caused by pathogens or insect outbreaks as it has been shown in one sample of *Salix alaxensis* from Alaska and 11 individuals of *P. mugo* from Czech Republic.

Appearance of CMORs is closely connected with xylogenesis (Wilmking et al. 2012) and can be generally explained by three reasons: auxin concentrations in the cambium (Kramer 2001), temperatures of the stem (Begum et al. 2008) and availability of carbohydrates and water (Hallinger et al. 2010). Moreover, the health of the tree (or shrub) canopy and root system is important.

Xylogenesis is a process of production and further differentiation of cells (Rossi et al. 2012). Generally, it starts when average daily temperatures overcome 2°- 4°C (Rossi et al. 2007). Low temperatures can inhibit resource distribution in plant (Rossi et al. 2007). Low stem temperatures can slow down auxin transportation and thus the beginning of xylogenesis (Begum et al. 2008). However, the link between tree-ring formation and xylogenesis is much more complicated. A lot of other factors should be taken into consideration, for example soil temperatures (Wilmking et al. 2012, Körner and Paulsen 2004), the ability of some trees to accumulate (Egierszdorff 1981) or produce auxin by themselves (Kramer 2001), stem length, tree age (Wilmking et al. 2012) etc. Differences in physiology of shrubs and trees conditioned variation in climate signal between these two growing forms.

2.3 Climate signal in shrubs and trees

García-Cervigón Morales et al. (2012) compare growth of *Juniperus Sabina* and *Pinus sylvestris* species at Iberian Mountain system. They have shown that in general, both species have very similar response to climatic parameters. Their growth positively correlates with warm temperatures of early spring season and sufficient water supply during summer months. Here however it must be highlighted that positive reaction on summer precipitation in this region is quite normal due to the general summer water stress.

Warm September on the opposite leads to the decline of both species growth. That can be explained either by the influence of the prolonged vegetation period or by longer water stress (Dirnbök et al. 2003, García-Cervigón Morales et al. 2012). *Juniperus* shrubs show earlier response to spring temperatures than *Pinus* trees (García-Cervigón Morales et al. 2012). The same earlier response of TRW is shown by Gazol and Camarero (2012) in North-Eastern Spain. In general, the climatic signal has been found to be stronger at *Pinus* trees than at *Juniperus* shrubs (García-Cervigón Morales et al. 2012). It can be explained by their different position in relation to environmental limits. *Juniperus* shrubs are growing close to the optimal conditions, while *Pinus* trees occupy areas at its altitudinal limit. Moreover, low stature of prostrate vegetation and reduced shading effect contribute positively to shrub growth (García-Cervigón Morales et al. 2012).

Büntgen et al. (2007) in the research in Tatra Mountains found out positive response of trees and shrubs (*Picea abies*, *Larix decidua* and *Pinus mugo*) to June - July temperatures. Shrub growth, however, has been negatively influenced by warm March – April months which is going in contrast with the findings of García-Cervigón Morales et al. (2012). Negative correlations with early spring temperatures can be explained by insufficient protective snow cover, short-term fluctuations of soil temperatures and desiccation due to increased evapotranspiration (Oberhuber 2004). Negative correlation between snow depth in early spring and *Salix arctica* growth is observed in Greenland (Schmidt et al. 2006). Thick snow cover can increase winter mineralization (Schimel et al. 2004). On the other hand increase in winter precipitation can move the beginning of growing season thus leading to the decline of growth (Blok et al. 2010). Moreover sites with a big snow depth can lead to the spreading of snow fungi on *Pinus mugo* individuals (Holtmeier 2009).

Büntgen et al. (2007) have shown positive correlation of shrub growth with temperatures in previous October and November months. Positive correlation with preceding October and November temperatures can be supported by carbon storage, mycorrhyzal root growth, and by creating better condition for needle maturation against early winter stress (Oberhuber 2004).

Gazol and Camarero (2012) pointed out that dwarf shrubs are less influenced by seasonal climate oscillation than trees. According to Solár and Janiga (2013) mountain pine adapts well to the variable climate conditions in high mountains.

Rixen et al. (2012) observed no changes in *Pinus mugo* shoot formation in comparison with *Larix decidua* during the cold years 2008 and 2009. This fact confirms less sensitivity of mountain pine to cold conditions. They also showed that vessels are more susceptible to frost events than needles in early period of the growing season.

Mountain pines can withstand conditions with low nutrient availability. Thus they are more competitive at high elevations and less competitive on sites, where the conditions are favorable for growth of other species (Holtmeier 2009). Dwarf shrubs feel well at dry and sunny sites impeding the establishment of spruce at such areas (Holtmeier 2009).

Tree species, elevation and physiological parameters modulate correlation of shrubs and tree growth with climate variables (Wilmking et al. 2004, Büntgen et al. 2007). General uncertainty in the results can be explained by nonlinear reaction of plant on climate changes (Fritts 1976), growth response to maximum rather than minimum temperatures (Wilson and Luckman 2003), changes in the longevity of the growing season (Frank and Esper 2005) etc.

2.4 The use of shrubs in dendrochronological research

Wooden shrubs growing at their environmental limits have become very potential for dendroclimatological and dendroecological research during the past years (Wilmking et al. 2012). Shrubs provide scientists with climatic information from regions with short climatologic data coverage and represent a model of perfect plant adaptation to the severe habitats they are growing in (Bär et al. 2005).

One of the perspective fields for shrub usage in dendrochronological research is by studing their growth response on climate warming. Hallinger et al. (2010) have found several evidence of shrub expansion into higher elevations as well as the presence of young individuals of *Juniperus nana* at its environmental margins. He has connected it with climate warming.

Solár and Janiga (2013) have predicted the increase in mountain pine area in higher elevations at Tatra Mountains. Lower elevations will however experience the decrease in

Pinus mugo stands according to the elevation movement of spruce. Dirnböck et al. (2003) have also concluded the increase in *Pinus mugo* stands in alpine and subalpine areas of Alps.

An increase in shrub cover can have important consequences for the alpine ecosystem including changes in the surface energy balance (Chapin et al. 2005, Euskirchen et al. 2009), turnover of soil organic matter (Weintraub and Schimel 2005) and frequency of fires (Leys et al. 2014). Furthermore, higher shrub cover may lead to increased soil shading, thereby reducing the energy input into the soil and reducing summer permafrost thaw (Blok et al. 2010).

Liang et al. (2012) have showed that growth of Wilson juniper is limited highly by moisture stress in May and June. This result is different from the one obtained in the circum-arctic tundra, where shrubs gain from high temperatures during the vegetation period (Hallinger et al., 2010; Blok et al., 2011). This difference in climate–growth relationship between two geographical regions shows that sites suffered from water stress now will gain only from warming supported by increased precipitation. Otherwise, the influence of warming in such regions will be negative. This finding is supported by Dirnböck et al. (2003) as well.

Speaking about climate warming, a lot of other factors influencing shrub upward movement should be taken into consideration, for example topography, soil properties, hydrological regime, nutrient availability, mycorrhyzal symbiosis etc. In most of the mountain ranges the local treeline (or shrubline) dynamics is much controlled and modulated by local factors. Global climate only increases the threshold for trees and shrubs survival, enlarges the amplitude of their possible movements (Holtmeier 2009).

The enhanced amount of CO_2 in the atmosphere leads to the increased sensitivity of shrubs to frost damage through their altered phenology or physiology. Absence of snow, caused by warming, can have more drastic ecological effect on tree growth. Bigger amount of frost events caused by CO_2 can limit the growth in the warming future (Rixen et al. 2012).

According to Kong et al. (2012) TRW can be also a good proxy for studying changes in regional net primary productivity (NPP) if TRW and NPP are limited by the same factor. Another possible usage of TRW from shrubs growing in the vicinity of glaciers can provide information about past glacier mass balance (Buras et al. 2012).

3 Study area

3.1 Geology

Krkonoše Mountains together with Jizera Mountains and several adjacent ranges of the Sudetes form the northern edge of the Bohemian Massif, which represents a wedge of the European Hercynids sticking between the Fenno-Sarmatian platform and the Alpine-Carpathian system. Most part of the Krkonoše Mountains is formed by Krkonoše-Jizera Mountain complex build of crystalline metamorphic rocks, such as, for example, mica schists, phyllites, orthogneisses of the Proterozoic to Paleozoic age. This crystalline complex has been folded two times in the Paleozoic. During the second folding in the Carboniferous, complex has been encroached by a granite pluton that forms the main part of the Polish Krkonoše and the entire Hraniční hřbet from Harrachov to Sněžka. Pluton is surrounded by a hard contact zone playing a very important role for the mountains’ geomorphological evolution. It is a zone where major deposits of ore have been found. An important role in relief formation also belongs to quartzite, basalt, and crystalline limestone, though their occurrence is much less ferquent in that region (Soukupová et al. 1995).

In the Mesozoic and the first half of the Tertiary, Krkonoše Mountains have been remodeled by chemical weathering into etchplen. The originally hidden granite core was uncovered forming so called tors: Mužské and Dívčí kameny (Men's and Girl's Stones), Harachovy kameny (Harrach's Stones), Polední kámen (Noon Stone). During the Upper Tertiary the territory has been uplifted by orographic movements in the Alpine and Carpathian systems. Uplifting restarted water erosion, leading to the formation of narrow valleys and sharp rocky relief (Soukupová et al. 1995).

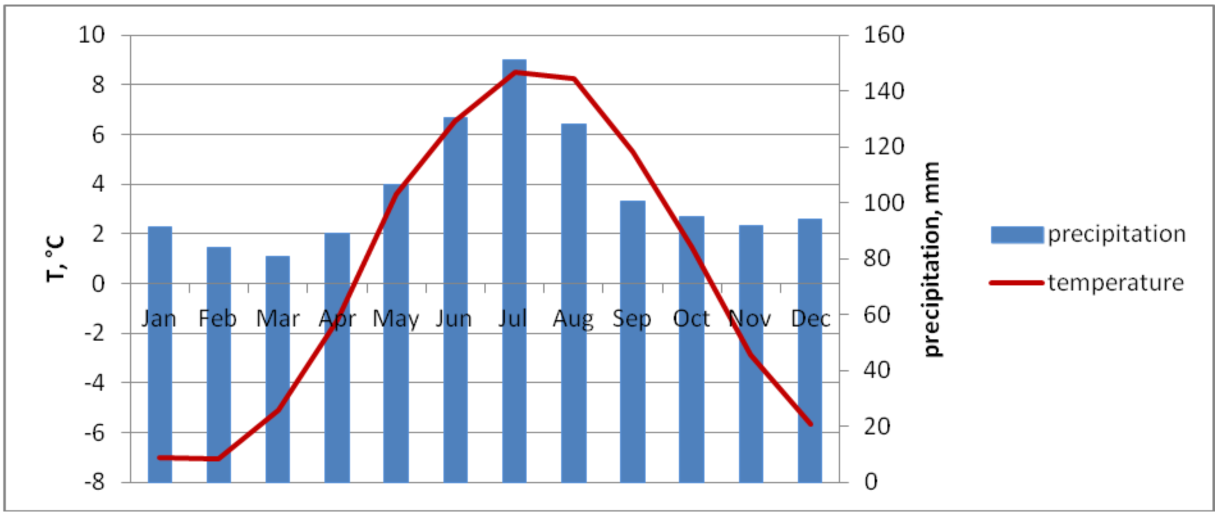
The relief of Krkonoše Mountains has been modelled by alpine glaciers and frost processes. Mountains however were never covered with glacier continuously. The main geomorphological forms are glacial cirques, moraines (Labský and Obří důl, lower part of Kotelní jámy), cryoplanation terraces, frost cliffs, polygonal soils etc. Among glacial lakes it is possible to name lakes in the cirques of Wielki and Maly Staw and in Sněžné jámy. Nowadays the most important remodeling processes in the mountains are anthropogenic changes, landslides and erosion (Soukupová et al. 1995).

3.2 Climate

Krkonoše Mountains are characterized by mild climate with strong influence of western wind and the Atlantic Ocean, which makes its climate quiet unstable. The average annual temperature in Krkonoše Mountains fluctuates between 0°C and 6°C. The coolest weather is on Sněžka Mountain – 0,2°C, while the valley positions are much warmer - Žacléř - 6.1 °C, Karpacz - 5.9 °C, Szklarska Poreba - 5.8 °C, Harrachov - 4.9 °C, Špindlerův Mlýn - 4.7 °C. Temperature inversions are very frequent at this region. Most of them occur in winter and autumn. The warmest month is July (14 °C in valleys, 8,4°C at Sněžka Mountain). The coldest month is January (4°C in valleys, 7 °C at Sněžka Mountain, Soukupová et al. 1995).

Precipitation changes with elevation from 800 mm on foothills to 1600 mm on the ridges of Krkonoše Mountains. Exceptionally there are rainfalls of disastrous character in this region.100-200 and more mm daily can fall in such situations (e.g. Obří důl 29. 07. 1897 – 266 mm). The annual distribution of temperatures and precipitation in Krkonoše Mountains is shown at Figure 2 (Soukupová et al. 1995).

Figure 2: Annual distribution of temperatures and precipitation at Krkonoše Mountains (1960 – 1991)



From the beginning of November and during winter and spring months continuous snow cover is formed. Depths of snow reach 100 – 300 cm. Snow can lay till the beginning of May at high altitudes. Winter winds to a high extent redistribute snow in the Mountains moving it from the windward slopes to lee slopes and depressions. Avalanche activity is rather frequent in Krkonoše Mountains (Obří, Labský or Modrý důl, Kotelní jámy or the valley of Bílé Labe).

There are more than 50 mapped avalanche tracks. Most of them occur during January – February and March (Soukupová et al. 1995).

Western and South-western winds together with the west-east direction of the Krkonoše valleys form so called anemo-orographic system. The strongest winds occur in winter time, the weakest – in summer period. Prevailing winds are south-western, western and north-western. Frequent western and north wind storm blow at the end of autumn and winter (Soukupová et al. 1995).

3.3 Hydrology

River network in Krkonoše Mountains has been formed since the Tertiary and Quaternary periods. Mountain relief had a big influence on its formation. Most of the main Krkonoše streams have their basic direction perpendicular to the main ridge with a lot of tributaries in subsequent direction. The river valleys are mostly narrow and in the mountain regions are densely forested. The entire region of the Krkonoše Mountains, with the exception of Janské Lázně has no sources of underground water and is exclusively dependent upon precipitation. Labe (Elbe), the biggest Czech river springs in the Krkonoše Mountains. It sources in Labská louka in the western Krkonoše Mountains, 1386.3 meters a.s.l. Labe drains about one third of the Czech part of the mountains. Among its tributaries are Medvědí potok (Bear's Brook), Bílé Labe (White Labe), and Dolský potok. Malé Labe (Small Labe) and Čistá (Clean) drain middle part of the Krkonoše Mountains, and eastern part is drained by Úpa river with Malá Úpa (Small Úpa) and Lysečinský potok (Lysečiny Brook). Western part is drained by Jizera river with its tributaries Mumlava, Huťský potok and Jizerka (Soukupová et al. 1995).

There is a water-shed between Labe and Odra river systems along Hraniční hřbet. Water from Polish slopes of Krkonoše flows away to the Baltic Sea; whereas water from Czech part of the mountains flows to the North Sea (Soukupová et al. 1995).

3.4 Soils

Soils of Krkonoše Mountains display an altitudinal zonation. Their development has been strongly influenced by cold and wet climate. Almost all the soils, except rendzinas on crystalline limestone, are acidic. Brown acidic soils prevail at lower altitudes of National park. Higher elevations are characterized by brown podsolic soils – the most common type in

Krkonoše Mountains. On isolated sites rankers can be found (especially on steep slopes covered with krummholz). Podzols are occurring above 1000 m a.s.l. Highest locations are characterized by frost sorted soils (polygonal and patterned). Fluvisols occur locally in floodplains, gley soils - around springs and in depressions, organic soils - in mountain mires of the forest belt and subarctic mires above the timberline (Soukupová et al. 1995).

3.5 Vegetation

Krkonoše Mountains are characterized by rich flora. More than 1250 taxa of vascular plant have been identified here. Moreover new taxa of bryophytes, lichens, algae, fungi, cyanophytes, myxomycetes are identified all the time. According to the altitudinal distribution it is possible to divide Krkonoše flora into following zones (Soukupová et al. 1995):

1) Submontane (400 – 800 m) – deciduous and mixed forests formed by *Fagus sylvatica*, *Acer pseudoplatanus*, *Fraxinus excelsior*, *Sorbus aucuparia*, and *Alnus incana*. Big part of the original forests has been cut and replaced by *Picea abies* and *Larix decidua*. Herbal layer consists of *Allium ursinum*, *Corydalis cava*, *Anemone nemorosa*, *Anemone ranunculoides*, *Dentaria enneaphyllo*, *Dentaria bulbifera*, and *Lilium martagon*.
2) Montane (800 – 1200 m) – native and planted spruce forests. Herb layer consists of *Athyrium distentifolium*, *Dryopteris filix-mas*, *Blechnum spicant*, *Calamagrostis villosa*, *Deschampsia flexuosa*, *Chaerophyllum hirsutum*, *Petasites albus*, *Petasites kablikianus,* and *Cardamine amara*. Enclaves of species-rich mountain meadows with *Viola sudetica*, *Campanula bohemica*, *Hieracium spp.*, *Achyrophorus uniflorus*, *Arnica montana*, family *Orchidaceae* originated in the 18th century.
3) Subalpine (1200 – 1450 m) is the most valuable ecosystems in Krkonoše Mountains. *Pinus mugo* stands, secondary mat-grasslands and subarctic mires with *Nardus stricta*, *Calamagrostis villosa*, *Carex*, *Vaccinium myrtillus*, *Vaccinium vitis-idaea*, *Vaccinium uliginosum*, *Oxycoccus microcarpus*, *Empertum hermaphroditum* are formed here. Among endemic species of this region can be named *Hieracium spp.*, *Pedicularis sudetica,* and *Rubus chamaemorus*.
4) Alpine (1450 – 1602 m) is characterized by many endemic species as *Sorbus sudetica*, *Campanula bohemica*, *Saxifraga moschata basaltica*, *Pimpinella saxifraga rupestris*, *Hieracium*. Summits of Krkonoše Mountains (Sněžka, Studniční hora, Luční hora,

Vysoké kolo, Kotel) are covered with *Juncus trifidus*, *Veronica bellidioides*, *Luzula spicata*, endemic *Hieracium alpinum agg.*, and *Thamnolia vermicularis* and *Rhizocarpon geographicum*.

The richest flora is found in the so-called Krkonoše botanical garden, where under the combine influence of near-the-ground wind systems, deposition and redistribution of snow, denudation of outcrops of mineral-rich rocks and landslides, deposition of airborne soil particles, seeds, spores and germs micro-evolution produces new varieties and species (Soukupová et al. 1995).

Peat bogs are another valuable characteristic of the Krkonoše Mountains. They started to form during the Atlantic period, when the climate was wet and cool. Peat bogs play an important role for Krkonoše flora and fauna (Soukupová et al. 1995).

Sněžka (1602,3 m a.s.l.) Mountain – is the highest summit of Krkonoše, it was modulated by the glaciogenic and cryogenic processes. Climatically it is a much stressed region inside of stony tundra (Soukupová et al. 1995).

Smogornia Ridge (1490 m a.s.l.) is represented by cryogenic relief with elongated polygons about 6 m in diameter (relic periglacial stony tundra). Arctic-alpine podzol soils are not developed to a full extent here (Soukupová et al. 1995).

3.6 *Pinus mugo* stands in Krkonoše Mountains

Dwarf pine sites represent isolated islands of arctic - alpine tundra in Krkonoše Mountains (Soukupová et al. 2001). These islands represent the northern natural limit of *Pinus mugo* occurrence. It is assumed, that the appearance of the ecotone is linked to the Pleistocene (Jankovská 2001). Krummholz understory is formed mainly by *Vaccinium myrtillus* and different kinds of bryophytes. Among the main grassland species can be named *Nardus stricta*, *Deschampsia flexuosa*, *Antchoxanthum alpinum*, *Carex bigelowii* (Wild and Winkler 2008).

Dwarf pine (*Pinus mugo* Turra) is the most competitive member among all the species at shrub zone (including *Salix silesiaca*, *Salix lapponum*, *Sorbus sudetica*). Originally dwarf pines inhabited fluvio-deluvial zone at the treeline, sheltered sites in the niveo-glaciogenic zone and organic soils at vegetated-cryogenic zone. Due to harsh conditions in the cryo-eolian zone, it is possible to find only separate individuals of dwarf pine there. Ideally it is supposed that shrub belt must cover elevations from 1200 m to 1450 m, in reality the distribution of

Pinus mugo is more complicated (Kyncl and Štursa 1995). Wild and Winkler (2008) stated two main mechanisms explaining the appearance of shrub zone in Krkonoše Mountains: disturbances (for example insect outbreaks) and life history trade off.

For a long time both *Pinus sylvestris* and *Pinus mugo* taxes have been not distinguished between each other, thus it is hard to say something detail about the history of shrub distribution in arctic-alpine zone during early history. First exploitation of that region is dated by the 9th century, when different trade ways crossed Krkonoše Mountains. 18th – 19th centuries are characterized by the development of chalet farming with grazing and mowing. Big damage to *Pinus mugo* stands has been made by the fortification system in 1938. Intensive colonization of Krkonoše Mountains led to the decrease in mountain pine areas in this region (Vacek et al. 2008).

The restoration of *Pinus mugo* stands started at 1879 with allochthonous seeds brought from Alps. Modern area of dwarf pine stands is approximately 2055 ha, 73% of the area are occupied by natural stands, 27% by allochthonous stands (half was established during the 1879 – 1945 and half - between 1952 – 1992, Lokvenc 2001).

Prostrate form of *Pinus mugo* is supposed to be the adaptation to the harsh climatic conditions in that environment. Mountain pine is highly flexible and resistant to brokerage. Due to layering it can colonize even avalanche tracks (Holtmeier 2009). As soon as the branch will touch the ground or some bark injury will occur, adventitious roots are formed. Apical and radial growth of adventitious branches results in development of “krummholz vegetation”.

Bitterli (1987) based on his research in the Alps concluded, that the mean TRW of mountain pine is declining with altitude and that shrub growth is significantly influenced by local stress factors. In my research the effect of elevation on TRW has been not observed. Bitterli (1987) also showed that young shrubs experience low increment, followed by the period of intensive growth and further stagnation. Kolisčuk (1990) explained this stagnation by the influence of inherent factors.

It is possible to observe *Pinus mugo* growth forms both erect and prostrate. In my research in Krkonoše there have been no observed stunted individuals of this shrub. However, Špinlerová and Martinková (2006) met during their research in Orilcké Hory stunted examples of *Pinus mugo*. They link it with young shrub age and with the influence of external factors. They have observed that branches of old trees lean more if they are shaded by other species.

Mountain pine in comparison with Norway spruce is less sensitive to extreme events and air pollution with sulphur compounds (Souček et al. 2001, Vacek et al. 2013). The most significant correlations of spruce with air pollution have been observed during the period 1985 – 1994 (Vacek et al. 2013), followed by a decrease in a number of needles between 1994 – 2008 years. Vacek et al. (2013) concluded that impact of air pollution is species specific, as the influence of sulphur on growth of *Fagus sylvatica*, has been even more dramatic (Vacek and Hejcman 2012).

Pinus mugo stands in the mountains can suffer strongly from insects' outbreaks. The increase of mean temperatures usually leads to the increase in the amount of insects. An increase in pine gall midge, for example, has led in 1994 – 1996 period to the mortality of a number of mountain pine individuals. Insects influence trees through damaging the current year needles and causing defoliation (Glynn and Lindelöw 2002). *Pinus mugo* in the Krkonoše mountains has been also intensively attacked by gall midge in 1940 (Kyncl and Wild 2004, Wilmking et al. 2012). Insects sometimes are quite selective. Sawflies, for example, attack preferably older needles.

Moreover, mountain pine communities create favorable conditions (wet environment and a big area of trunks) for the development of fungi (Ronikier 2009), causing rotting processes in shrubs. The research carried out on *Pinus mugo* in Swiss national park by Dobbertin et al. (2001) has shown that the most probable reason of shrub mortality has been root rot fungi *Heterobasidion annosum.* In my research in Krkonoše Mountains about 10% of discs (especially at older stem parts) have rotten center. Deep investigation of this phenomenon has not been carried out.

4 Statistical analyses of dendrochronological data

4.1 Standardization of tree ring series

This chapter is focused on statistical methods used for extracting information from tree-ring data. Different detrending and estimation techniques are discussed in order to show their advantages and disadvantages. This problematic has been widely studied from the beginning of dendrochronological research. Depending on the data type, goals and scale of the research (decades, centuries etc.) various standardization methods are used to evaluate the reliable chronology (Cook 1985).

According to Cook's aggregated model (Cook and Kairiukstis 1990), TRW is the result of combined influence of different factors, from climatic controls to anthropogenic disturbances:

$$\mathbf{R_t = A_t + C_t + \delta D_{1t} + \delta D_{2t} + E_t}$$

where, $\mathbf{R_t}$ - is a tree-ring width in the given year, $\mathbf{A_t}$ - age related trend, $\mathbf{C_t}$ - climatic signal, $\mathbf{\delta D_{1t}}$ - disturbances caused by endogenous factors (for example, forest management; effects only individual trees not the whole site), $\mathbf{\delta D_{2t}}$ - disturbances caused by exogenous factors (fires, insects, diseases, severe frosts; influence the whole stand), $\mathbf{E_t}$ - unexplained variability (micro scale characteristics, methodological errors; uncorrelated between trees in the stand). Variable $\boldsymbol{\delta}$ indicates either presence ($\delta = 1$) or absence ($\delta = 0$) of the event. The length and amplitude of the event is also important (Cook 1985). If the event is short in comparison with the series length, its effect can be swallowed by long-period fluctuation. On the contrary, if the disturbance event is too large and lasts for a long period of time, high frequency climate variability will be lost (Cook 1985).

Unexplained variance can originate from: 1) the uncertainty of the detrending methods (Cook and Kairiukstis 1990), 2) from the non-linear relationship between tree growth and climate controls (Fritts 1976); 3) different rate of response to minimum and maximum temperatures (Wilson and Luckman 2003); slow ecological shifts due to the changes in vegetation period length (Frank and Esper 2005).

In this research the main attention is paid to the $\mathbf{C_t}$ element, as evaluation of the common climatic signal is the main stated goal. All other parameters of the model ($\mathbf{G_t = f(A_t, \delta D_{1t}, \delta D_{2t})}$) are supposed to be non-climatic signal, or noise, and will be removed. For removing the non-climate signal the technique called standardization, or detrending is usually used. Detrending procedure itself is conducted with the help of the detrending curve, which reflects the theoretical growth of the tree with stable climatic conditions (Fritts 1976, Cook 1985). At the same time, the process of standardization transforms non-stationary tree-ring width into the stationary tree-ring indices with a constant variance and mean value equal to one or zero.

4.2 Brief description of main standardization methods

With the development of dendroclimatology, the list of used detrending curves has clearly widened from horizontal curves, negative exponentials (including modified negative exponentials, Fritts 1976) to complicated splines, RCS curves, methods based on basal area increment and different statistical models (Bunn et al. 2004, Biondi and Qeadan 2008, Linderholm et al. 2010). Here will be described the most common methods used in dendrochronology:

1) Negative exponential curve is the first detrending technique, used in dendroclimatology. It represents the ideal growth trend for moderate age trees, growing in open spaces without competitors and any other bigger disturbances. Growth trend in such case looks like an exponential decay (Fritts 1976). This method however must be used with a big carefulness, as it can be not appropriate for closed stands, stands with a complex history of anthropogenic usage or disturbance history. For old tree stands, for example, modified exponential curve has been introduced (Fritts 1976). Sometimes negative exponential curve is used in combination with other detrending methods (double detrending), where the detrending with the exponential curve is usually followed by detrending with the smoothing spline (Pichler and Oberhuber 2007).
2) Smoothing spline detrending is widely used, when complex growth, affected by competition and disturbances are analyzed (Cook 1985). It is a flexible and data-adaptive curve (Cook and Peters 1981). However, the result is much dependent on user parameters chosen for spline construction. It is possible to influence the preservation of low-frequency or high-frequency signal Stating the rigidity of the curve (Melvin and Briffa 2008). The two main parameters needed for spline construction are frequency cutoff and length of the wave. 50% frequency cutoff is

usually used as it creates the most appropriate signal to noise ratio (SNR, Cook 1985). While setting up the parameters possible distortion of the trend must be taken into consideration (Melvin and Briffa 2008). The bias created by trend distortion is more obvious to occur at the youngest (i.e. most recent) parts of the whole chronology, where a lot of individual tree-ring series are overlapped (Melvin and Briffa 2008). Melvin and Briffa (2008) showed that if the spline is too flexible, the indices can be distorted by the existence of some extreme values. Thus some low-frequency information will be lost. If the standardizing curve is not flexible enough, it can bias the resulted indexed chronology – so called uncertainty principle (Cook 1985). Rigid splines are more appropriate for preserving low-frequency variability (Melvin and Briffa 2008);

3) RCS curve (or regional standardization curve) is a traditional detrending technique (Esper et al. 2002) widely used in dendrochronology (Bunn et al. 2004, Melvin et al. 2007, Biondi and Qeadan 2008, Linderholm et al. 2010, Bontemps and Esper 2011). It is based not on mathematical modelling as previous two methods, but on the measurements from a given site. To construct the RCS curve, samples are needed to be aligned according to their cambial age and further averaged. The resulting line is then smoothed and represents the common growth trend on a given site under stable climate conditions (Bunn et al. 2004). RCS detrending is a very useful method on sites with a lot of samples. RCS curve is effective in estimating past climates (Melvin and Briffa 2008, Büntgen et al. 2012) and low-frequency fluctuations in the chronology (Forbes et al. 2010). For preserving high-frequency variations other methods are suggested (Bunn et al. 2004, Linderholm et al. 2010);
4) Detrending based on a basal increment. This method is suitable for describing individual and stand-level changes. The method is based on assumption, that tree-ring circumference is a circle and that the increment of basal area is constant in time. The advantage of this method is in its numerical stability and possibility of application even for small sample depths (Biondi and Qeadan 2008);
5) Büntgen et al. (2012) showed that a high replication of samples for each region can suppress site inhomogeneity, thus excluding the need of standardization.

It is worth mentioning, that some authors (Cook and Peters 1997) suggest making data transformation before standardization, to stabilize variance of the data.

4.3 Construction of the standard chronology

Standard chronology is constructed from the dimensionless tree-ring width indices, which are got by standardization. Tree-ring indices represent the fluctuation of tree growth according to climate changes (Melvin and Briffa 2008). The indices can be calculated using two different methods – ratios and residuals:

a) $I_t = {R_t}/{G_t}$,

where I_t – is an index for year *t*, R_t - is a measured tree-ring width, G_t - is an expected growth value according to the detrending model (Cook and Peters 1997). Calculating indices using ratios can create big outliers in the resulted indexed chronologies thus influencing the standard chronology. This problem is mainly occurs in data with a very small tree-ring widths (Biondi and Qeadan 2008);

b) $I_t = R_t - G_t$

This method is usually suggested when the trend line is approaching zero (tree-ring width acquires value from 0 to 0,5 mm), or diverges negatively at either of two ends of the series (Cook and Peters 1997). Before using the subtraction method it is advised to stabilize the variance of the data (Cook and Peters 1997).

Standard chronology is made by averaging cross-dated detrended series. It is usually advised to use the biweight mean rather than the normal average, as it will help to avoid big outliers. However, there are situations, when the standard average brings better results (Cook 1985). If data has a normal distribution, the usage of biweight mean can lead to the loss of information, as it is not the best estimator of central tendency (Cook 1985). Another example of inappropriate use of biweight mean is when outliers are presented in one calendar year in more than 40% of samples. In such situation, biweight mean and normal average will give similar results (Cook 1985). The resulted chronology is then truncated, usually to the period represented by minimum 5 samples (Esper et al. 2003).

Some part of desirable information is always lost with the detrending. The goal of the researcher is to make this loss as small, as it is possible. Moreover autocorrelation process must be taken into consideration, as cambial growth in the given year is usually influenced by the conditions in the year previous (Fritts 1976). If autocorrelation is positive, climate compound will be mainly concentrated in the low-frequency variation called red noise (Cook

1985). Climate in the model is usually more persistent than it is in reality. It can be resulted from autocorrelation process (Fritts 1976), uncertainties in the method or other micro site factors, as for example, soil water stress (Cook 1985).

Different statistical models are used to remove autocorrelation, for example ARMA model (Cook and Kairiukstis 1990). The order of autocorrelation is chosen on base of the minimum AIC criterion. In case of several minimal AICs, the minimum that is going first will be chosen (Cook 1985). First minimum AIC does not mean the best suitable model. However, the main aim of this procedure is to remove short-lag persistence, as usually trees react quiet quickly on climate changes and disturbance event (Cook 1985). Long-term fluctuations remains preserved. Autocorrelation order can be different within different series adding more complexity to the model. The power of autocorrelation also increases with the increasing length of the series. In this situation the pooled order autocorrelation is advised (Cook 1985).

4.4 Estimation of the standardized series and standard chronology

The estimation of the chronology quality is based first of all on the estimation of common variability presented in all series from a given site (Cook and Kairiukstis 1990). The aim is to identify how much measured chronology is differ from the ideal chronology representing this location. Thus it is needed to estimate the common signal in the chronology and the noise, specific only for individual samples (Cook and Kairiukstis 1990). This noise does not correlate between series and will be reduced to some extent by standardization method and averaging of the series. Some noise however will remain. Parts of the chronology covered by small number of samples can be influenced by this noise and induce problems with data interpretation (Cook and Kairiukstis 1990).

There are a lot of different statistics, helping to estimate quality of the data and its suitability for chronology creation:

a) **Mean sensitivity** (MS) – is a statistic created for the description of tree-ring data variability, detrended or raw (Biondi and Qeadan 2008, Bunn et al. 2013). MS has a very old tradition in dendrochronology and was has been first offered by Douglass (1920). It measures the tree-ring variability from year to year (Speer 2010). Till nowadays MS importance and possible further applications in dendrochronology are widely discussed (Biondi and Qeadan 2008, Bunn et al. 2013). Sensitivity can be calculated using several formulae. For example, Cook (1985) used following formula:

$$\mathbf{MS} = \frac{2}{n-1}\sum_{t=2}^{n}\frac{|w_t - w_{t-1}|}{w_t + w_{t-1}}$$

where, **w** – is a measure of growth (ring width or ring density), **n** – is a length of the tree-ring series, **t** – 1, 2, 3, …, n – year in the tree ring series. This definition of MS is used for calculations in ARSTAN program.

Bunn et al. (2013) have used for dplR package in R program the formula:

$$\mathbf{MS} = \frac{n}{n-1}\frac{\sum_{t=2}^{n}|w_t - w_{t-1}|}{\sum_{t=1}^{n} w_t}$$

This formula is usually used for series, where non-climatic trend is obvious (Bunn et al. 2013). MS values can theoretically vary from 0 to 2, in practice its values usually vary from 0.1 to 0.6 (Biondi and Qeadan 2008). The main disadvantage of MS according to some authors is that it basically describes the relation between two adjacent years (interannual variation, Biondi and Qeadan 2008). For more precise result all possible lags in the series must be considered (so called mean sensitivity function, Biondi and Qeadan 2008). For this purpose Gini coefficient was introduced (Biondi and Qeadan 2008). Its main advantage is that Gini coefficient is based on the relationship between all possible pairs in the data (Biondi and Qeadan 2008).

MS is useful for comparison between the same tree species. Biological properties of each particular species can cause a big variance in MS values, thus making it impossible to compare trees from different families with each other. For example, variance in tree-ring series of evergreen individuals is higher than at deciduous ones (Bunn et al. 2013).

As it has been shown by Bunn et al (2013), MS is a function of standard deviation and autocorrelation. The practical mean sensitivity can reach 1 if autocorrelation is strongly negative or variance of the data is rather large (it occurs very seldom). Moreover MS will be proportional to standard deviation, if autocorrelation processes are not too strong (Bunn et al. 2013).

On base of their study Bunn et al. (2013) showed, that standard deviation and autocorrelation order can be more useful for describing sensitivity in growth of trees. For deeper understanding of variations in growth they recommend to use such useful tools as ARMA and GARCH models.

b) **Series intercorrelation** represents the common stand level signal (Speer 2010):

$$\mathbf{r_{xy}} = \frac{\sum_{t=1}^{t=n}(x_t - m_x)(y_t - m_y)}{(n-1)s_x s_y}$$

where, $\mathbf{x_t}$ - is a value for the core sample, $\mathbf{y_t}$ – is a value for the master chronology, $\mathbf{m_x}$ – is a mean index value for the core sample, $\mathbf{m_y}$ – is a mean index value for the master chronology, $\mathbf{s_x}$ – is a standard deviation for the core sample, $\mathbf{s_y}$ – is a standard deviation for master chronology, **n** – a number of years being compared.

c) **Gleichläufigkeit (sign test)** is a measure of similarity between two chronologies (Speer 2010):

$\Delta_i = (x_{i+1} - X_i)$, $\Delta_i > 0$: $G_{ix} = +\frac{1}{2}$, $\Delta_i = 0$: $G_{ix} = 0$, $\Delta_i < 0$: $G_{ix} = -1/2$

$$G_{(x,y)} = \frac{1}{n-1}\sum_{i=1}^{n-1}|G_{ix} + G_{iy}|$$

d) **Running** $\bar{r}$ is used to estimate the signal strength in the chronology (Speer 2010);

e) **Subsample signal strength** is the amount of signal captured by subsample of cores from some master chronology (Speer 2010):

$$SSS = \frac{t'[1 + (t-1)\bar{r}]}{t[1 + (t'-1)\bar{r}]}$$

where, t' - is a number of cores or trees in the subsample of the population, t – is a number of trees in the population, $\bar{r}$ – is a mean interseries correlation.

f) **Expressed population signal** (EPS) is a measure of common variability in the chronology (Cook and Kairiukstis 1990):

$$EPS_t = \frac{t r_{bt}}{t r_{bt} + (1 - r_{bt})}$$

where, t – is an average number of tree series (using 1 core per tree), r_{bt} – is mean between tree correlation. The border value for EPS to consider the sufficient quality of the chronology is equals to 0,85. If EPS < 0,85 then the chronology is supposed to be influenced by tree-level signal (Speer 2010).

4.5 Sampling and statistical analysis of woody shrubs at high altitudes and latitudes

Dwarf shrubs growing above the altitudinal treeline or to the north of latitudinal treeline are usually characterized by prostrate polycormon forms from several centimeters (*Salix arctica*) to 2 meters (*Pinus mugo*) high. These morphological aspects bring some difficulties to data collecting and further tree-ring analysis. Usually the stem of such plants is too small in diameter and has an eccentric pith to be cored. Moreover a big amount of continuously missing rings along the stem length, influence of local condition on the formation of wood and the existence of short-length shrubs chronologies makes it difficult to use the same cross-dating methods as for stunted trees (Gazol and Camarero 2012).

According to the morphological peculiarities, the techniques of shrub sampling and their further analysis differ from the general procedure described at Stokes and Smiley (1996). Due to the prostrate form of shrubs and a big amount of continuously missing outer rings, a method of sectioning in regular intervals has been suggested by Kolishchuk (1990). Further cross-dating of separate sections from one tree allows getting a complete chronology from the individual. The bigger problem arises during the statistical processing of series, as there is no defined method for shrub series data standardization.

For tree-ring measurements in small shrubs (such as *Salix arctica* or *Empetrum hermaphroditum)* microscopic examination is used (Woodcock and Bradley 1994, Bär et al. 2005). Tree-ring widths of shrubs, such as *Pinus mugo*, are large enough to use standard measuring techniques widely described in scientific articles (Kyncl and Wild 2004, Hallinger et al. 2010, Linderholm et al. 2010). Some examples of different methods used for dwarf plant analysis are represented in Table 1.

Table 1: Different detrending methods used for dwarf shrub analysis

Research	**Tree species**	**Standardization technique**	**Ratios/residuals**	**Power transformation**	**Standard chronology construction**
Palombo et al. 2014	*Pinus mugo*	20-year spline	ratios	NO	biweight mean average
Xiao et al. 2012	*Zygophyllum xanthoxylum*	not specified	ratios	NO	Biweight mean average
García-Cervigón Morales et al. 2012	*Juniperus sabina*	horizontal line	ratios	NO	Biweight mean average
Liang et al. 2012	*Juniperus pingii* var. *wilsoni*	negative exponential curve or horizontal line	ratios	NO	Biweight mean average
Hallinger et al. 2010	*Juniperus nana*	linear regression and negative exponential curves (averaging of individual sections within one tree preceded the process of standardization)	ratios	NO	mean average
Büntgen et al. 2007	*Picea abies, Larix decidua, Pinus mugo*	300 year spline with 50% frequency-response cutoff	residuals	YES	Biweight mean average

According to Büntgen and Schweingruber (2010) the averaging of measured series within each tree before detrending used in Hallinger et al. (2010) is not totally correct, as averaging of individual disks from one stem can bring artificial prevalence of juvenile stages (the higher the position of the disk on the stem is, the more juvenile wood is added to the chronology, thus biasing tree-ring widths). Büntgen and Schweingruber (2010) suggest standardizing individual disk's series separately and making an averaging procedure on each stem-level only after getting dimensionless indices. Moreover Büntgen and Schweingruber (2010) advice to use power-transformation of data and computing indices as differences (residuals) between power-transformed data and standardization curve.

In my analyses of *Pinus mugo* chronologies from Krkonoše Mountains I will follow the procedure offered by Büntgen and Schweingruber (2010).

5 Materials and Methods

5.1 Sampling

The research was carried out on samples from *Pinus mugo*, growing above the closed spruce forest in Krkonoše Mountains. Samples were gathered from four sites categorized according to their elevation: (i) two sites adjacent to upper limit of closed forest, (ii) two sites on the upper margin of dwarf pine occurrence.

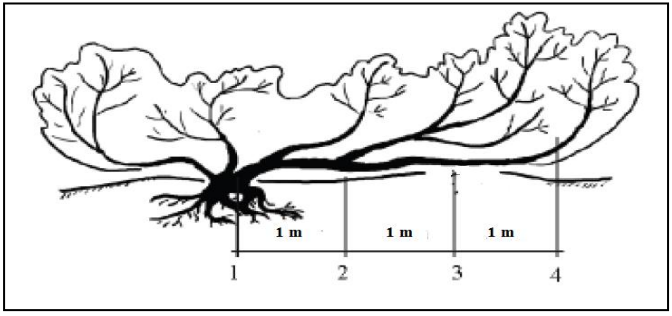
Studied sites were situated at two locations (Figure 3): 1) East slope of Sněžka Mountain in 1350 m a. s. l. (PM-Sn1350) and in 1500 m a. s. l. (PM-Sn1500); 2) Smogornia (Stříbrný hřbět) in 1490 m a. s. l. (PM-Sm1490) and south slope of Chertuv ridge (Čertová strouha) in 1300 m a. s. l. (PM-Sm1300).

Figure 3: Location of four pine and two spruce sites in Krkonoše Mountains (map application of Krkonoše Mountains National Park)

Samples were gathered using serial-sectioning method (Figure 4) advised by Kolishchuk (1990). Due to the prostrate form of shrubs and a big amount of continuously missing outer rings it was necessary to take samples from individual trees at regular intervals to catch the full period of growth. Since our aim was to create as long tree-ring chronologies as possible, we selected and sampled visually oldest trees within each site. Based on preliminary analysis of expressed population signal (Wigley et al. 1984) and "gleichläfigkeit" coefficient (Knibe 2011), the minimum sample size from each site was stated as 15 trees. From each branch there were always taken more than 3 stem discs, depending on the branch length. Branches 1 to 12 from PM-Sm1490 were sampled at every 50 cm of the branch length. Their further analysis showed that 1 m distance is enough for cross dating. Thus the rest of the branches were sampled at every 1 m of their length.

According to the aim of the research, four *Pinus mugo* chronologies were further compared with two *Picea abies* chronologies derived from Lví důl (PA-Kl, border of closed forests on Sněžka Mountain) and Čertová bystřina (PA-Kc, border of closed forests on Smogornia Mountain, Figure 3).

Figure 4: Model of tree-ring sample collection (Kyncl and Wild 2004)



5.2 Statistical analysis of sampled material

Sampled disks were further sanded in the laboratory, tree-ring widths were measured to the nearest 0,01 mm using positioning table TimeTable (Stokes and Smiley 1996) and individual series were cross dated using Past 4 software, version 4.3 (Knibbe 2011).

As shrub dendroclimatology is less developed than dendroclimatology of trees and there is no one preferable method for tree-ring standardization. Four different methods were used for detrending to see which one can produce the best results:

1) **RCS curve standardization with one RCS curve for all individual series at each site (RCS1).** RCS curve was constructed by aligning of individual series according to their cambial age, their further averaging and smoothing by 20-year spline. RCS curve represents the common growth signal on a given site under stable climate conditions (Bunn et al. 2004). Resulted RCS curves were used for detrending of individual series. Series with no pith were excluded from the calculation. Individual RCS curves from four pine sites are depicted in Figure 9. All RCS curves were truncated to minimal 5 samples representing a cambial year.

2) **RCS curve standardization with two RCS curves (separate curves for younger and older parts of individual series were constructed, RCS2).** RCS curve for younger parts of the stem was made from series not older than 1960 year (usually the first and second discs where used). If no discs in the branch fitted this criterion, only the first, disc was taken. RCS for older stem parts was constructed from the rest series. Series with no pith were excluded from the calculation. Figure 10a-10b shows RCS curves for younger and older parts of the shrub. All RCS curves were truncated to minimal 5 samples representing a cambial year.
3) **Spline standardization with two different wave-lengths.** Standardization with a spline curve was carried out in two ways: using a more flexible 40-year wave length spline (spline40) and a relatively stiff 150-year wave length spline (spline150).
4) **Standardization by averaging the individual series within one site (AVE).** All series were pruned to approximate length of 50 years before averaging (Figure 5 - 8).

Norway spruce samples were detrended via four methods: negative exponential, spline150, spline40 and RCS.

Before detrending procedure was carried out adaptive power transformation was applied to the data to stabilize variance. Indexed chronologies were calculated using residuals (subtracting the modelled value from the observed TRW). Mean chronologies for all types of standardized data (Figures 15 – 18) were calculated using biweight average. Afterwards all chronologies were truncated to the period where each calendar year was represented by minimum 5 samples.

Several statistics (standard deviation, mean sensitivity, first order autocorrelation, gini coefficient, skew, EPS) were calculated for chronologies evaluation. On base of EPS value (EPS > 0,86, Figure 11 – 14) all the chronologies were truncated to the period 1920 – 2013 for further analysis and correlation with climatic parameters. Period from 1965 – 2011 was used at PA-Kc chronology on base of its EPS value. Standard chronologies were used for correlation with climate variables.

5.3 Evaluation of climate signal in sampled material

Climate-growth relationship has been analyzed on base of partial correlations between climate parameters (temperature, precipitation, Palmer drought severity index, snow depth) and standard chronologies from given sites. Correlations between individual chronologies of pine and spruce were calculated. Climate data (temperature and precipitation values) from Sněžka Mountain climate station have been used. The values of snow depth were calculated on base of the model described in Van der Schrier et al. (2007). Palmer drought severity index (PDSI) has been taken from the CRU database (Mitchell and Jones 2005 updated).

Partial correlations were calculated for all chronologies obtained by different detrending methods as well. For climate signal comparison between spruce and pine, spruce chronologies obtained by "spline150" and pine chronologies obtained by "RCS1" methods were used. RCS1 method gave a very good result for shrub chronologies. However, it has not been suitable enough for spruce chronologies. For deeper analysis of climate growth relationship pointer years and moving correlations were calculated for four pine and two spruce sites.

6 Results

6.1 Analysis of raw *Pinus mugo* and *Picea abies* series

Number of branches and number of discs gathered from each site is shown in Table 2. As it was mentioned in Chapter 5.1, more than 3 discs have been sampled from each shrub, as the average length of stem is about 4 m.

Table 2: Number of branches collected from each site (number of sampled discs from each site is shown in parenthesis)

Site	Number of branches (sampled discs)
PM-Sn1350	23 (112)
PM-Sn1500	19 (69)
PM-SmSm1300	22 (94)
PM-Sm1490	31 (147)

Mean series length at PM-Sm1490 site is 126 years, at PM-Sm1300 is 107 years, at PM-Sn1350 is 122 years and at PM-Sn1500 site is 95 years. The oldest shrub at PM-Sm1490 is found to be 209 years, at PM-Sm1300 – 136 years old, at PM-Sn1350 – 145 years old and at PM-Sn1500 – 148 years old. In general the biggest number of old shrubs (older than 100 years) has been found at PM-Sm1490 site. The percentage of such shrubs at that site is 85% among all the sampled individuals. Basic statistics of raw pine and spruce series are shown below (Table 3).

Table 3: Basic statistics of raw series at four *Pinus mugo* sites and two *Picea abies* sites (calculated in ARSTAN program, raw series are recorded to the attached CD)

Site	TRW (mm)	Standard deviation	Skew	Mean sensitivity	Gini coefficient	First order autocorrelation
PM-Sn1350	0,46	0,19	0,48	0,22	0,23	0,70
PM-Sn1500	0,44	0,16	0,43	0,21	0,21	0,67
PM-Sm1490	0,41	0,16	0,53	0,23	0,22	0,67
PM-Sm1300	0,41	0,16	0,45	0,23	0,22	0,62
PA-Kl	1,28	0,69	0,82	0,22	0,3	0,81
PA-Kc	1,57	0,96	0,9	0,23	0,33	0,84

Mean sensitivity has been found to be higher than 0,2 at all pine and spruce sites. The sensitivity of *P. mugo* at PM-Sm1490 and PM-Sm1300 sites is higher than at PM-Sn1350 and PM-Sn1500 sites. The sensitivity of *P. abies* trees is higher at PA-Kc site than at PA-Kl site. The difference in tree sensitivity between two tree families is not shown. Gini coefficients follow the same trend as mean sensitivity values (Table 3).

Mean TRW of *P. mugo* is 0,43 mm. It is quite a low value often leading to problems with precise identification of tree-ring borders during the measurement. For comparison, the mean TRW in *P. abies* is about three times wider (~1,4 mm).

All sites, both *P. mugo* and *P. abies,* are characterized by high values of first order autocorrelation. For PA-Kc and PA-Kl sites the value of autocorrelation is visibly higher. There is no visible tendency in autocorrelation difference between upper and lower sites.

6.2 Analysis of mountain pine chronologies from PM-Sm1490, PM-Sm1300, PM-Sn1350 and PM-Sn1500 sites

As it has been discussed in Chapter 5.2, five different methods have been used for series standardization: RCS standardization with one curve, RCS standardization with two curves, spline detrending with 40 and 150 wave-lengths and averaging of series without detrending. Basic statistics for all used standardized methods at each site are collected in Table 4 – 7.

It has been seen that MS values of chronologies, obtained by different methods, are very close to each other (Table 4 – 7). The smallest sensitivity is obtained at PM-Sn1500 site. Mean standard deviation of tree-ring indices is visibly smaller (from two to three times) at “AVE” chronologies. The skew values on the opposite are the largest at “AVE” chronologies.

First order autocorrelation used for constructing residual chronologies is given in Table 8. Different orders of autocorrelation at “spline40” method have been applied at different sites. The highest order is used for PM-Sm1490 chronology. First or second order autocorrelation is used for other detrending methods.

Table 4: Mean statistics for standardized chronologies at PM-Sm1490 (calculated in ARSTAN program)

Method	Mean standard deviation	Mean skew	Mean sensitivity	Mean ar1
spline40	0,26	0,07	0,21	0,45
spline150	0,30	0,08	0,22	0,60
RCS1	0,35	0,12	0,21	0,68
RCS2	0,3	0,11	0,21	0,59
AVE	0,14	0,45	0,23	0,61

Table 5: Mean statistics for standardized chronologies at PM-Sm1300 (calculated in ARSTAN program)

Method	Mean standard deviation	Mean skew	Mean sensitivity	Mean ar1
spline40	0,26	0,03	0,22	0,36
spline150	0,31	0,04	0,23	0,52
RCS1	0,36	0,15	0,22	0,62
RCS2	0,30	0,05	0,22	0,52
AVE	0,16	0,37	0,22	0,57

Table 6: Mean statistics for standardized chronologies at PM-Sn1350 (calculated in ARSTAN program)

Method	Mean standard deviation	Mean skew	Mean sensitivity	Mean ar1
spline40	0,25	0,17	0,22	0,42
spline150	0,30	0,19	0,22	0,59
RCS1	0,37	0,19	0,22	0,72
RCS2	0,32	0,32	0,22	0,61
AVE	0,17	0,38	0,22	0,60

Table 7: Mean statistics for standardized chronologies from PM-Sn1500 (calculated in ARSTAN program)

Method	Mean standard deviation	Mean skew	Mean sensitivity	Mean ar1
spline40	0,23	0,05	0,19	0,42
spline150	0,28	0,03	0,20	0,60
RCS1	0,34	0,02	0,20	0,67
RCS2	0,28	0,06	0,19	0,60
AVE	0,15	0,34	0,20	0,63

Table 8: Autocorrelation order used for creating residual chronologies (calculated in ARSTAN program)

Method	PM-Sm1490	PM-Sm1300	PM-Sn1350	PM-Sn1500
spline40	8	2	2	3
spline150	1	1	2	1
RCS1	1	1	1	1
RCS2	1	1	2	1
AVE	5	2	2	1

Expressed population signal (EPS) has been calculated for each chronology (Figures 11 – 14). Chronologies at PM-Sm1490 site give the reliable result (EPS>0,85) from year 1910, at PM-Sm1300 site the result is more diverse. The longest reliable chronology is produced with RCS1 detrending (from year 1915). At PM-Sn1350 chronology EPS signal has rather big fluctuations on the whole length of the chronology. Period from 1915 – 2013 is considered reliable enough for further calculations. At PM-Sn1500 all the methods produce chronologies with EPS>0,85 from year 1910. For further analysis and correlation with climatic parameters pine standard chronologies produced by different detrending methods and truncated to period 1920 – 2013 have been used.

Pruned series used for AVE method are depicted in Figures 5 - 8. RCS curves used for RCS1 and RCS2 detrending are shown in Figures 9 – 10a,b. It is seen, that pine growth at PM-Sm1490 is quite stable in time (Figure 9). The same is true for older series at that site (Figure 10b). Younger series at PM-Sm1490 on the contrary show some variability in growth. At other sites the growth of young series is more or less stable (Figure 10a).

Figure 5: Pruned series at PM-Sm1490 for AVE method (approximate length of pruned series is 50 years)

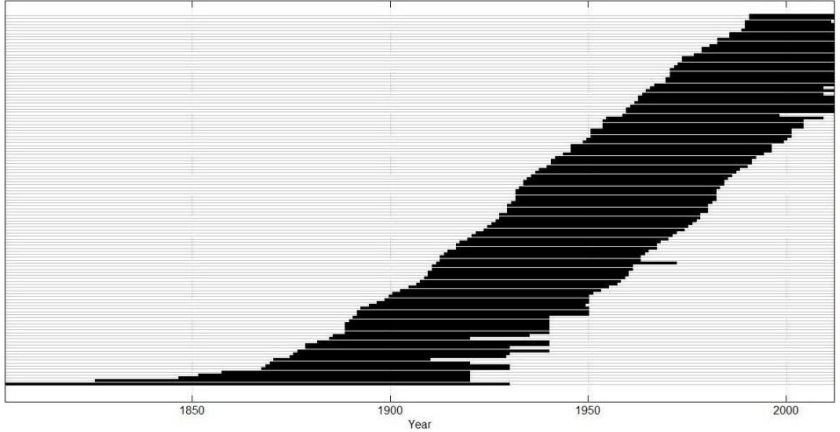


Figure 6: Pruned series at PM-Sm1300 for AVE method (approximate length of pruned series is 50 years)

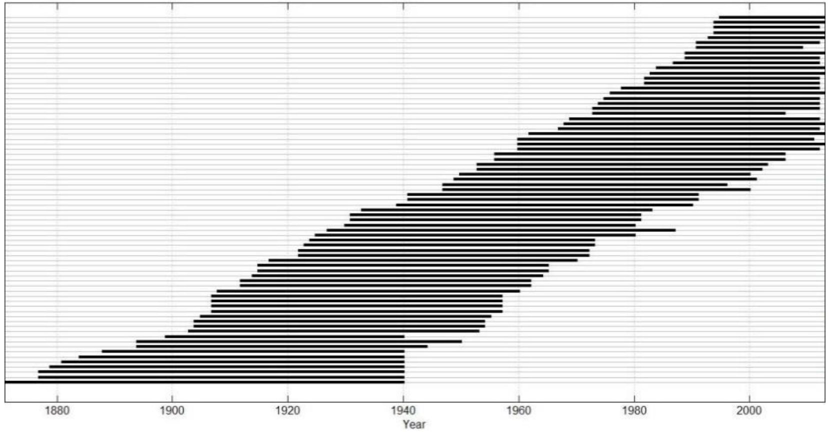


Figure 7: Pruned series at PM-Sn1350 for AVE method (approximate length of pruned series is 50 years)

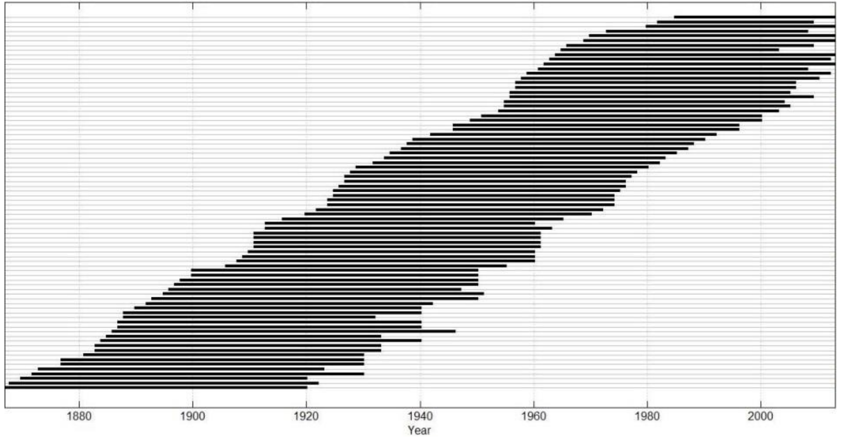


Figure 8: Pruned series at PM-Sm1500 for AVE method (approximate length of pruned series is 50 years)

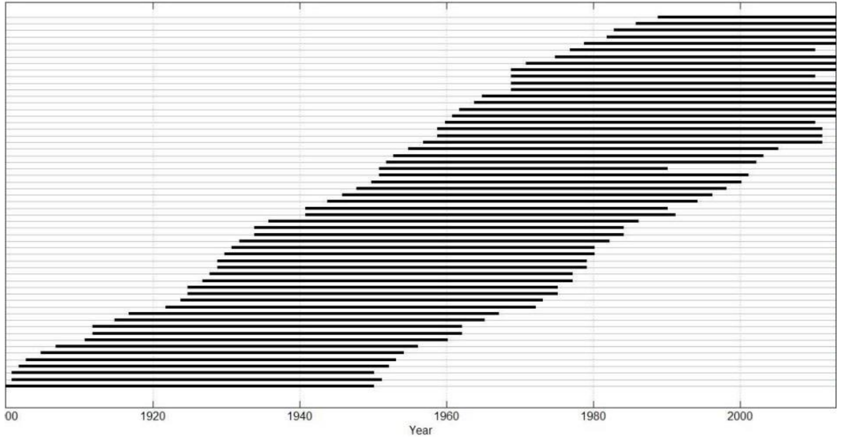


Figure 9: RCS curves for individual sites (smoothed using 20-year spline)

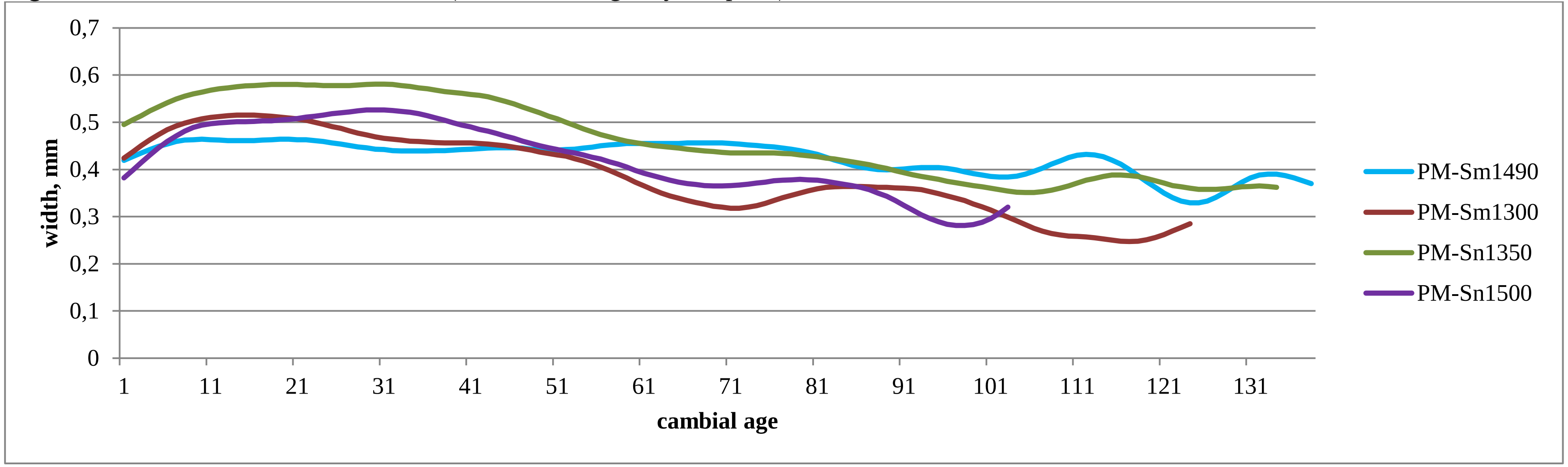


Figure 10a: RCS curves for younger parts of shrubs at each site (smoothed using 20-year spline)

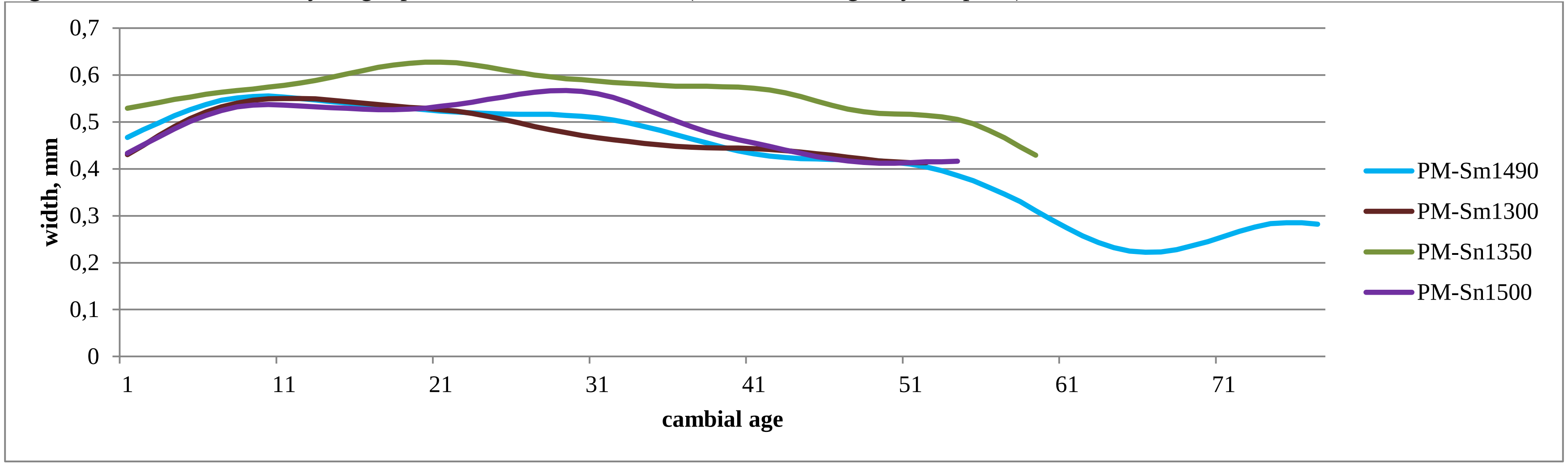


Figure 10b: RCS curves for older parts of shrubs at each site (smoothed using 20-year spline)

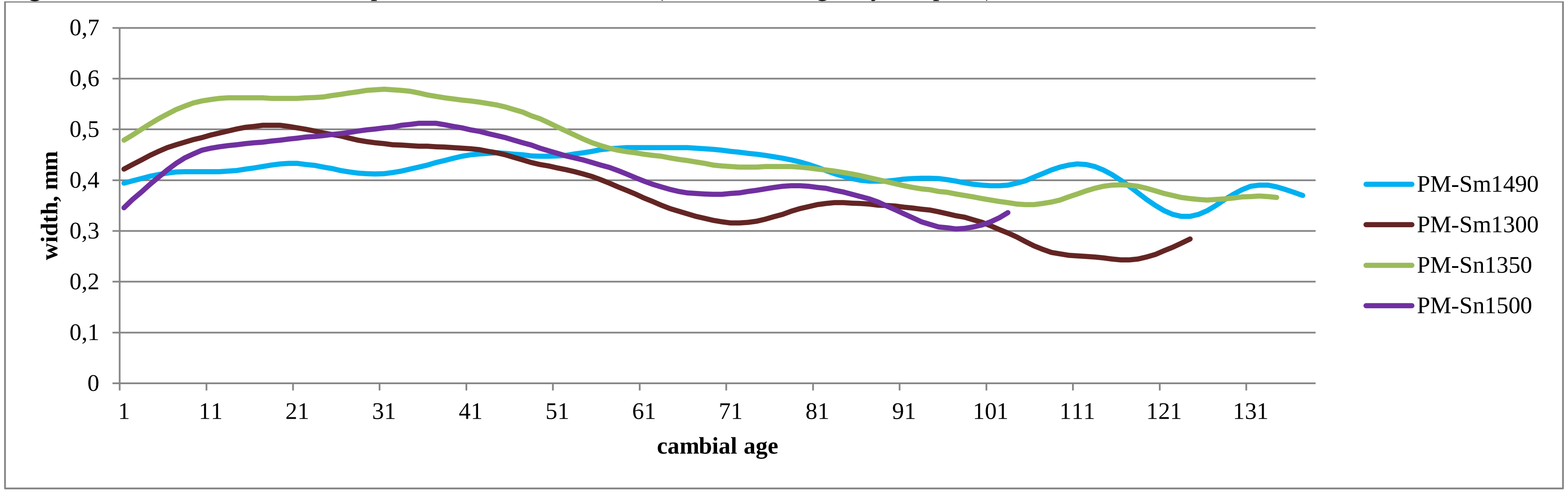


Figure 11: EPS of detrended data obtained by different standardization methods at PM-Sm1490 site ("standard" – standard chronology, "residual" – residual chronology, black line indicates EPS = 0,86)

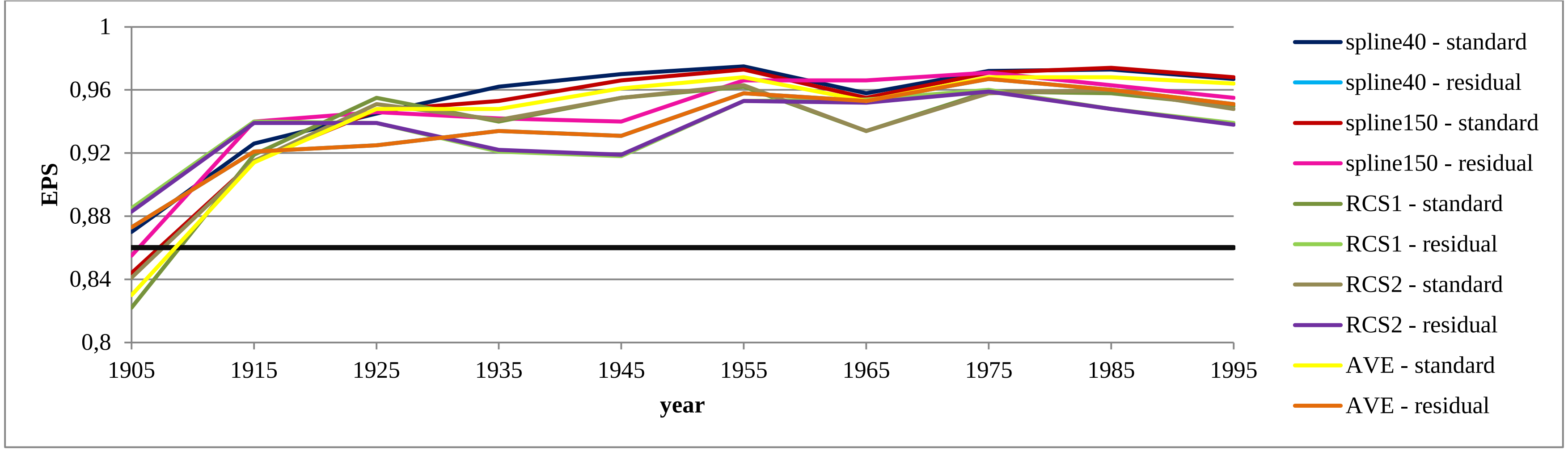


Figure 12: EPS of detrended data obtained by different standardization methods at PM-Sm1300 site ("standard" – standard chronology, "residual" – residual chronology, black line indicates EPS = 0,86)

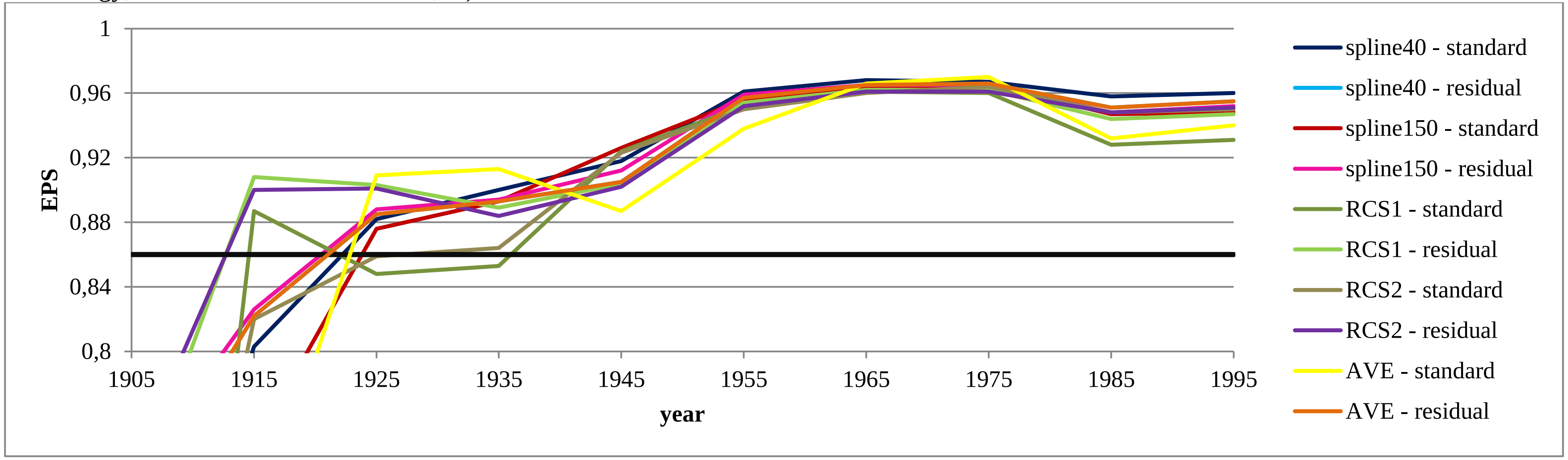


Figure 13: EPS of detrended data obtained by different standardization methods at PM-Sn1350 site ("standard" – standard chronology, "residual" – residual chronology, black line indicates EPS = 0,86)

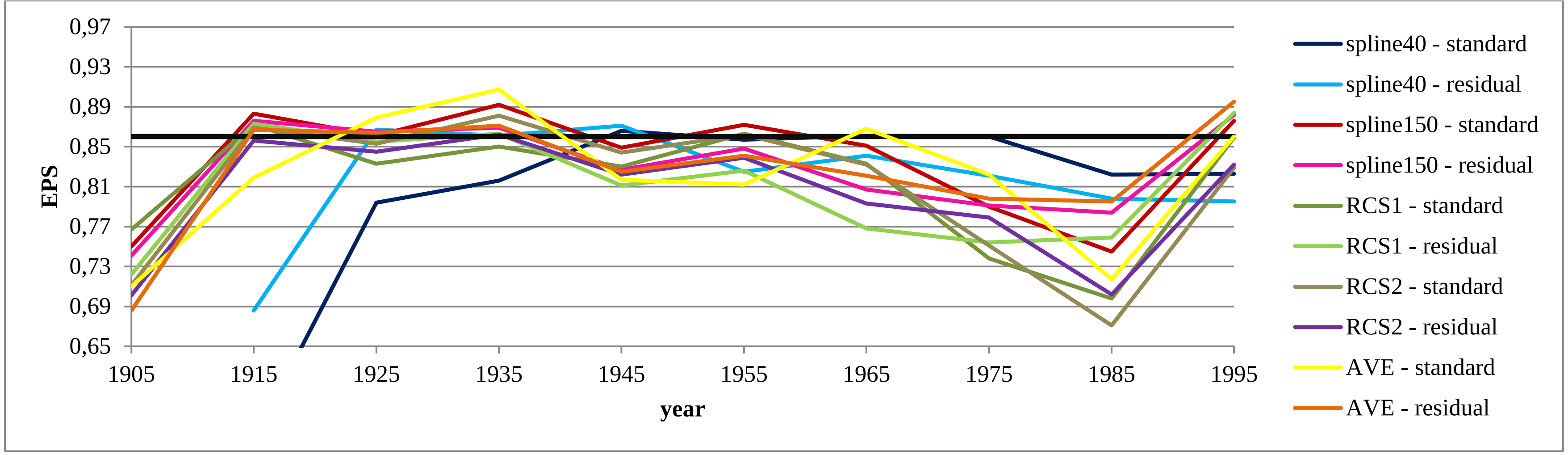


Figure 14: EPS of detrended data obtained by different standardization methods at PM-Sn1500 site ("standard" – standard chronology, "residual" – residual chronology, black line indicates EPS = 0,86)

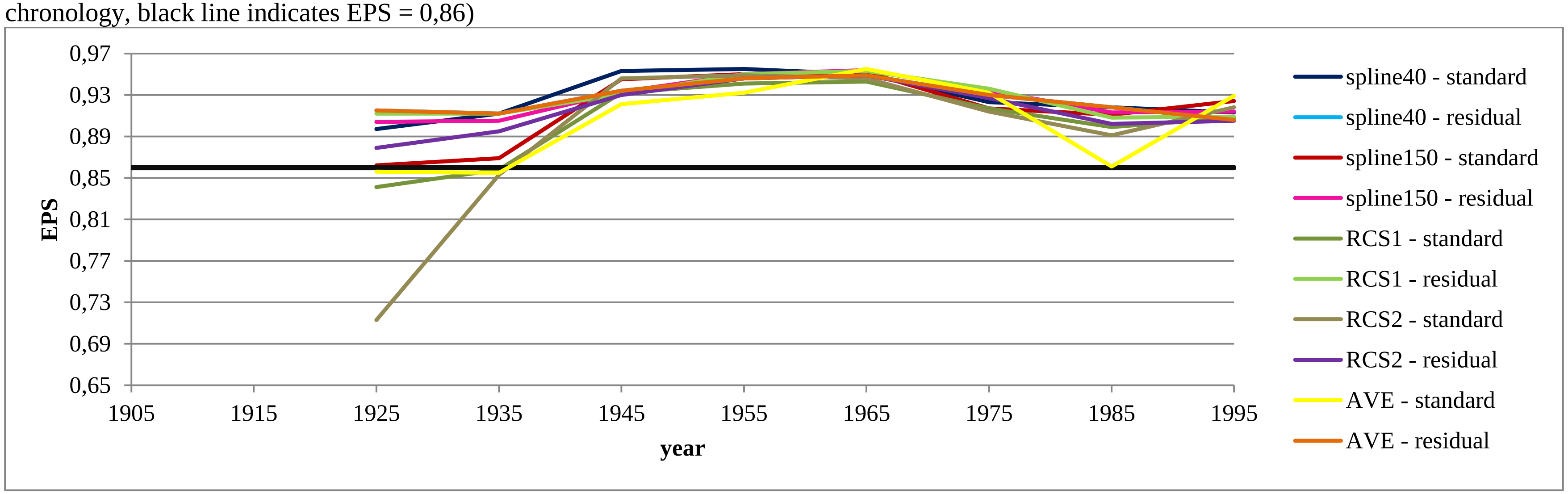


Figure 15: Mean standard chronologies produced by different detrending methods at PM-Sm1490 site

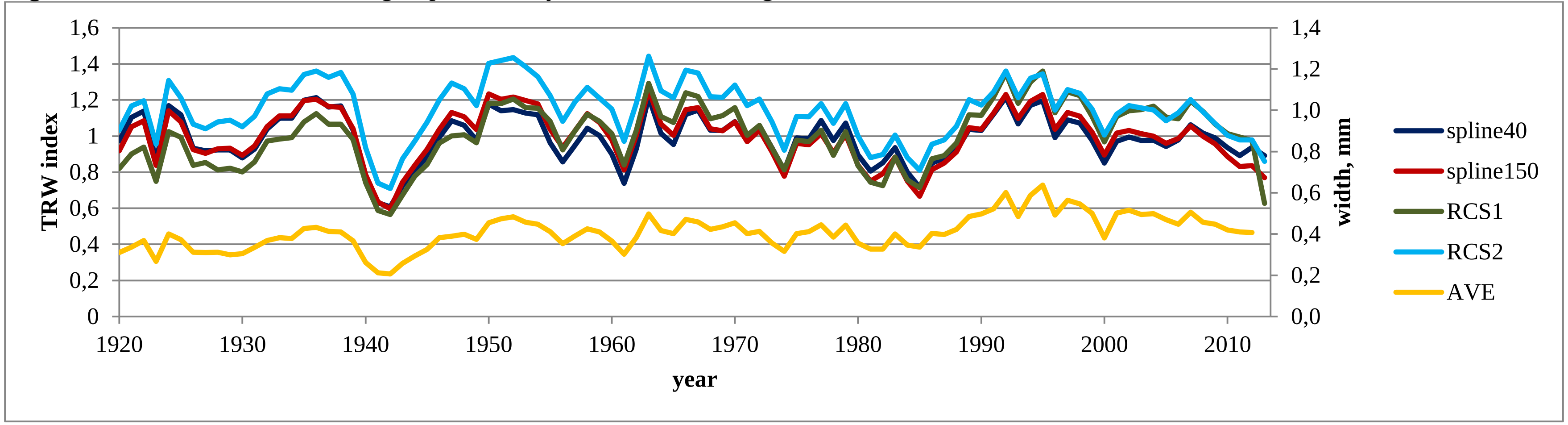


Figure 16: Mean standard chronologies produced by different detrending methods at PM-Sm1300 site

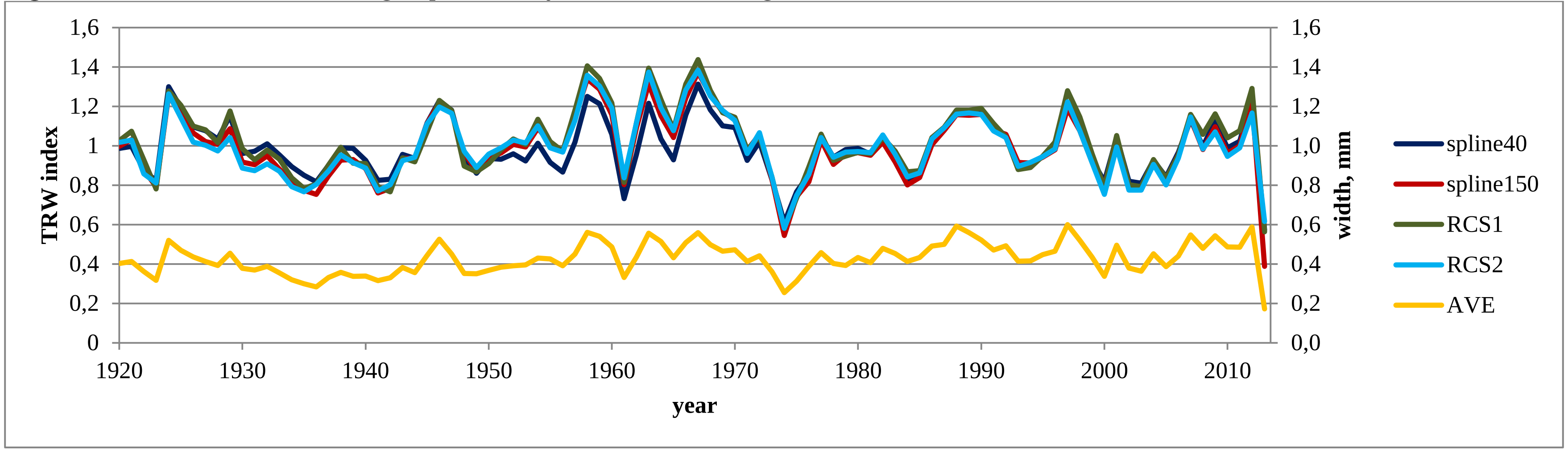


Figure 17: Mean standard chronologies produced by different detrending methods at PM-Sn1350 site

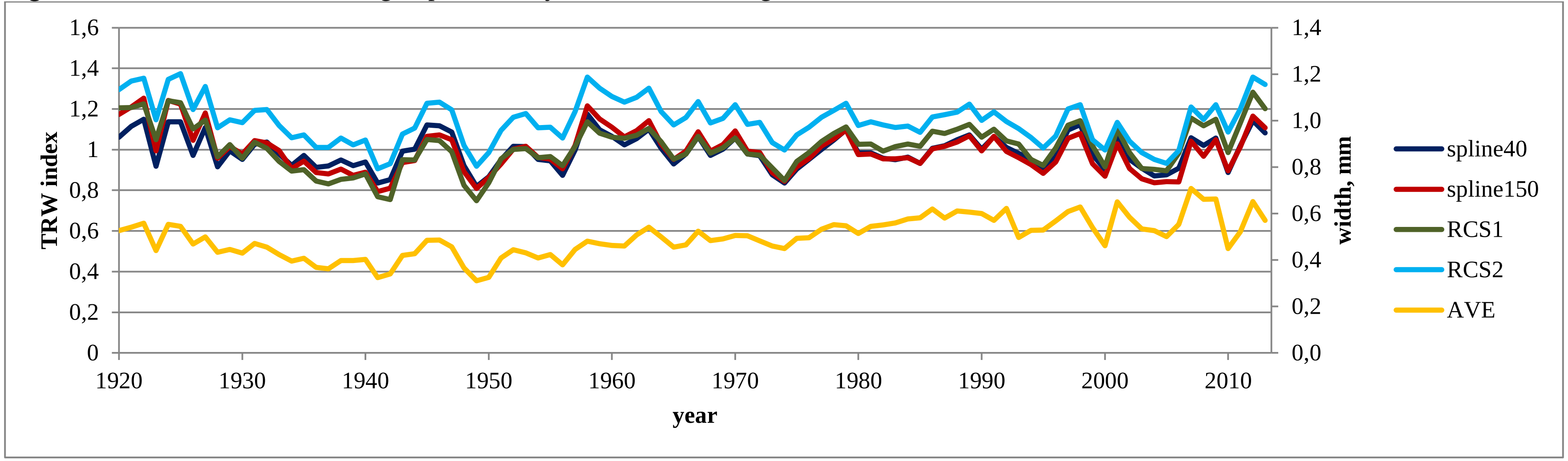


Figure 18: Mean standard chronologies produced by different detrending methods at PM-Sn1500 site

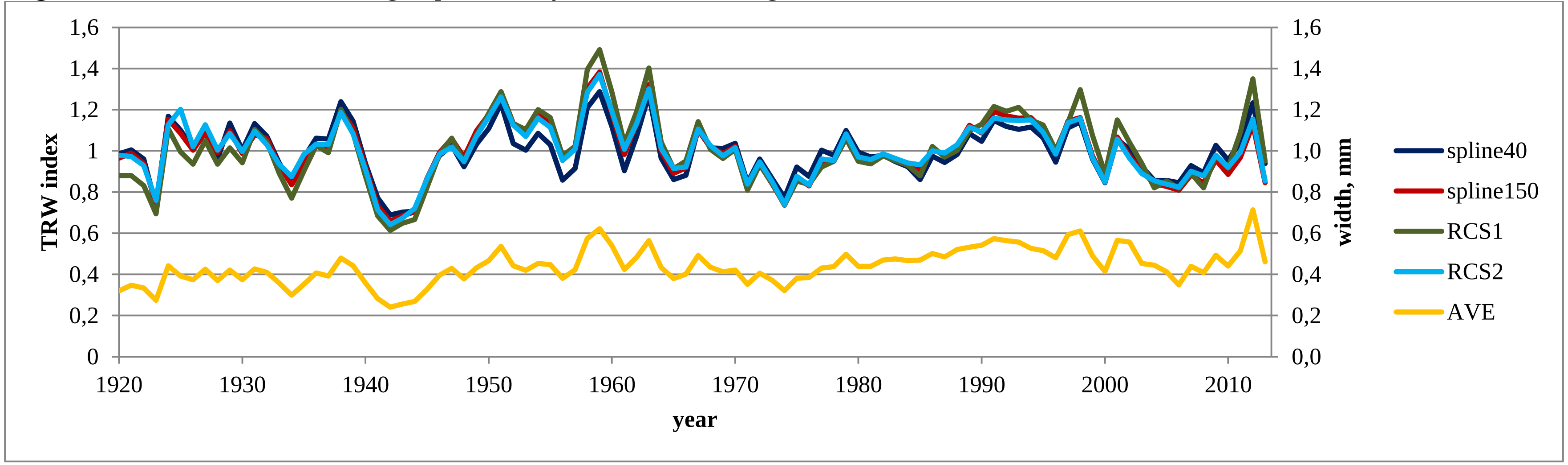


Figure 19: Mean residual chronologies produced by different detrending methods at PM-Sm1490 site

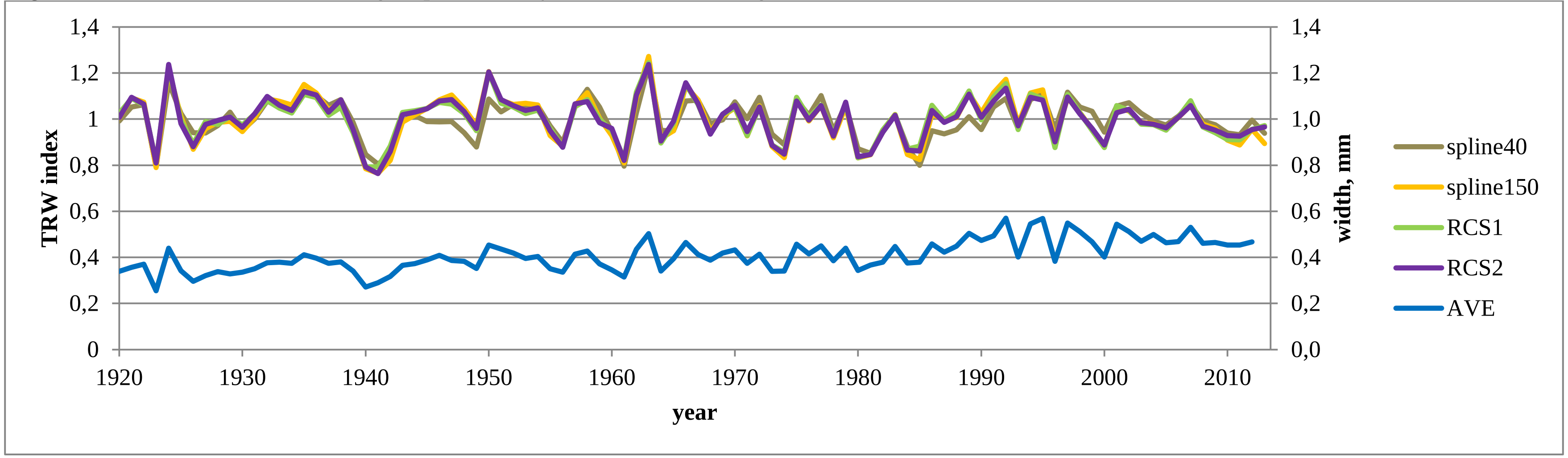


Figure 20: Mean residual chronologies produced by different detrending methods at PM-Sm1300 site

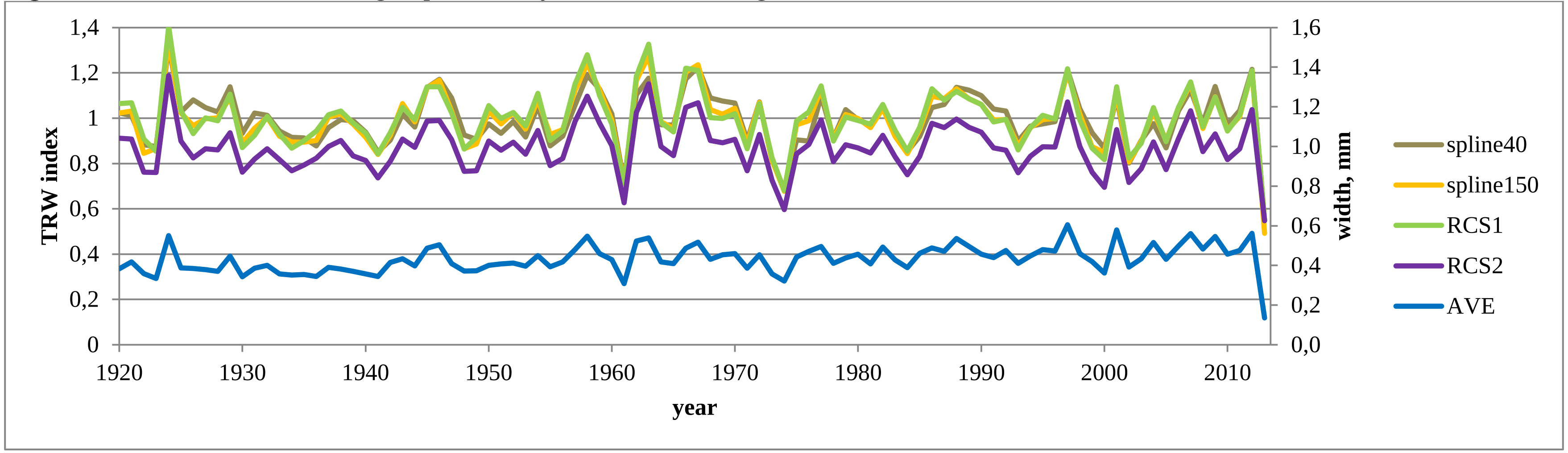


Figure 21: Mean residual chronologies produced by different detrending methods at PM-Sn1350 site

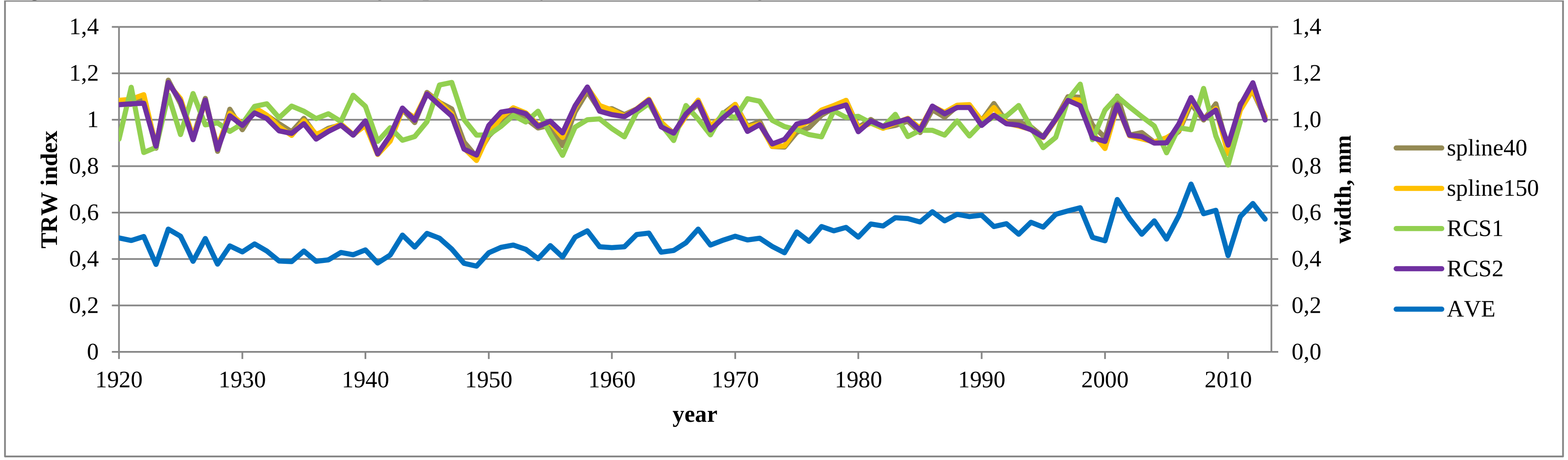
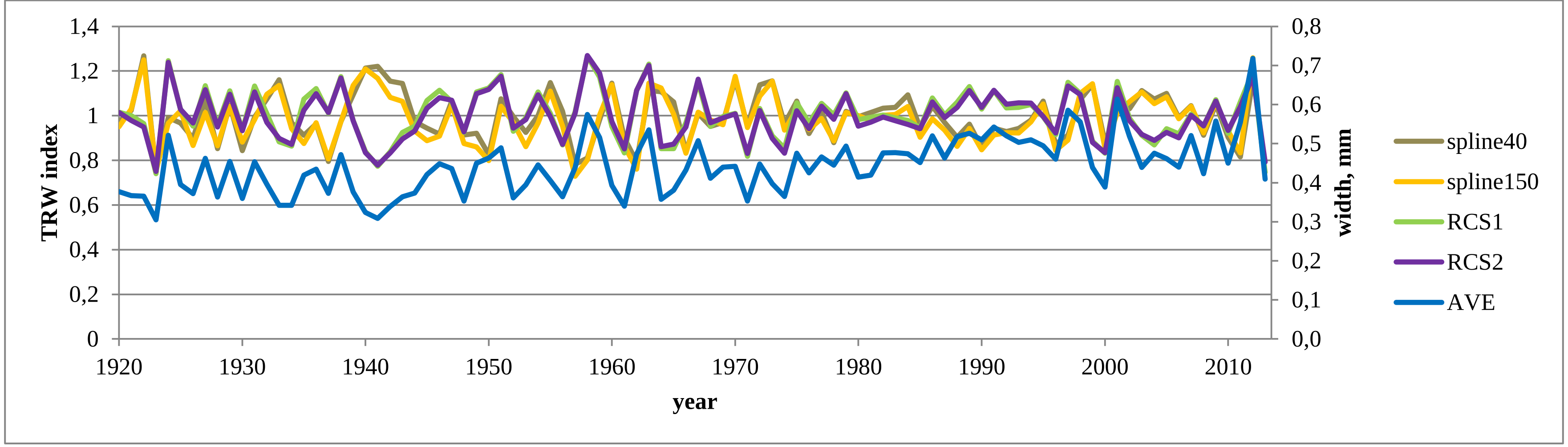


Figure 22: Mean residual chronologies produced by different detrending methods at PM-Sn1500 site



Mean standard chronologies from all pine sites are shown in Figures 15 – 18. Mean residual chronologies from four pine sites are depicted in Figure 19 – 22. It is seen, that at two upper sites (PM-Sm1490 and PM-Sn1500) pine growth has been extremely suppressed during the first part of 1940s. The decrease of growth at lower sites (PM-Sm1300 and PM-Sn1350) has been observed as well. However, growth decline has not been so obvious, as at upper sites. Decline of growth has been observed at PM-Sn1490 in the first half of 1980s. Decrease in TRW increment is also observed in the middle 2000s at PM-Sn1500.

6.3 Analysis of Norway spruce chronologies from PA-Kl and PA-Kc sites

Norway spruce series have been detrended by four different methods (RCS, spline40, spline150 and negative exponential). Basic statistics of detrended series from PA-Kl and PA-Kc sites are collected in Table 9. MS of detrended series is smaller at PA-Kl site than at PA-Kc site. Resulting chronologies are shown in Figures 23 - 24.

For further comparison with pine chronologies, spruce chronologies obtained by "spline150" method have been used. According to EPS values PA-Kl chronology has been truncated to the period 1920 – 2010 and PA-Kc chronology to the period 1965 – 2011 for their further correlation with climate variables. Residual chronologies from PA-Kl and PA-Kc are depicted in Figures 25 – 26.

Table 9: Basic statistics for standardized chronologies from two Norway spruce sites (calculated in ARSTAN program)

Site PA-Kl	**Mean standard deviation**	**Mean skew**	**Mean sensitivity**	**Mean ar1**
RCS	0,32	-0,15	0,18	0,80
Spline40	0,32	-0,10	0,17	0,79
Spline150	0,26	-0,07	0,19	0,63
Negative exponential	0,29	-0,19	0,19	0,71
Site PA-Kc	**Mean standard deviation**	**Mean skew**	**Mean sensitivity**	**Mean ar1**
RCS	0,32	-0,06	0,19	0,76
Spline40	0,32	-0,07	0,22	0,75
Spline150	0,30	-0,04	0,21	0,64
Negative exponential	0,30	-0,10	0,21	0,67

It can be seen that spruce growth have been suppressed in early 1940s and late 1970s – 1980s years (Figures 23 – 24). That is going in accordance with the result from pine sites (Figures 15 – 18). All *Pinus mugo* and *Picea abies* chronologies (standard and residual) are combined in Figures 27 and 28 respectively. For further correlation with climatic variables mean standard chronologies from pine and spruce sites have been used.

Figure 23: Mean standard chronologies produced by different detrending methods at PA-Kc site

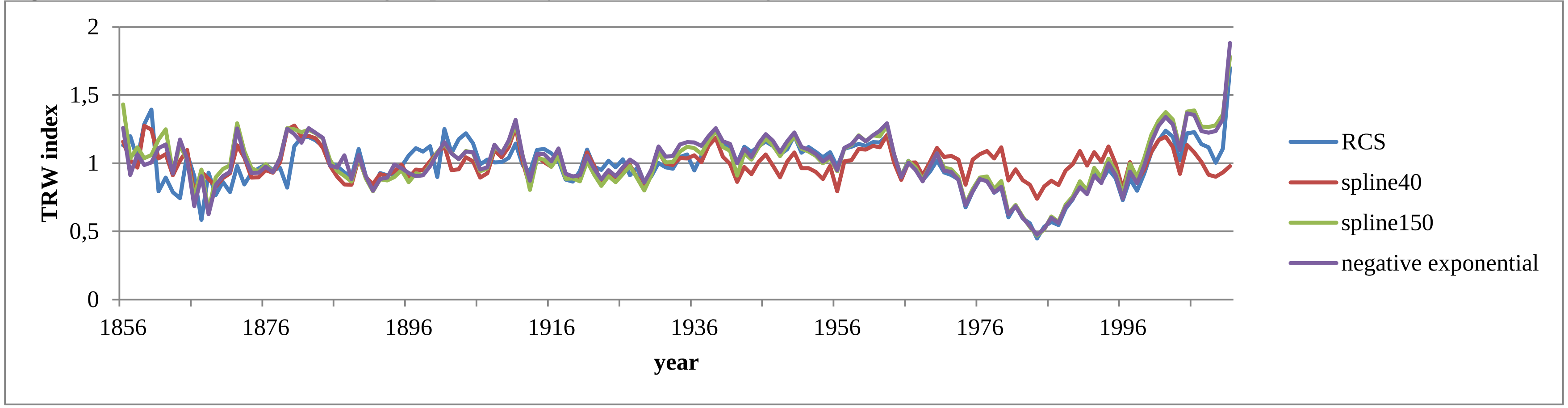


Figure 24: Mean standard chronologies produced by different detrending methods at PA-Kl site

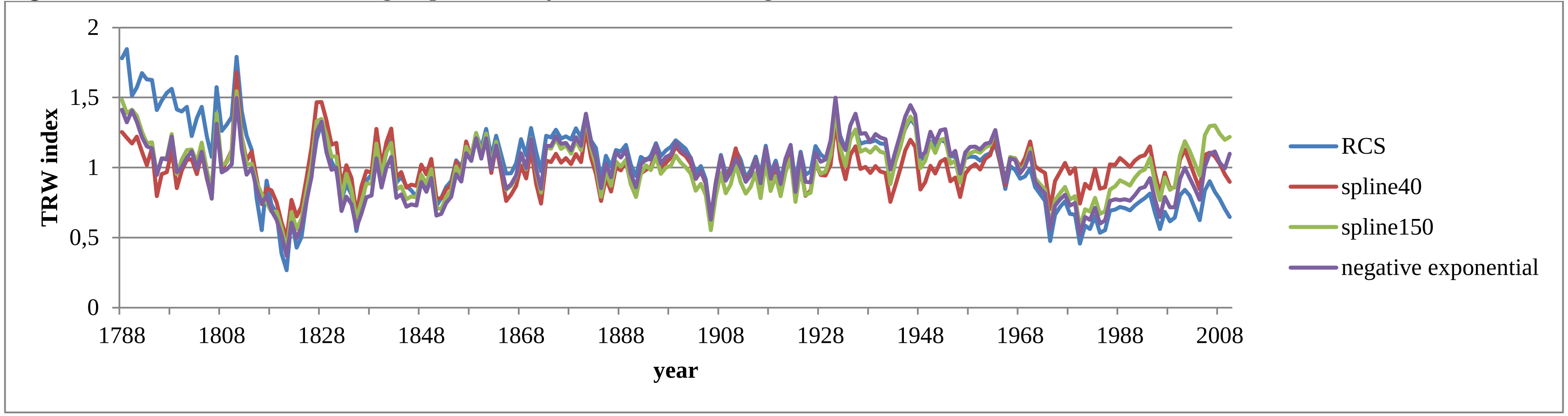


Figure 25: Mean residual chronologies produced by different detrending methods at PA-Kc site

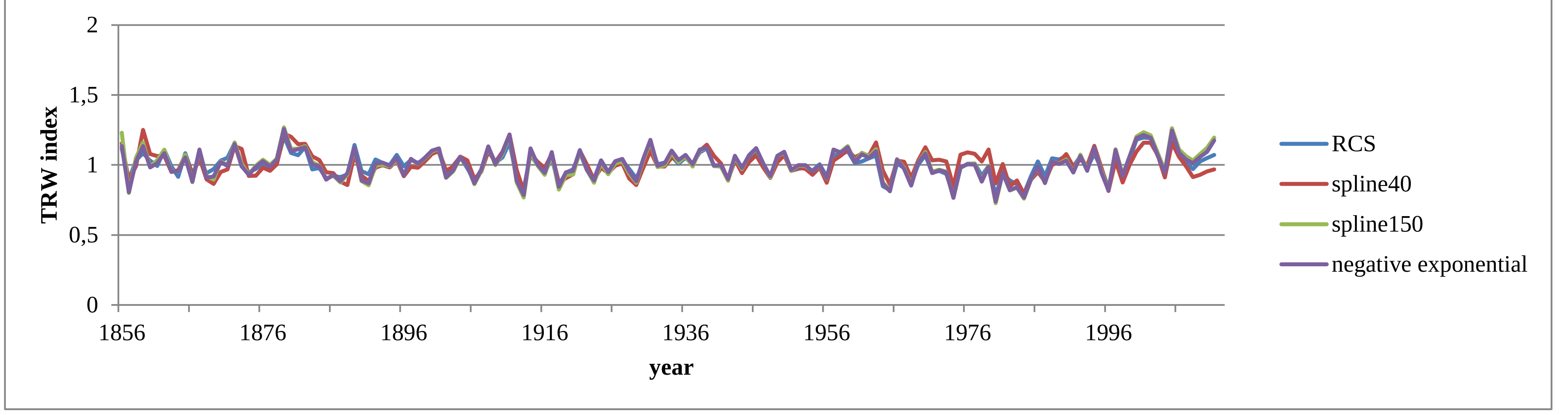


Figure 26: Mean residual chronologies produced by different detrending methods at PA-Kl site

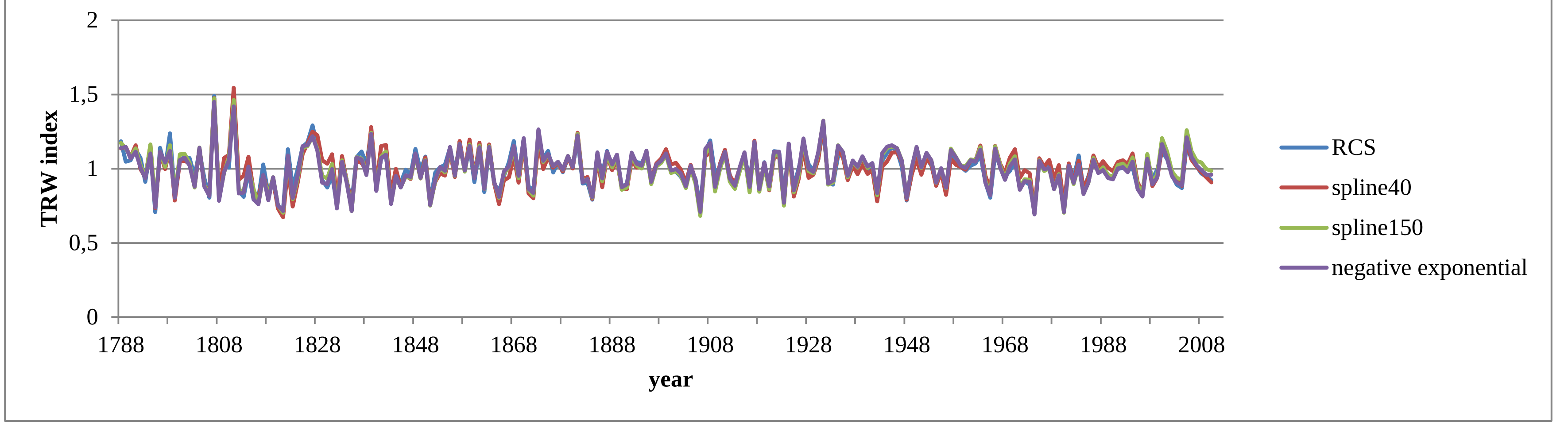


Figure 27: Mean standard chronologies from four *Pinus mugo* (chronologies obtained by "RCS1" method) and two *Picea abies* (chronologies obtained by "spline150" method) sites

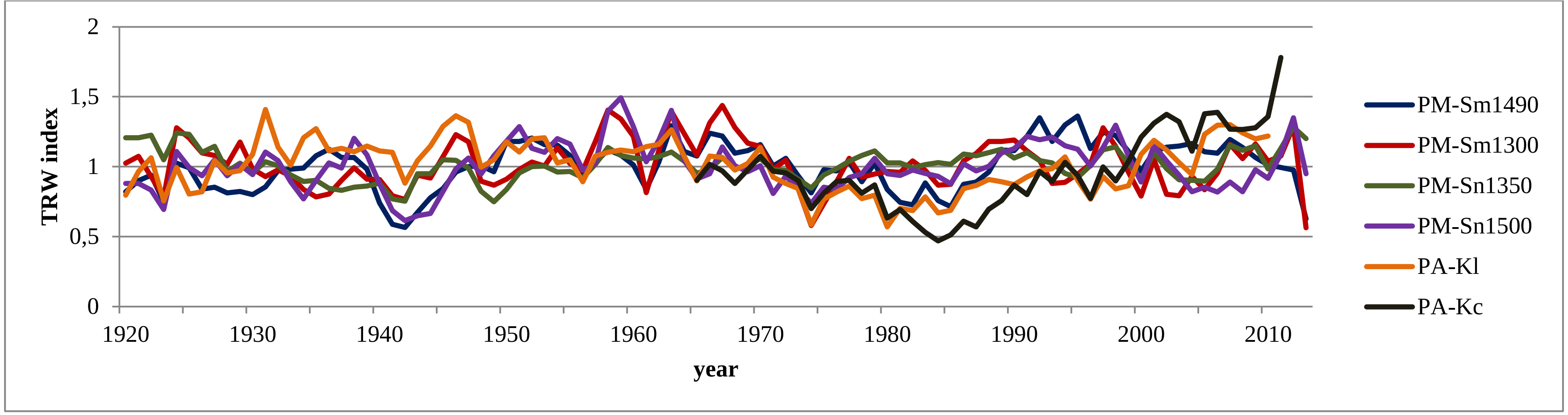
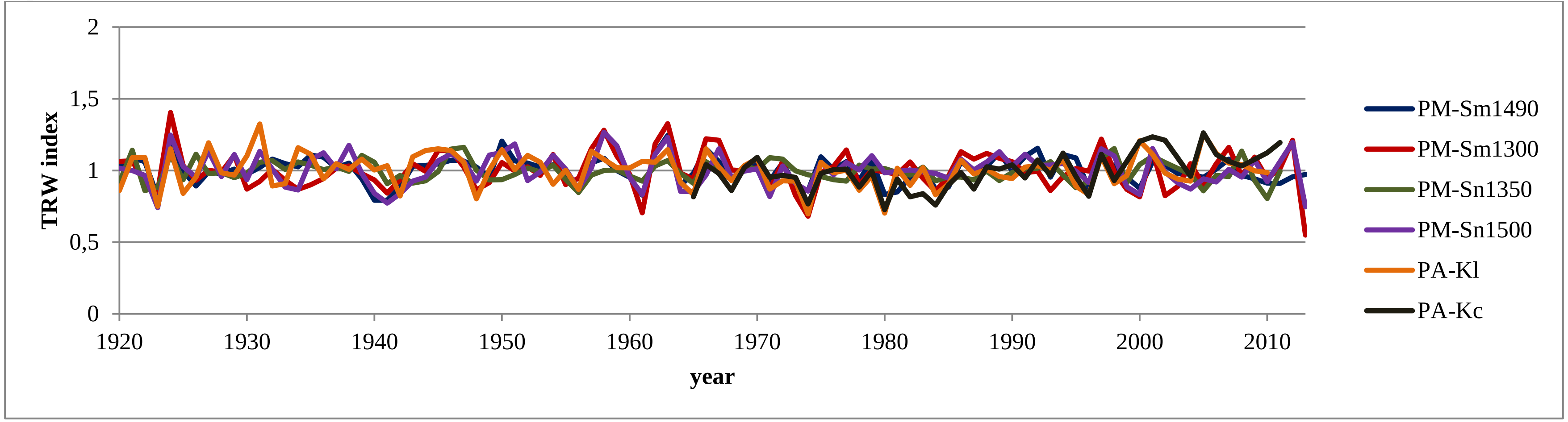


Figure 28: Mean residual chronologies from four *Pinus mugo* (chronologies obtained by "RCS1" method) and two *Picea abies* (chronologies obtained by "spline150" method) sites



6.4 Climate signal in *Pinus mugo* shrubs

Correlations between four truncated *Pinus mugo* chronologies (method “RCS1”) and two truncated *Picea abies* chronologies (method “spline150”) are shown in Table 10. The highest correlation is shown between PM-Sn1350 and PM-Sm1300 chronologies (r = 0,535) and PM-Sn1500 and PM-Sm1490 chronologies (r = 0,472). Both *Picea abies* sites, PA-Kl and PA-Kc, have the highest correlation with PM-Sm1490 chronology (r = 0,401 and 0,374 respectively). High correlation is also observed between PM-Sm1300 and PM-Sn1500 chronologies (r = 0,464). All correlations between PM-Sm1490 and other pine and spruce sites are significant at p<0,05.

Table 10: Correlation between standard chronologies of four *Pinus mugo* and two *Picea abies* sites (Pearson correlation is used, red color indicates significant values at p < 0,05)

	PM-Sm1490	PM-Sm1300	PM-Sn1350	PM-Sn1500	PA-Kl	PA-Kc
PM-Sm1490	1					
PM-Sm1300	0,331	1				
PM-Sn1350	0,221	0,535	1			
PM-Sn1500	0,472	0,464	0,048	1		
PA-Kl	0,401	0,203	0,036	0,16	1	
PA-Kc	0,374	0,059	-0,11	0,078	0,824	1

Pearson correlations of pine indexed chronologies (RCS1 method) with climatic parameters (temperature and precipitation) are shown in Figures 29 and 30 respectively. Correlations between different sites and climatic parameters differ a lot. Partial correlations with temperature and precipitation are similar to the correlations without removing of relationship between temperatures and precipitation (Figures 31 – 32). Growth of shrubs at upper sites (PM-Sm1490 and PM-Sn1500) and growth of shrubs at lower sites (PM-Sm1300 and PM-Sn1350) are controlled by different climatic parameters. Indexed tree-ring chronologies at PM-Sm1490 and PM-Sn1500 significantly correlate with high temperatures of May – August period (r=0,42 and r=0,28 respectively). Moreover shrub growth at PM-Sm1490 is positively influenced by spring temperatures (March – May period) of the previous year (r=0,25, significant at p<0,05). TRW increment at PM-Sm1490 positively correlates with January temperatures (r=0,32, significant at p<0,05). No significant correlations with temperatures at PM-Sm1300 site have been found. Shrub growth at PM-Sn1350 showed negative response to warm June – July period of the previous year (r= -0,34). TRW increment at PM-Sm1490 and PM-Sn1500 has positive correlation coefficients with temperatures of almost all months during the year, while at PM-Sn1350 and PM-Sm1300 the reaction of tree growth to climatic controls is more variable.

Results of correlation between precipitation and radial growth showed very diverse results. Radial growth of PM-Sm1490 chronology significantly correlates only with precipitation totals in January month (r=0,26), while PM-Sn1500 chronology is negatively influenced by precipitation during previous May – August period (r= -0,23, significant at p<0,05). Growth of shrubs at PM-Sm1300 significantly influenced by precipitation during June – July month (r=0,24). Both PM-Sn1350 and PM-Sm1300 are negatively influenced by wet conditions during previous year August month (r= -0,27 and r= -0,35 respectively, both correlation coefficients are significant at p<0,05). All correlations with previous year months are considered after the removal of autocorrelation effect.

Correlations between all the chronologies and Palmer drought severity index (PDSI) have been calculated to get deeper insight into climate-growth relationship of mountain pine shrubs. Both PM-Sm1490 and PM-Sn1500 chronologies negatively correlate with PDSI during the whole year. Significant negative correlations are found on both of them. Tree growth negatively correlates with drought during spring and following summer at PM-Sm1490 and PM-Sn1500 sites. Significantly negative influence of dry January/February months at PM-Sm1490 and PM-Sn1500 (r= -0,28/-0,22 and r= -0,31/-0,27 respectively) have been found. The relation between growth at two lower sites (PM-Sn1350 and PM-Sm1300) and PDSI has been rather diverse with no significant values being found.

Correlation of radial growth with maximum snow depths on all pine sites returned negative values; no significant correlation coefficients have been found (Table 11).

Table 11: Correlation of PM-Sm1490, PM-Sm1300, PM-Sn1350 and PM-Sn1500 chronologies with maximum snow depth (*** indicates significant correlations at p<0,05)

	PM-Sm1490	**PM-Sm1300**	**PM-Sn1500**	**PM-Sn1350**	**PA-Kl**	**PA-Kc**
r	-0,135	0,014	-0,20	-0,181	0,069	0,092

Figure 29: Correlation of a) PM-Sm1490, b) PM-Sm1300, c)PM-Sn1350 and d)PM-Sn1500 chronologies with temepratures (empty rectangle indicates significance at p<0,05)

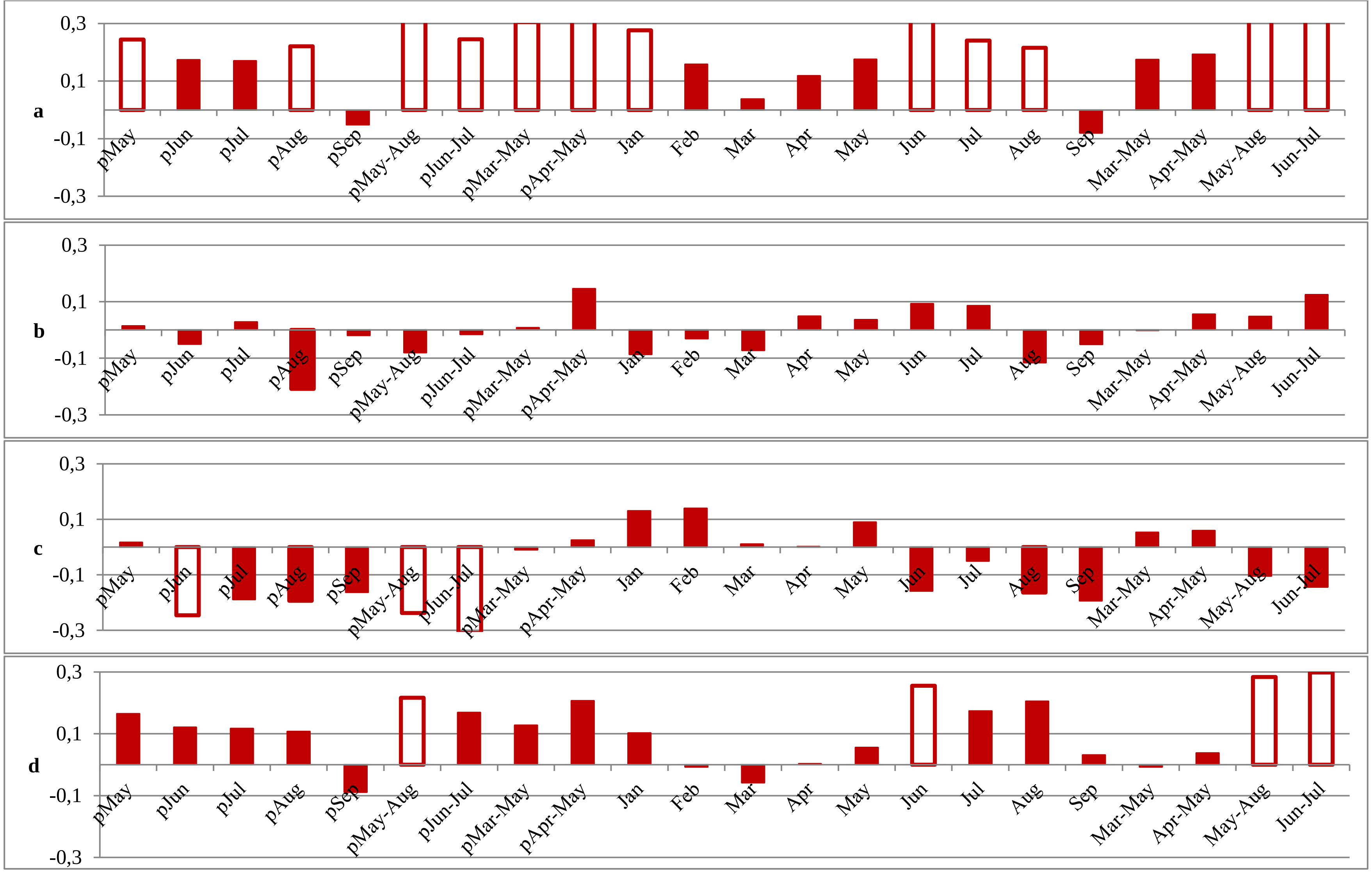


Figure 30: Correlation of a) PM-Sm1490, b) PM-Sm1300, c)PM-Sn1350 and d)PM-Sn1500 chronologies with precipitation (empty rectangle indicates significance at p<0,05)

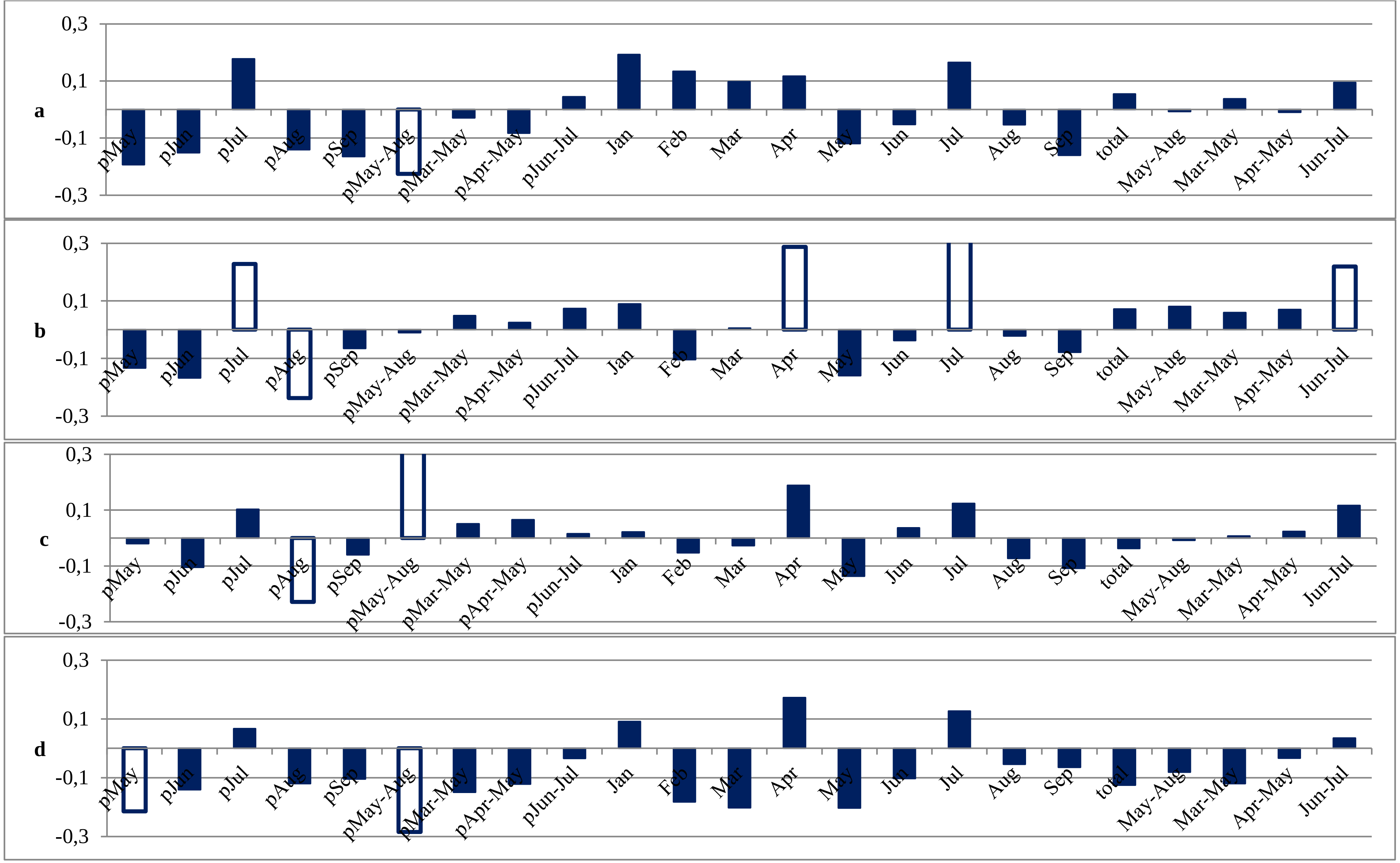


Figure 31: Partial correlation of a) PM-Sm1490, b) PM-Sm1300, c)PM-Sn1350 and d)PM-Sn1500 chronologies with temperatures (empty rectangle indicates significance at p<0,05)

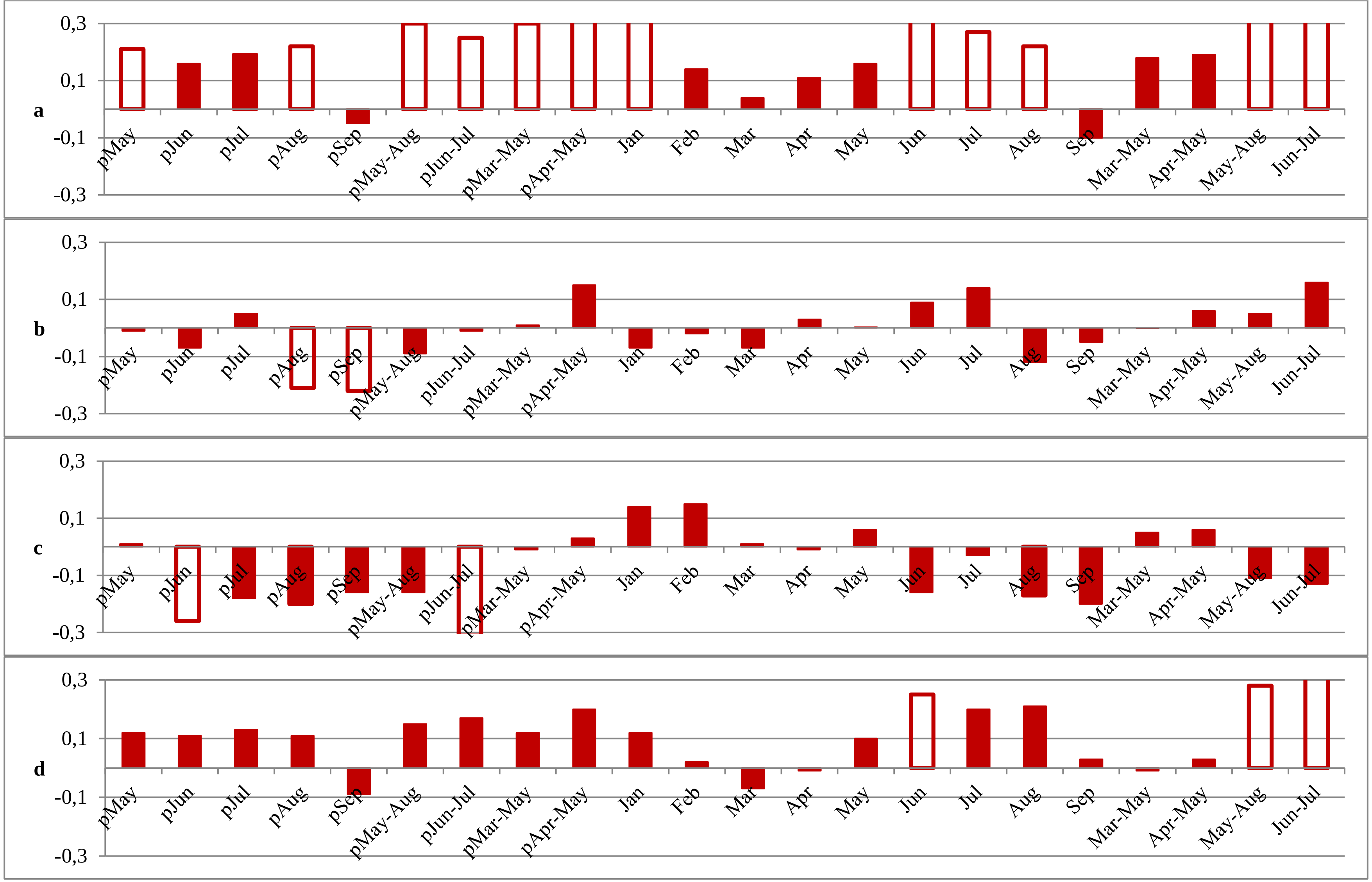


Figure 32: Partial correlation of a) PM-Sm1490, b) PM-Sm1300, c)PM-Sn1350 and d)PM-Sn1500 chronologies with precipitation (empty rectangle indicates significance at p<0,05)

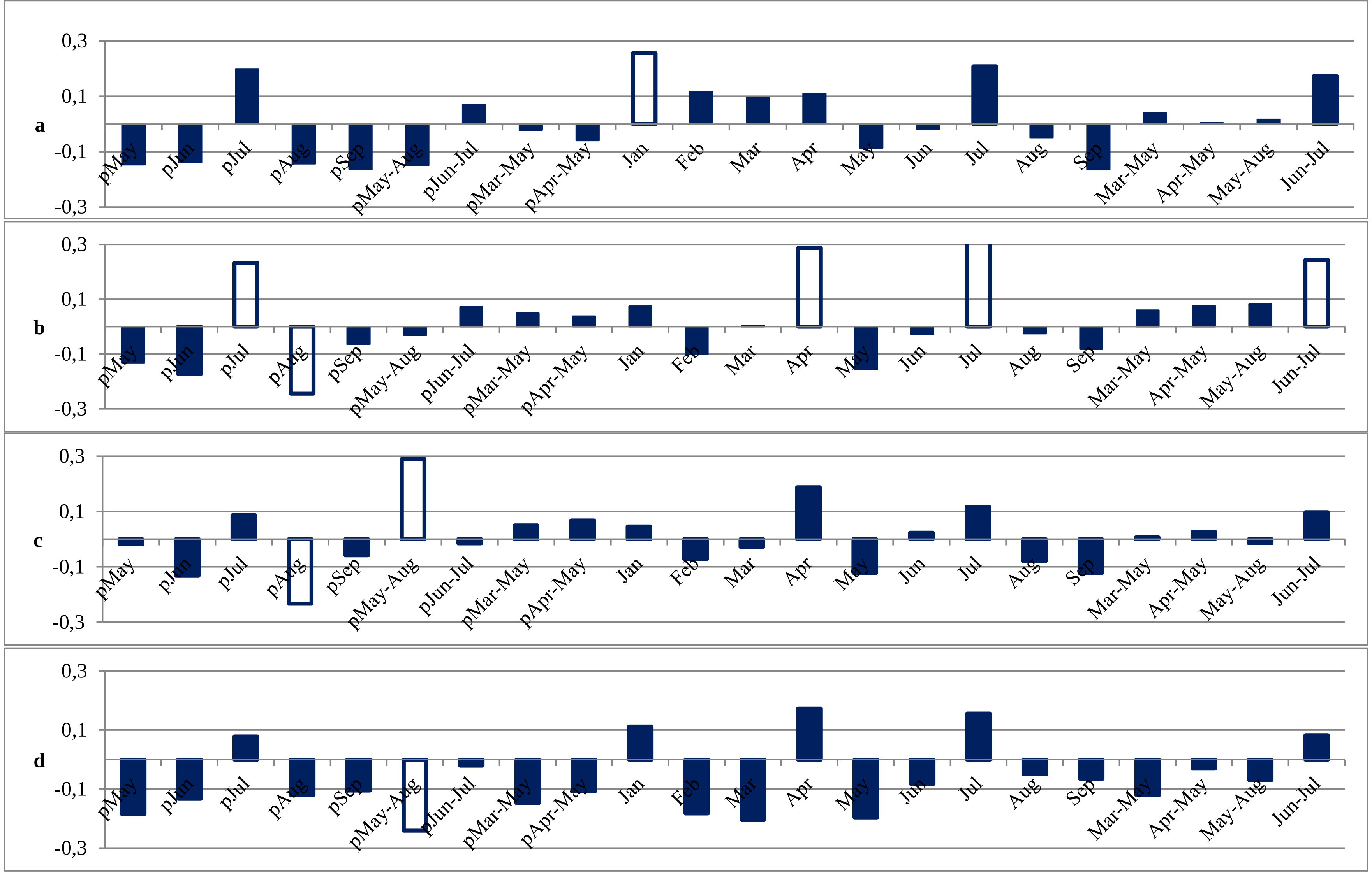
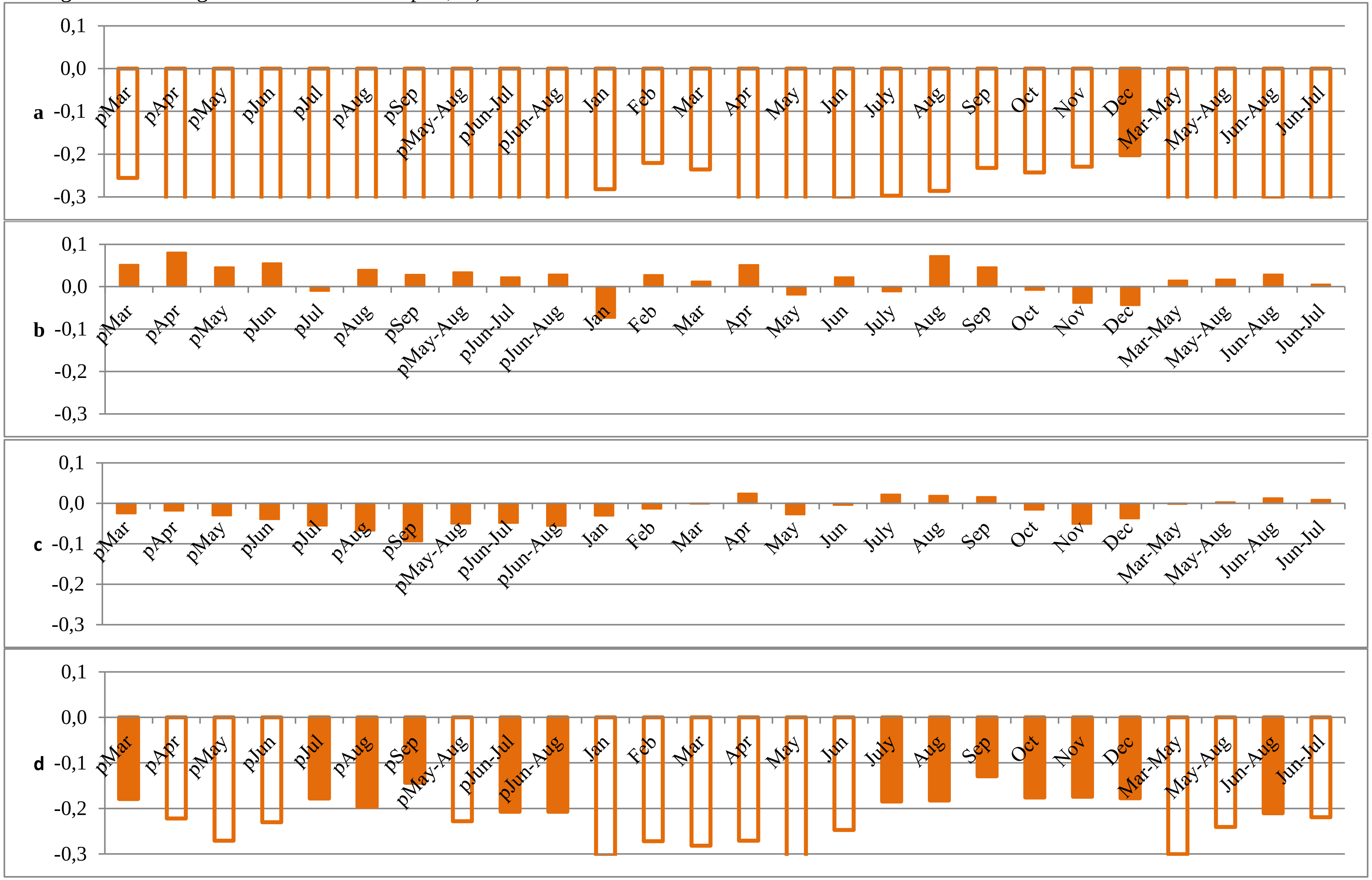


Figure 33: Correlation of a) PM-Sm1490, b) PM-Sm1300, c)PM-Sn1350 and d)PM-Sn1500 chronologies with Palmer drought severity index (empty rectangle indicates significant correlation at $p<0,05$)



6.5 Climate signal in *Pinus mugo* chronologies obtained by different detrending methods

According to the aim of the research the comparison of climate signal obtained by different standardization methods has been made made (Figures 34 -36).

Compare climate signal obtained by different detrending methods, it is obvious, that the results differ a lot:

a) PM-Sm1490: all methods show positive significant correlations between temperatures of May – August period and January month with TRW. All methods except “RCS2” point out the significance of warm June and July month on shrub growth. Only “AVE” method shows the significance of warm August on tree-ring increment (r=0,32). The link of TRW with precipitation is also very clear. All the methods except “RCS2” show the importance of snow in January. Only “spline40” reflects the significant importance of precipitation in June - July period (r=0,26). Considering the relation between TRW and PDSI, only “RCS2” gives insignificant results during the whole year. Other methods support the significantly negative influence of droughts on tree-ring increment;

b) PM-Sm1300: almost all methods give insignificant correlation coefficient between TRW and temperatures of the given year. “RCS2” chronology highlights the importance of May – August temperatures on shrub growth (r=0,46). “spline40” and “spline150” show negative influence of warm previous August on TRW (r= -0,29 and r= -0,26 respectively; the result is considered after the removal of autocorrelation effect). All standardization methods highlight the significance of wet April and June - July months on shrub growth. Significantly negative effect of wet previous August is pointed out by all methods (the result is considered after the removal of autocorrelation effect). Neither of methods shows the significant correlation of shrub growth with droughts.

c) PM-Sn1350: “AVE” chronology significantly correlates with warm January (r=0,23). Significantly negative effect of August temperatures is given by “spline150” (r= -0,24). “spline150”, “RCS1” and “RCS2” show negative influence of previous year warm June – July period (r= -0,27, r= -0,34 and r= -0,27 respectively; the result is considered after the removal of autocorrelation effect). Significant result with precipitation of the given year is provided only by “RCS2” method which shows the importance of June – July precipitation on shrub growth (r=0,22). “spline40”, “RCS1” and “AVE” methods show significantly negative influence of previous year wet August on TRW (r= -0,3, r= -0,27 and r= -0,36 respectively; the result is considered after the removal of autocorrelation effect). Neither of detrending methods produces chronologies significantly correlated with droughts.

d) PM-Sn1500: “RCS1” and “AVE” methods show the significant importance of warm May – August period on shrub growth. “spline40” chronology negatively correlates with precipitation in February month (r= -0,22). Influence of wet April on the contrary is significantly positive (”spline40” and “spline150”). “RCS1” and “AVE” chronologies negatively correlate with precipitation of previous May – August period (r= -0,23 and r= -0,22; the result is considered after the removal of autocorrelation effect). Same methods point out the negative influence of droughts during spring and following summer on shrub growth. Spline methods and “RCS2” produce no significant correlations between TRW and droughts.

The results between different methods vary a lot. The best climate signal in pine chronologies is obtained by “RCS1” and “AVE” standardization methods. Climate signal between two upper sites (PM-Sm1490 and PM-Sn1500) is similar to each other. Climate signal at two lower sites (PM-Sn1350 and PM-Sm1300) is quite mixed and does not show clear climate effect on shrub growth.

Figure 34: Correlation of a) PM-Sm1490, b) PM-Sm1300, c) PM-Sn1350 and d) PM-Sn1500 chronologies obtained by different detrending methods with temperature (r above or below the back line is significant at p<0,05)

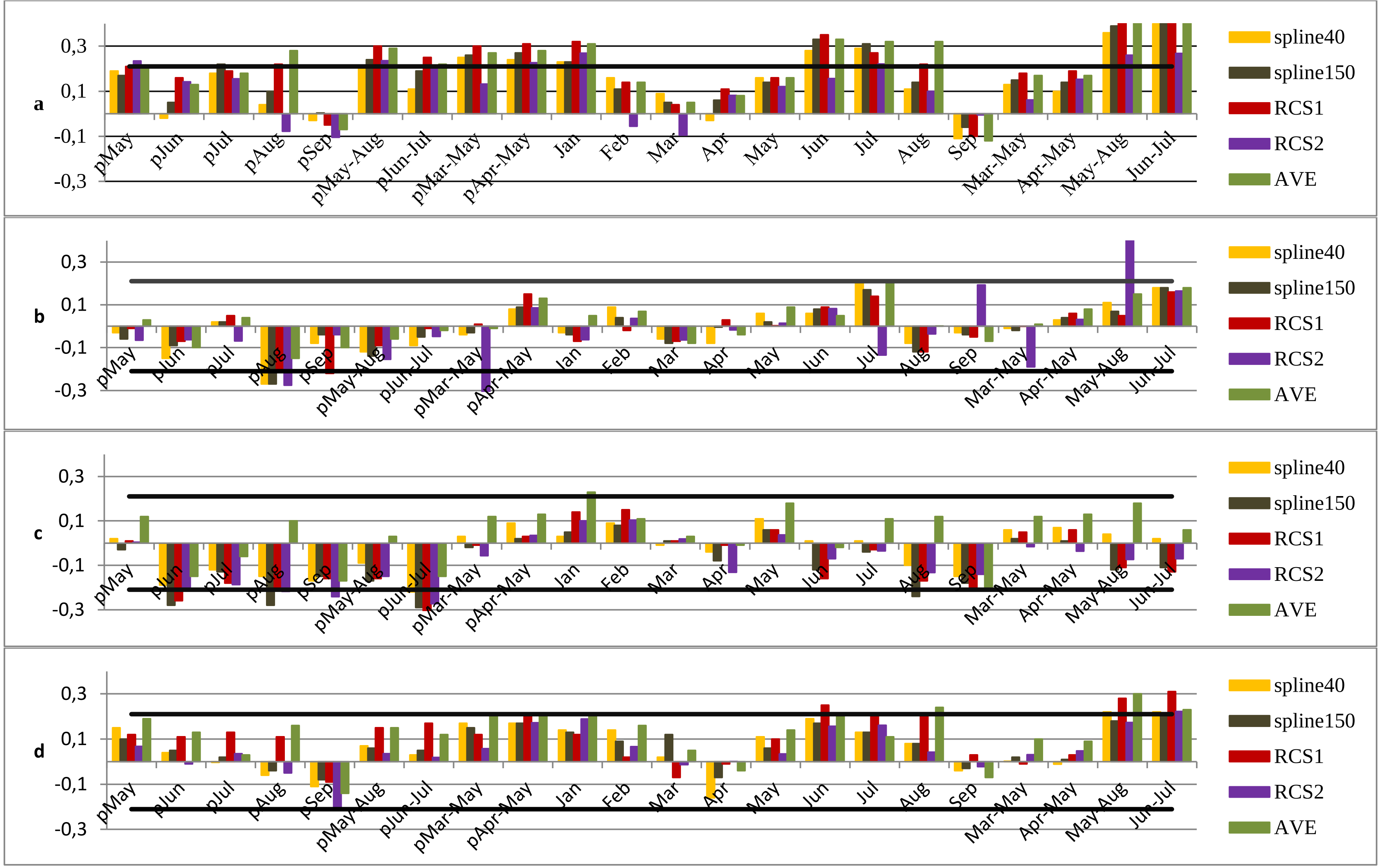


Figure 35: Correlation of a) PM-Sm1490, b) PM-Sm1300, c) PM-Sn1350 and d) PM-Sn1500 chronologies obtained by different detrending methods with precipitation (r above or below the back line is significant at p<0,05)

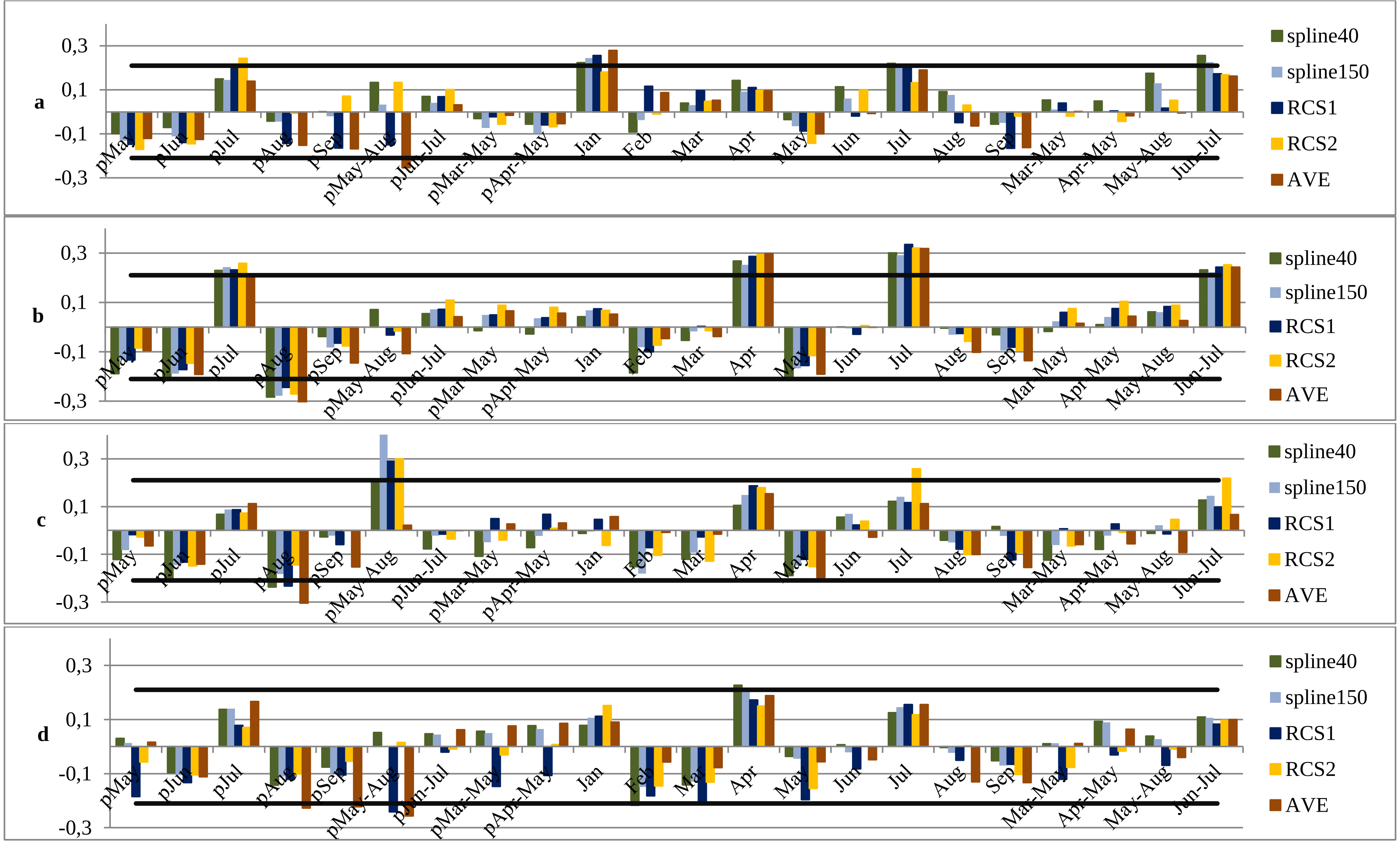
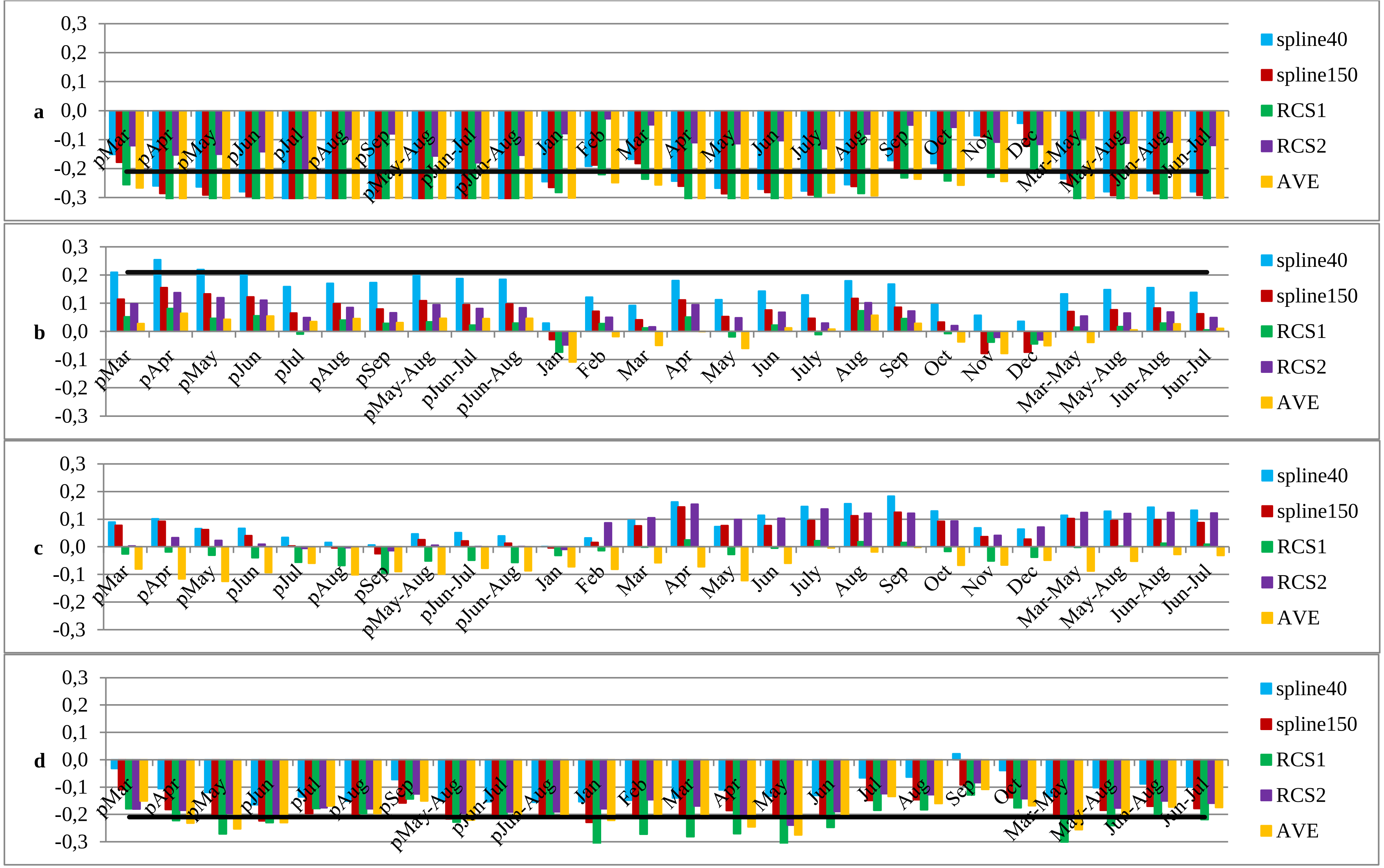


Figure 36: Correlation of a) PM-Sm1490, b) PM-Sm1300, c) PM-Sn1350 and d) PM-Sn1500 chronologies obtained by different detrending methods with PDSI (r above or below the back line is significant at $p<0,05$)



6.6 Climate signal in *Picea abies* trees

Spruce chronologies obtained by “spline150” method have been used for climate-signal evaluation. Correlation and partial correlation of spruce TRW with temperatures (Figures 37 and 39 respectively) show similar results obtained for both PA-Kl and PA-Kc sites. On both sites tree-ring widths are significantly influenced by temperatures of May - August period (r=0,424 and r=0,416 respectively) especially June – July months (r=0,52 and r=0,45 respectively). TRW increment at PA-Kc is significantly supported by warm February month (r=0,29). No significant correlations with precipitation between both spruce sites during the year of growth (Figures 38 and 40) have been found. The availability of precipitation during previous June – July period shows however negative effect on TRW at PA-Kc (r= -0,3; the result is considered after the removal of autocorrelation effect). Neither of two spruce chronologies significantly correlates with PDSI (Figure 41).

6.7 Pointer years in *Pinus mugo* and *Picea abies* chronologies

All four *Pinus mugo* chronologies show extremely narrow tree-rings in 1941, 1942 and 1974 years (Figure 42). Abnormaly wide tree-rings are found in 1958, 1963, 1997 and 1998 years. In general the period from 1920 to 1927 is quite favorable for shrub growth at PM-Sn1350. On the contarry, period from 1934 to 1950 is characterized by unfavorable conditions for tree-ring increment at all pine sites. During the period from 1950 to 1970 only positive pointer years at all pine sites are observed. On the contary the period from 1970 to 1985 is quite unfavorable for shrub growth. No positive pointer years are observed on any pine site. Period from 1991 to 1998 is very favorable for shrub growth at PM-Sn1500 and PM-Sm1490.

As well as for *Pinus mugo* sites, years 1942 and 1974 are very unfavorable for spruce growth on both sites (Figure 43). On the contrary, year 1963 is characterized by good conditions supporting TRW increment. Other significant years for tree growth at PA-Kl site are 1923, 1925, 1956, 1980 and 1996, when TRW are found to be abnormally thin. Years 1931, 1946, 1970 are on the contrary very favorable for TRW increment. Years 1923, 1929, 1984 and 1996 are characterized by bad growth conditions at PA-Kc site. Year 2002 on the opposite seems to be very successful for tree growth at PA-Kc.

Temperature and precipitation anomalies of the most significant years at four pine sites are shown in Figures 44 - 45. Years 1941, 1942 and 1974 are characterized by extremely cold winter with a lot of snow even in the beginning of spring thus suppressing TRW increment. Years 1958, 1963, 1997 and 1998 had very warm spring and summer months supporting the early initiation of growing season and intensive shrub growth. For pointer years calculation pine chronologies obtained by “RCS1” standardization method have been used.

6.8 Moving correlations

Moving correlations have been calculated on base of 31 year moving average. Moving correlations between all *Pinus mugo* sites are shown in Figure 46, between *Pinus mugo* and *Picea abies* sites – at Figure 47. Pine chronologies obtained by “RCS1” standardization method and spruce chronologies obtained by “spline150” method have been used for correlations.

It is seen from the graph (Figure 46) that pine growth on PM-Sm1490 and PM-Sn1500 follows the same trend. The same is true for PM-Sm1300 and PM-Sn1350, PM-Sn1350 and PM-Sn1500, PM-Sm1300 and PM-Sn1500. Some difference in growth is observed between PM-Sm1490 and two lower sites (PM-Sm1300 and PM-Sm1350) after 1965.

Considering pine and spruce sites, it can be seen from Figure 47 that growth of pine at all sites significantly correlates with growth of spruce at PA-Kl after 1930 year. The same is true for PA-Kc site. However growth of spruce there better correlates with two upper sites than two lower sites of pine. Correlation between PM-Sn1350 and PA-Kc stands is found to be non-significant.

Moving correlations between pine sites and the most important climate variables (significant partial correlations from Figures 31 – 32) are depicted in Figures 48 and 49. Growth of pine at PM-Sm1490 significantly correlates with June – July temperatures during the whole period from 1920 to 2013. Correlation of pine growth at PM-Sn1500 with the same climate variable is significant till 1975, after that growth seems to be much influenced by other factors as well. Growth of pine at PM-Sm1490 significantly correlates with January precipitation from the firsrt half of 1930s to 2013. Correlation of TRW increment with July precipitation at PM-Sm1300 is significant on almost whole period from 1920 to 2013.

Figure 37: Correlation of a)PA-Kl and b) PA-Kc chronologies with temperatures (empty rectangle indicates significant correlation at p<0,05)

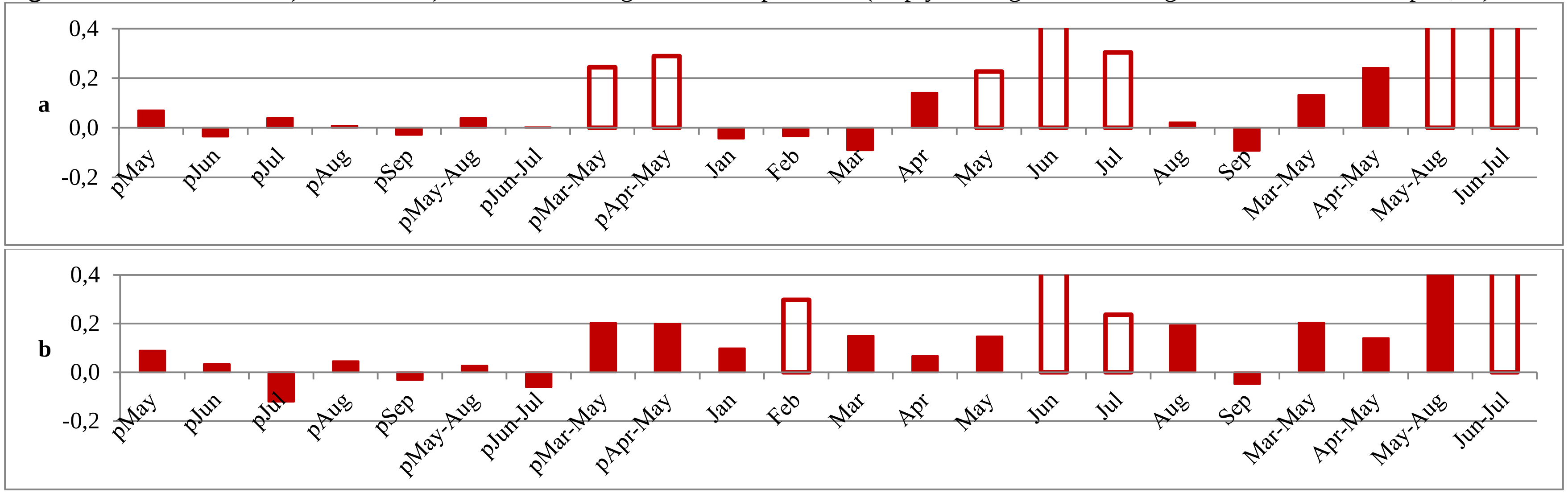


Figure 38: Correlation of a)PA-Kl and b) PA-Kc chronologies with precipitation (empty rectangle indicates significant correlation at p<0,05)

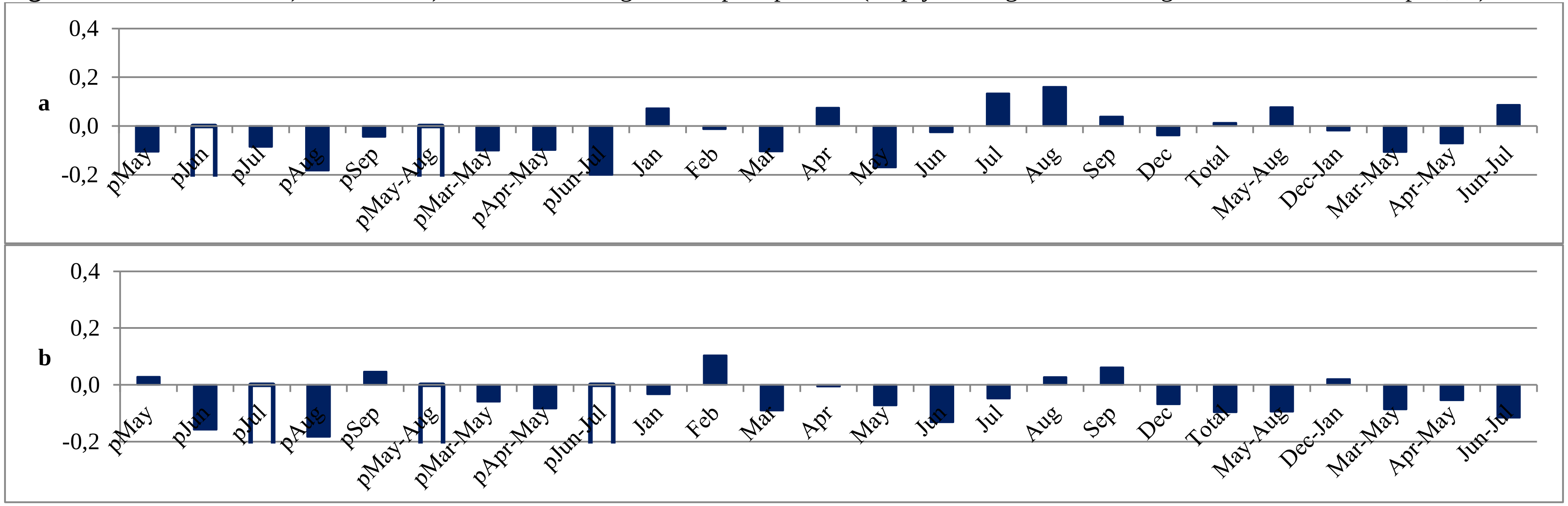


Figure 39: Partial correlation of a)PA-Kl and b) PA-Kc chronologies with temperatures (empty rectangle indicates significant correlation at p<0,05)

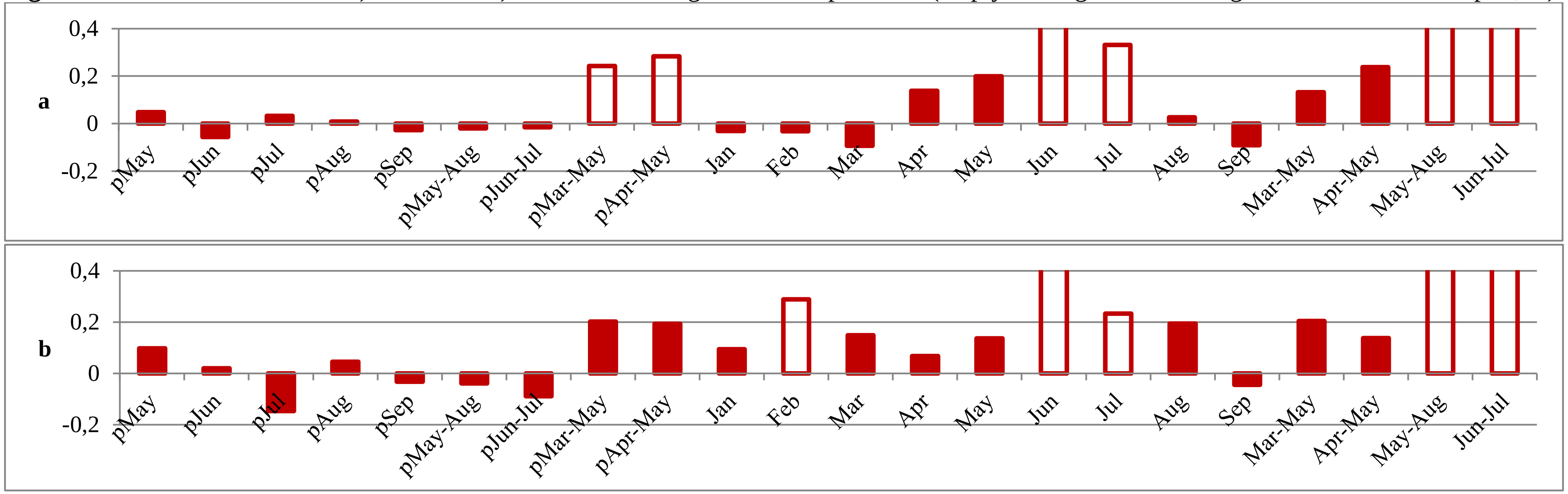


Figure 40: Partial correlation of a)PA-Kl and b) PA-Kc chronologies with precipitation (empty rectangle indicates significant correlation at p<0,05)

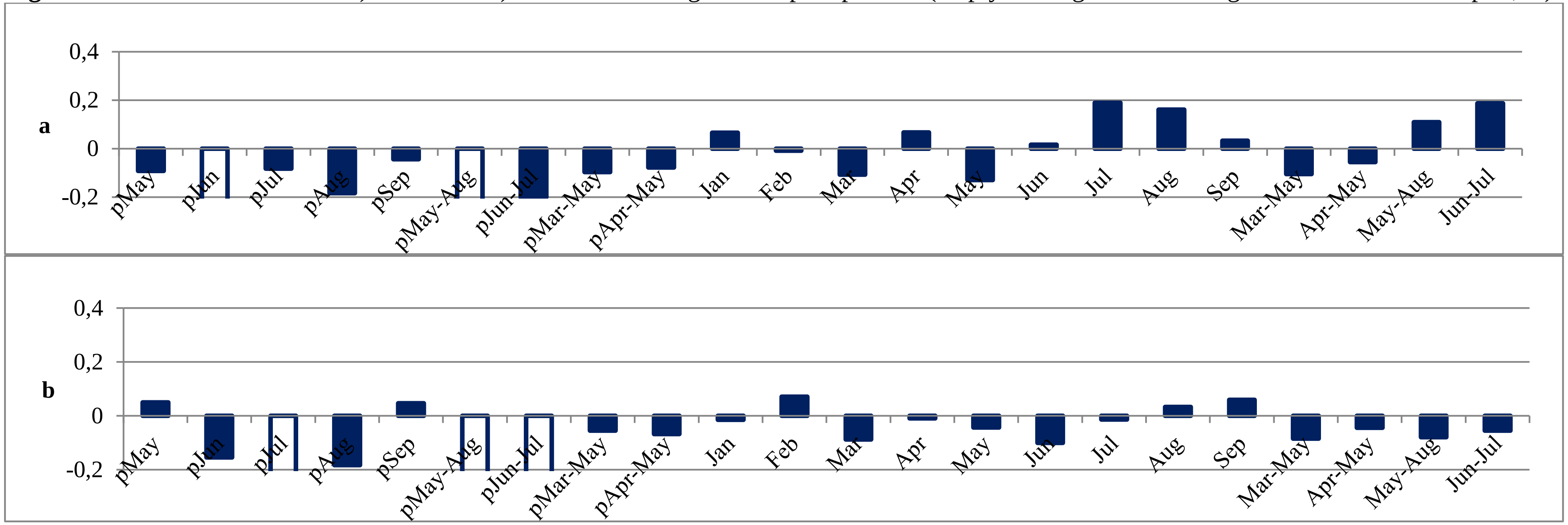


Figure 41: Correlation of a)PA-Kl and b) PA-Kc chronologies with PDSI (empty rectangle indicates significant correlation at p<0,05)

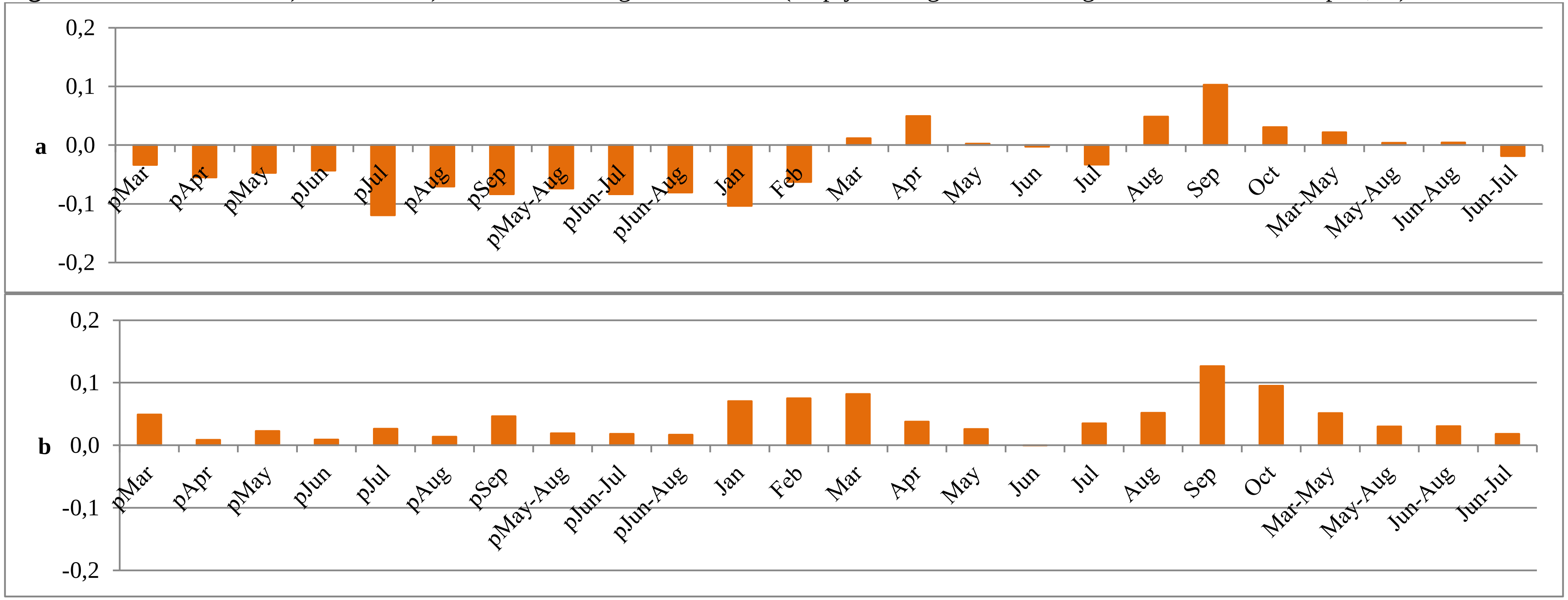


Figure 42: Pointer years at four *Pinus mugo* chronologies (3 – extremely positive year, 2 – strongly positive year, 1 – weakly positive year; -3 – extremely negative year, -2 – strongly negative year, -1 – weakly negative year)

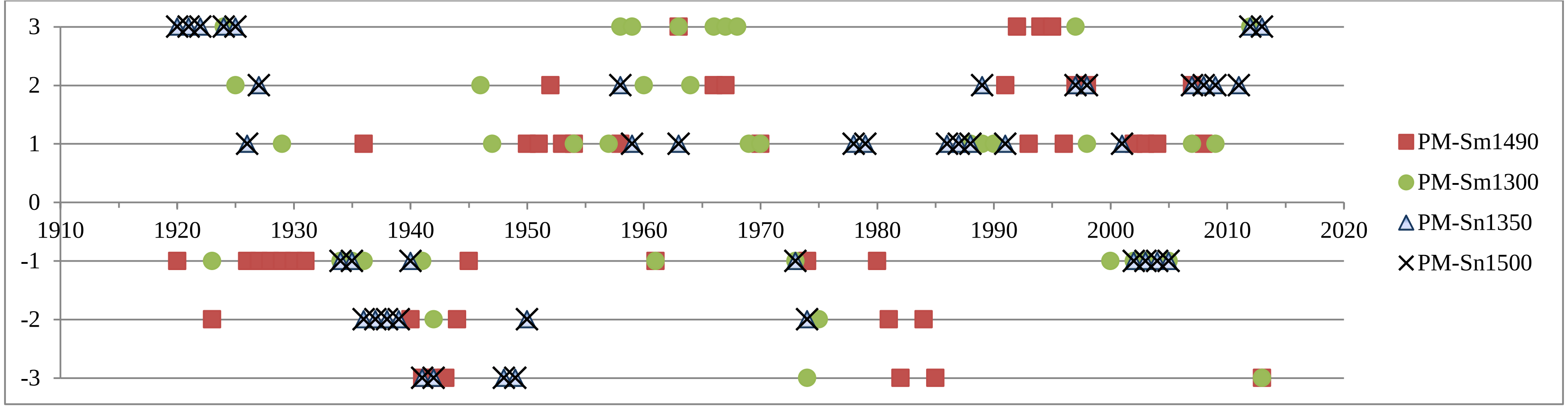


Figure 43: Pointer years at two *Picea abies* chronologies (3 – extremely positive year, 2 – strongly positive year, 1 – weakly positive year; -3 – extremely negative year, -2 – strongly negative year, -1 – weakly negative year)

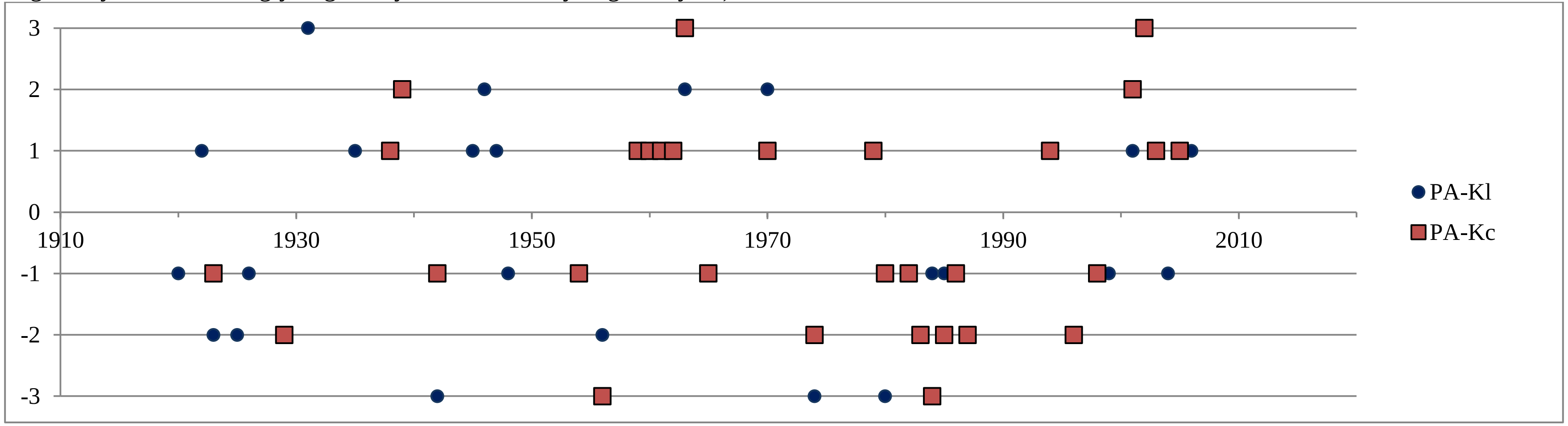
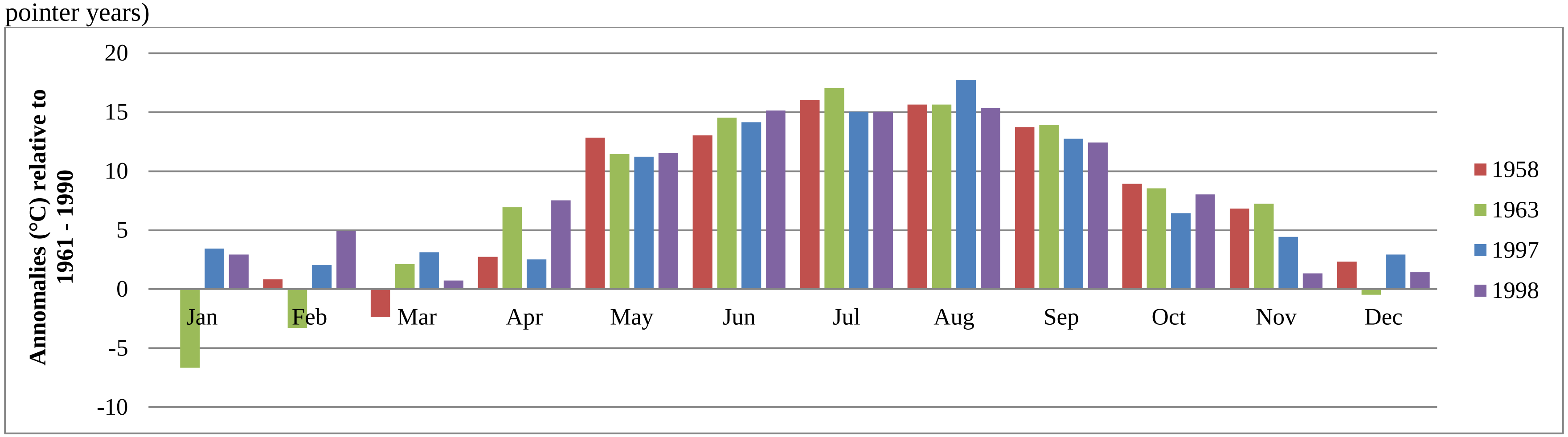


Figure 44: Temperature anomalies relative to 1961 – 1990 period for 1958, 1963, 1997 and 1998 (positive pointer years) and 1941, 1942, 1974 (negative pointer years)



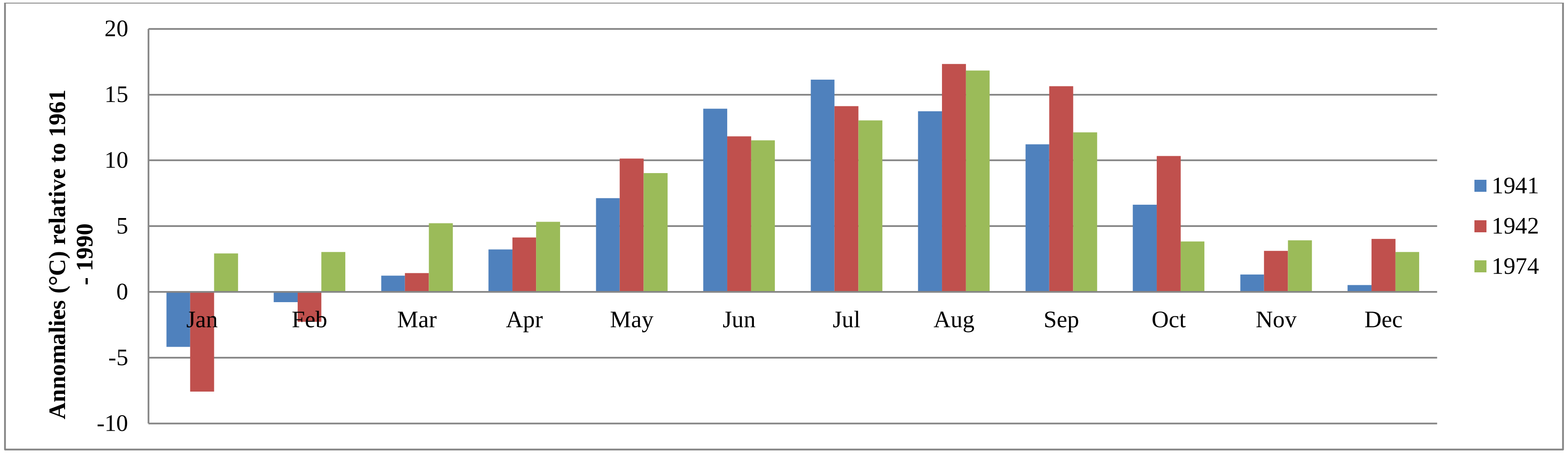


Figure 45: Precipitation anomalies relative to 1961 – 1990 period for 1958, 1963, 1997 and 1998 (positive pointer years) and 1941, 1942, 1974 (negative pointer years)

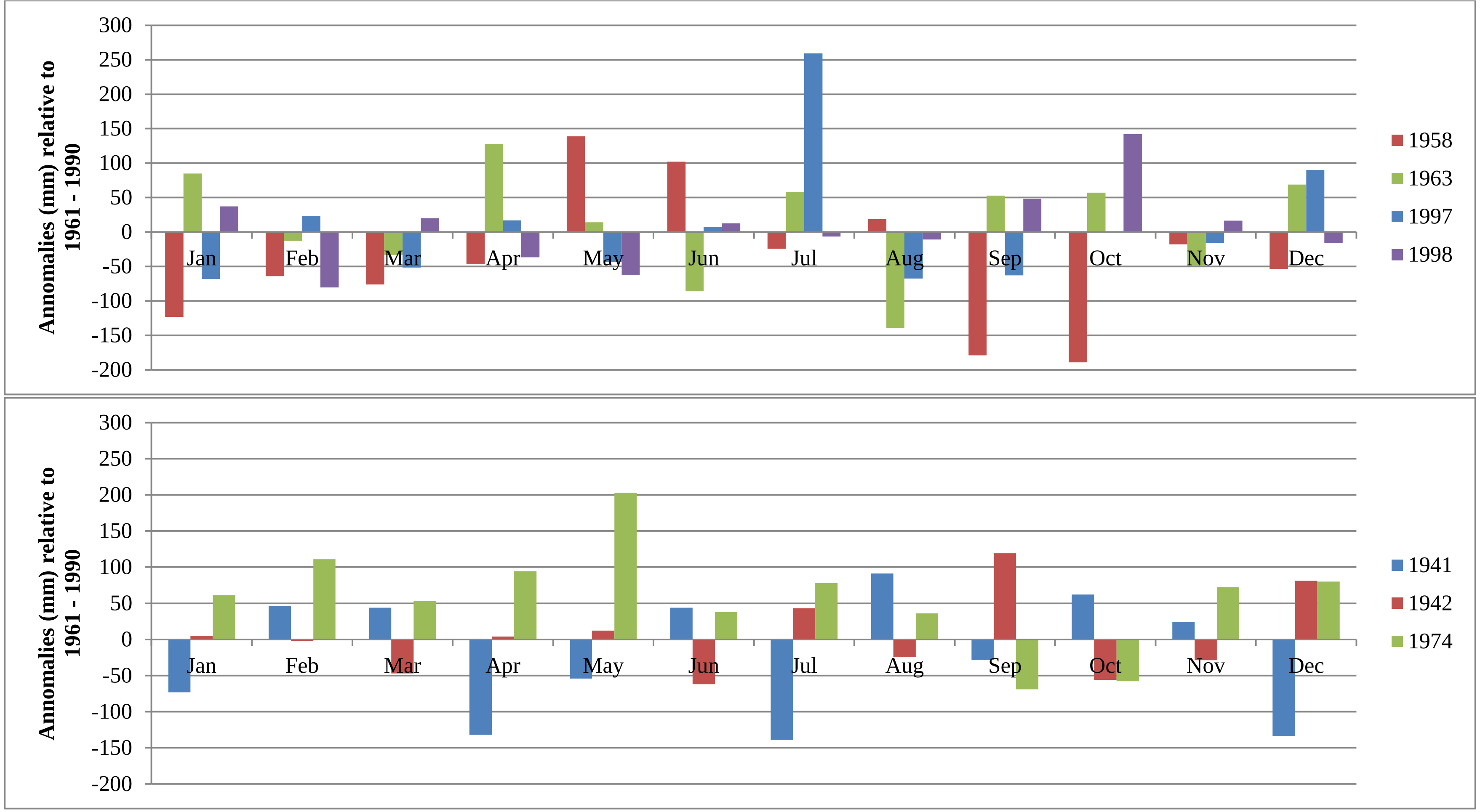


Figure 46: Moving correlations between four sites of *Pinus mugo* stands (black line shows the level of significance at p<0,05)

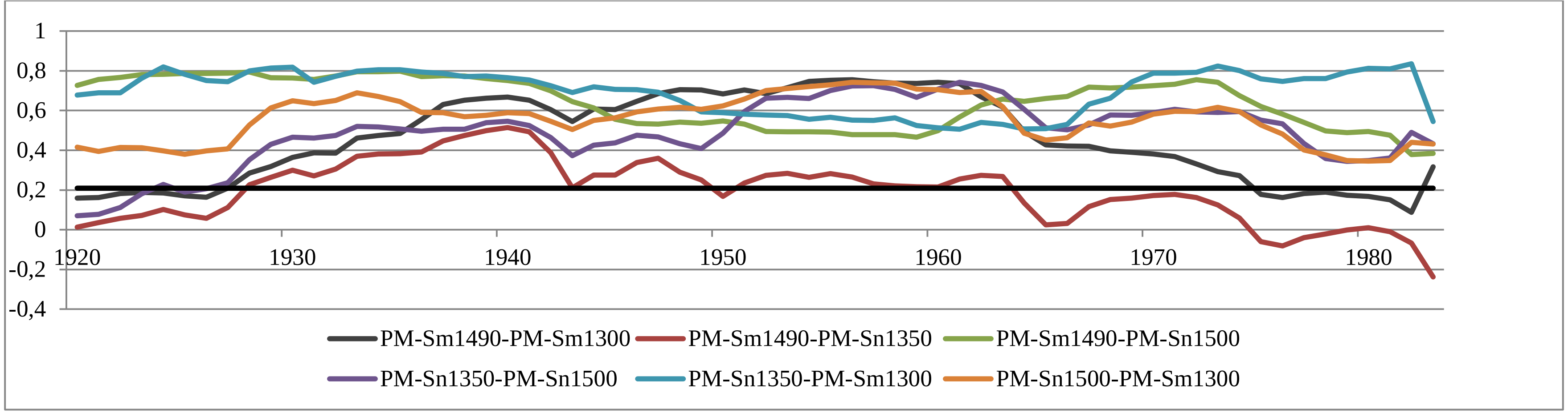


Figure 47: Moving correlations between four sites of *Pinus mugo* and two sites of *Picea abies* stands (black line shows the level of significance at p<0,05)

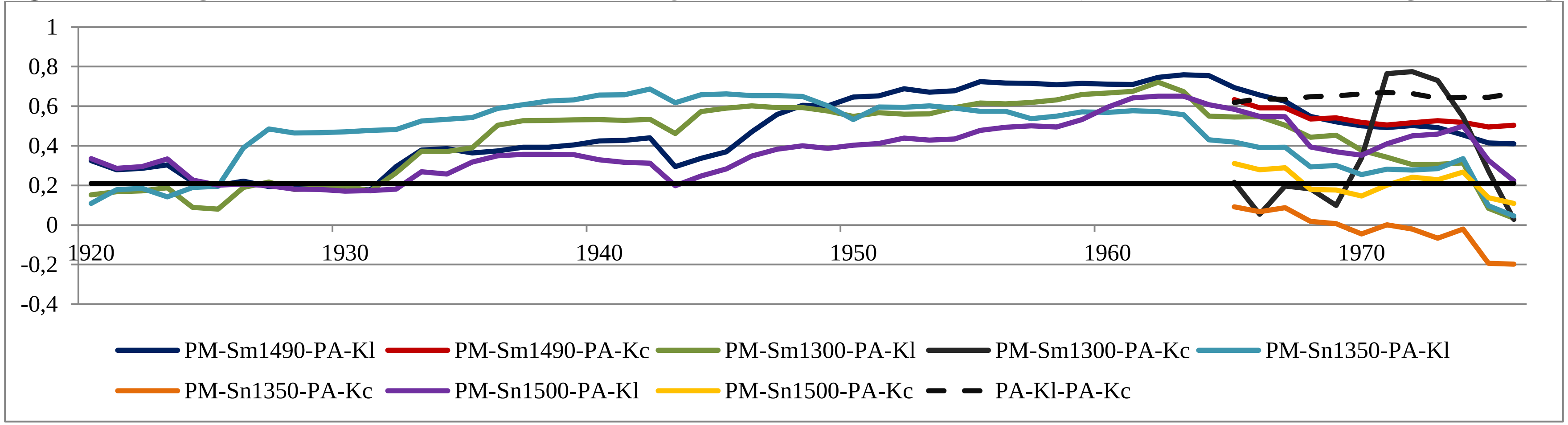


Figure 48: Moving correlations of PM-Sm1490 and PM-Sm1500 chronologies with the most significant temperature parameters (black line shows the level of significance at p<0,05)

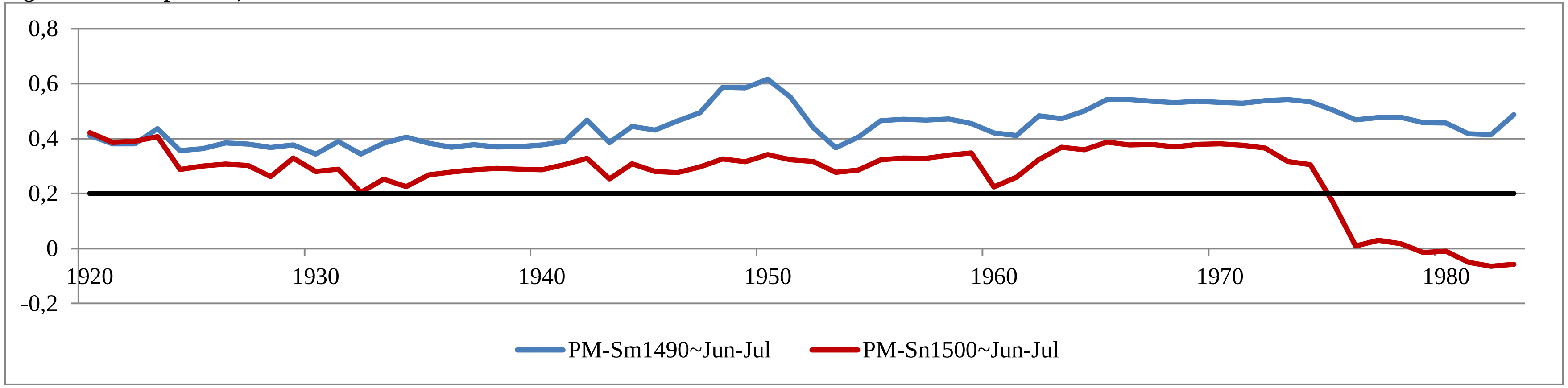
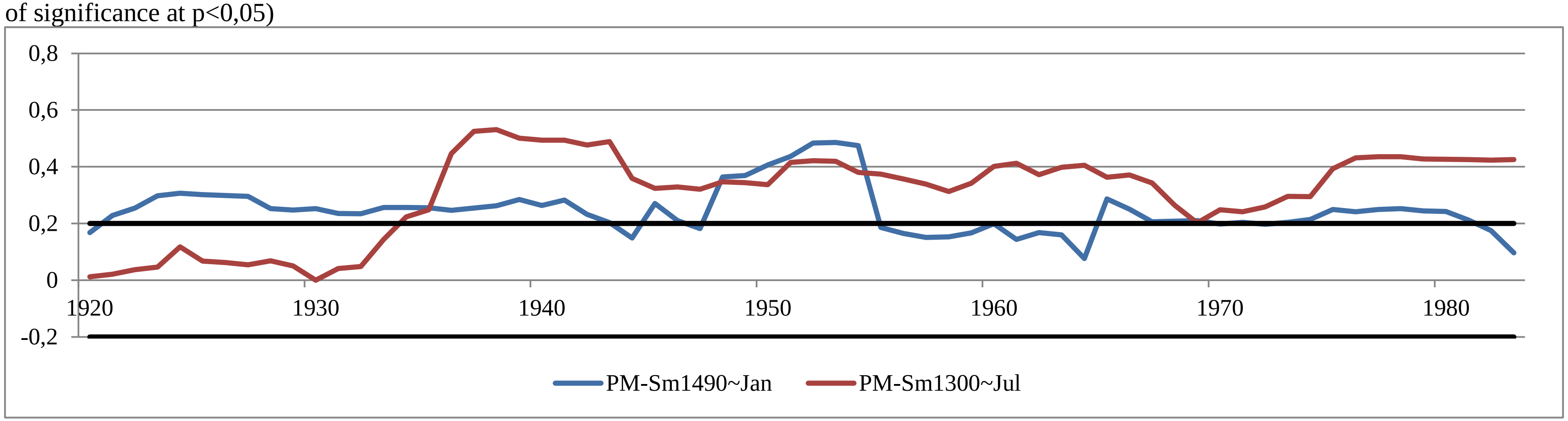


Figure 49: Moving correlations of PM-Sm1490 and PM-Sm1300 chronologies with the most significant precipitation parameters (black line shows the level of significance at p<0,05)



7 Discussion

7.1 Site specific climate signal in *Pinus mugo* shrubs

Dwarf pine is the most competitive member among all the species at shrub zone at Krkonoše Mountains (including *Salix silesiaca*, *Salix lapponum*, *Sorbus sudetica*). Its prostrate form helps it perfectly cope with unfavorable climate conditions of high altitude environment (Solár and Janiga 2013). In this work climatic signal in *P. mugo* shrubs has been analyzed on four sites located in different altitudes on slopes of Sněžka Mountain and Smogornia ridge. The influence of temperature and precipitation on shrub growth has been studied. Discussion provided in this chapter will be based on the results obtained by "RCS1" method.

The strongest temperature signal has been found at two upper sites (PM-Sm1490 and PM-Sn1500) with May – August period (especially June – July months). Correlation coefficients between TRW and June – July temperatures equals to 0,44 (PM-Sm1490) and 0,31 (PM-Sn1500). It is seen that June – July signal at PM-Sn1490 is stronger than at PM-Sn1500. The importance of temperatures during the vegetation period in shrubs is shown in other research as well (Grace and Norton 1990, Rozema et al. 2009, Block et al. 2011). Moreover Blok et al. (2011) showed that temperatures in the beginning of growing season play much more important role than temperatures of late July and August months. Temperature is extremely important for a number of physiological processes occurring in the tree (cell division, cell differentiation, photosynthesis, transpiration, metabolism, etc., Pallardy 2008).

Shrub growth at PM-Sm1490 significantly correlates with temperatures of January month (r=0,32). Positive correlation with January – February temperatures have been found also by Grace and Norton (1990). Palombo et al. (2014) on the opposite have shown the negative influence of winter temperatures on shrub growth. Positive influence of winter period can be explained by less frost damages and less intensive frost hardening, due to which growth began earlier (Churakova et al. 2014). Less severe frost during winter prevent xylem vessels from destroying, thus leading to less severe embolism and stem dehydration (Sperry and Sullivan 1992). Warm temperatures during winter initiate earlier snow melt, thus increasing the availability of water in the beginning of the growing season (Peterson and Peterson 1994). Though *Pinus mugo* individuals are not so susceptible to winter frosts (Rixen et al. 2012), it is obvious that warm winter will support the growth.

P. mugo growth at PM-Sm1490 can be positively influenced by warm March – May period of the previous year (0,25; values are considered after the removal of autocorrelation effect). Jarvis and Linder (2000) show that generally growth of boreal coniferous well correlates with previous year temperatures. Relation with previous year spring temperatures (thus with favorable initiation of growing season) can be explained by sufficient nutrient supply for the year of growth and the year following (Fritts 1976).

Shrub growth at PM-Sn1350 negatively correlates with warm June-July months of the previous year (-0,34). Palombo et al. (2014) observe the same effect in their research and link it with the occurrence of drought during growing season. It is seen that strong temperature signal in shrubs is observed mainly at upper sites, when at lower sites shrub growth either connected with climate conditions of the previous year or does not reflect any clear temperature signal (PM-Sm1300). Big role of temperatures in shrub growth has been found by Grace and Norton (1990) on the example of dwarf *Pinus sylvestris* individuals.

Precipitation signal at all pine sites is weaker than temperature one. Radial growth at PM-Sm1490 positively correlates only with precipitation in January month (r=0,26). Blok et al. (2011) at their research of *B. nana* and *S. pulchra* do not show any influence of winter precipitation on shrub growth. The effect of snow during winter can have positive and negative consequences. On the one side, snow cover in January protects soil from deep freezing thus creating better temperature regime for metabolic processes and cell division occurring in plants (Schmidt et al. 2006, Churakova et al. 2014). On the other side it can delay the initiation of growing season thus leading to the decline in growth (Holtemeier 2009). Strong correlation of PM-Sm1490 site rather than other sites with winter precipitation can be explained by more exposed position of this site to winds and hence more intensive redistribution of snow to lower areas. Growth of shrubs at PM-Sn1500 is negatively influenced by previous year May – August precipitation (r= -0,23). Negative influence of wet previous year August is reflected at both lower sites. Unfavorable influence of precipitation during preceding May – August period is supported by findings of Palombo et al. (2014). Grace and Norton (1990) link it with the unfavorable influence of wet and cool summer on shrub growth. Blok et al. (2011) on the contrary show positive relationship between previous year precipitation during May – August and shrub growth in Kytalyk area. According to Fritts (1976) cool growing season negatively influence the availability of shrubs to accumulate nutrients for the next year. Growth of shrubs at PM-Sm1300 is positively influenced by the amount of precipitation during June – July months (r=0,24). The necessity of water during the period of intensive growth at shrubs is also confirmed by Büntgen et al. (2007), García-

Cervigón Morales et al. (2012), Kong et al. (2012) and Palombo et al. (2014). It indicates that mountain pine gains from warm and wet vegetation period.

Difference between upper and lower sites has been pronounced also in the reaction of shrub growth to droughts. Shrub growth at PM-Sm1490 has been shown to be very sensitive to droughts. The same has been true for PM-Sn1500, especially during winter and spring months. The influence of water stress on lower sites is not significant. There have been found no significant correlations between shrub growth and PDSI. Such result can lead to the conclusion that upper sites suffer more from dry conditions. The link with winter drought can be explained by deeper soil freezing and water stress according to the redistribution of snow to lower elevations (Wieser and Tausz 2007). Insufficient protective snow cover leads to short-term fluctuations of soil temperatures and desiccation due to increased evapotranspiration (Oberhuber 2004). In case of future climate warming, upper sites will suffer more from water stress during the growing season. This finding well corresponds with growth response of shrubs to precipitation. Similar results have been found by Dirnböck et al. (2003) and Liang et al. (2012).

According to discussed material, climate signal is stronger at upper sites than at lower ones. Thus upper sites will be more sensitive to any climate changes. Climate signal at two lower sites have been found to be very weak or mixed to a high degree.

It is necessary to admit, that shrub growth at four studied sites is very site specific. The modulated influence of shrub growth by local conditions is discussed, for example, by Wilmking et al. (2004), Büntgen et al. (2007), Treml et al. (2012). There are a lot of reasons explaining different growth response in studied sites, for example, competition, water stress (for upper sites), vicinity of the closed forest margin (for lower sites, Wieser and Tausz 2007). Influence of forest margins are mainly shown through specific microclimate, lower albedo, competition effect etc. Lower position of PM-Sm1300 and PM-Sn1350 on the slope provides them better conditions for snow accumulation and wind protection. Frequent correlations with previous year climate variables point out the delayed effect of climate parameters on shrub growth.

7.2 Differences in climate signal of trees and shrubs

Same types of chronologies should be used to make the comparison between climate signal in different tree species. In this research however I used spruce chronologies obtained by

„spline150“ method and dwarf pine chronologies obtained by „RCS1“ method. The usage of different methods can be explained by the quality of the obtained chronologies. While for *P. mugo* chronologies the best results have been given by “RCS1” or “AVE” methods, for *P. abies* chronologies they have not been suitable enough. “Spline150” method on the contrary showed the satisfactory result.

Growth trends of *Picea abies* showed similar results with two upper *Pinus mugo* sites (PM-Sm1490 and PM-Sn1500). Both species reacts positively on the temperatures during May – August period, especially June – July months. Correlation coefficients of PA-Kl and PA-Kc with June – July temperatures equals to 0,52 and 0,42 respectively. Thus it is obvious that June – July signal is stronger at spruce than at pine. Stronger climate signal in pine trees rather than juniper shrubs has been also shown by García-Cervigón Morales et al. (2012) in their research in Iberian Mountain system. Moreover they showed earlier response of juniper shrubs than of pine trees to spring temperatures. Earlier response of shrubs TRW increment is also confirmed by Gazol and Camarero (2012). The initiation of growth between mountain pine and spruce has not been studied in the framework of this research. However it can be a promising topic for future investigation. Tree growth at PA-Kc site showed positive correlation with February temperatures (r=0,29). Positive influence of January temperatures has been found at PM-Sm1490 site, thus confirming again the importance of winter temperatures for both shrubs and trees growth. Temperature signal in this particular occasion has been found stronger at PM-Sm1490 than at PA-Kc.

In general it has been shown, that temperature signal is stronger at spruce trees than at pine shrubs at Krkonoše Mountains. García-Cervigón Morales et al. (2012) have come to the same conclusion at their research of juniper shrubs and pine trees in Spain.

Both spruce sites show no significant relationship with PDSI index. The same result has been found at PM-Sn1350 and PM-Sm1300 sites. It indicates that spruce stands as well as lower pine stands favor from their position down the slope with better availability of protective snow cover in winter and sufficient precipitation in summer.

Negative influence of precipitation during the previous year May – August period has been found at PA-Kc (r= -0,3). The same is true for two lower sites of mountain pine (PM-Sm1300 and PM-Sn1350). It confirms the importance of successive previous year growing season for both species.

Positive correlation with prior October and November temperatures has been found in his research by Oberhuber (2004). It can be explained by several reasons, including carbon storage, mycorrhyzal root growth, and creation of better condition for buds and needle maturation against early winter stress. Positive correlations with October - November temperatures have been observed at all sites of *Pinus mugo* and *Picea abies* in Krkonoše Mountains as well. Though the correlations have not been significant at p<0,05, it can be still of potential interest in terms of changing climate conditions.

In general difference in climate signal between trees and shrubs can be explained by their physiology and their different position according to environmental limits (García-Cervigón Morales et al. 2012, Körner 2012). While spruce is growing closer to its environmental margin, pine occupies sites closer to its optimal distribution. As generally timberline is considered to be a bioclimatic phenomenon (Körner and Paulsen 2004) it can explain the difference in temperature signal strength between pine and spruce stands. According to Körner (2012) prostrate vegetation is capable of creating its own microclimate preventing it from extreme cold during winter. Spruce is more exposed to ambient air and thus more susceptible to winter frost and winter embolism. Convective transfer of heat at trees prevents them from taking advantage of thermal solar heating during the growing season. Shrubs on the opposite benefit from it (Körner 2012).

Very important role in mountain pine growth belongs to its strategy of continuously missing tree-rings. It helps the shrub to limit the costs on the developing of tissues and helps it to survive in harsh alpine conditions (Körner 2012, Wilmking et al. 2012). Less susceptibility of shrubs than trees to extreme climate events have been shown in number of research (Souček et al. 2001, Rixen et al. 2012, Vacek et al. 2013).

Similar trend in climate signal between pine and spruce chronologies is explained first of all by the fact, that their growth at high altitudes of Krkonoše Mountains is determined by climate. Another reason is lying in similar physiology of coniferous species. Martínez-Vilalta et al. (2004), for example, have shown that all *Pinus* species are very vulnerable to xylem embolism. Thus it is possible to assume, that both species (especially at PM-Sm1490, PM-Sm1500, PA-Kl and PA-Kc sites) will have similar response to climate controls, differing however in its strength. Considering precipitation signal, it is obvious, that topography to a high degree modulate the response of trees and shrubs on the availability of precipitation during the year.

7.3 Extreme growth years

Growth of mountain pine is influenced by a big number of environmental factors, very often modulated by local conditions. Some climate or disturbance events are reflected only in some trees, others will be present in all population.

Years 1963 and 1997 have been found very successful for TRW increments on all *Pinus mugo* sites. The released growth in 1963 can be supported by several reasons: favorable climatic conditions (warm spring and summer) and released growth in openings after tree death caused by insect *Thecodiplosis brachyntera* during 1936 – 1956 years (Kyncl and Wild 2004). Year 1963 has been very successful for spruce growth on both PA-Kl and PA-Kc sites as well.

Extremely high decline of growth has been observed during the years 1941, 1942 and 1974 at mountain pine sites. Years 1942 and 1974 have been reflected in growth decrease of spruce as well. Years 1941 and 1942 belongs to the coldest years from 1930. Moreover the effect of frost has been combined with the attack of gall midge (Kyncl and Wild 2004, Wilmking et al. 2012). Insects influence trees through damaging the current year needles and causing defoliation (Glynn and Lindelöw 2002). Another attack of gall midge has been observed in 1994 – 1996 (Glynn and Lindelöw 2002).

Decline of growth during 1974 can be caused by cold summer. The same effect has been shown by Sander et al. (1995) on spruce samples from Krkonoše Mountains. It should be highlighted that, for example, 1956 year (year with extreme winter frosts) and 1980 year (with cold summer) were not reflected in *Pinus mugo* growth in comparison with spruce trees from Sander et al. (1995). Unfavorable conditions of 1956 and 1980 are supported by chronologies from PA-Kl and PA-Kc. Less sensitivity of mountain pine to cold conditions have been found by Rixen et al. (2012).

If the unfavorable factor will influence the tree growth for a longer period of time or will work in combination with other factors, it can have a stronger and longer-lasted effect. For example the growth of trees at PM-Sm1490 and PM-Sn1500 has been suppressed from 1940 – 1945, though the extreme frost were present only during 1940 – 1942.

1980s years are characterized by intensive sulfur and nitrogen emissions in Krkonoše Mountains. This period is well reflected in the decline of growth at PA-Kl and PA-Kc sites. Among *Pinus mugo* sites the decrease in growth has been observed only at PM-Sm1490 site. Other sites did not show any reaction on air pollution. This evidence can be explained probably by differences in response of younger and older trees to emissions or by higher retention of pollutants in soil due to the lower slope gradient at PM-Sm1490. In general, as it has been mentioned in Chapter 1, the growth of mountain pine is less susceptible to emissions than growth of spruce (Souček et al. 2001, Vacek et al. 2012). First part of 1990s is characterized by the release of growth at all mountain pine sites that can be partially connected with the end of air pollution.

7.4 Different approaches to standardization of shrubs

As it has been shown in this research, the resulted climate signal is highly dependent on the statistical methods, used for TRW series analyzing. Unfortunately till nowadays there is still no precise method of data processing for shrubs individuals. The only step which agreed among scientists is a method of serial-sectioning offered by Kolishchuk (1990). Further steps however are much more important as they will define the quality of the results.

Key thing that is must be discussed, if series must be synchronized and averaged first within the branch (or tree) and then within the site. Or it is better to synchronize all the series like individual cores straight away on the level of the whole site. Different solutions have been described in Table 1. To my opinion synchronization of series within one stem can lead to a bias of TRW in the overlapping parts of the series as the differences in TRW will be smoothed. As it was shown by Kyncl and Wild (2004) and Lukačík et al. (2014), the variability of TRW near the stem base is much higher than at younger parts of the stem. Moreover there are more missing rings at stem base (Kyncl and Wild 2004). Thus I will suggest following the method of Büntgen and Schweingruber (2010), offering to look at series as individual tree cores.

Method of detrending is also very important. As the biological growth trend of mountain pine has not been known well it is important to choose the method that will remain as much climatic signal as it is possible. TRW of *Pinus mugo* are very narrow thus it is advised to make power transformation of data and construct the chronology on base of the residuals. In my research I have tried to compare four different standardization methods in order to choose the best one suitable for mountain pine. Smoothing spline is a very good method especially if the biological growth trend is unknown, because it is rather flexible and can adapt to any data. However it is a mathematical function and strongly depends on user parameters. Thus for example 150-year spline will remain from low to middle-frequency information. 40-year spline will remove the information on length longer than 40 years. Any of them will give pretty good results, however it will not be the absolute true reflection of growth on the given site. And as it was shown in Chapter 6, it is not the best variant for standardization of shrubs individuals, though it is quite good for detrending spruce chronologies.

RCS curves or AVE methods on the opposite are based on the material from particular site, thus reflecting changes specific to the given place. From the other side it means that the standard chronology will be also influenced by local signal. Moreover in case of *Pinus mugo* or other shrub species I will suggest using different RCS curves for younger and older parts as the increment of stem in different parts varies greatly. On base of my results I can notice, that all the methods obtain different climate signal from shrub individuals. The strongest climate signal has been obtained by “RCS1”and “AVE” methods, methods reflected the real growth conditions at given sites.

All standardization methods show the importance of June – July and January temperatures at PM-Sm1490. All methods highlighted the importance of April and June – July precipitations at PM-Sm1300. Results shown by all methods point out the importance of the given climate variable on shrub growth. The results shown by only one or two methods should be carefully considered in regard to the used method and the strength of obtained climate signal. For example, “RCS2” method shows significant correlation of shrub growth at PM-Sm1300 with May – August temperatures (r=0,46). Correlation coefficient obtained by other methods has not even reach 2 value. Thus there is a question, if shrubs really react positively to the temperatures of the growing season, which is logical, or there is some problem in used method. To my point of view young series at mountain pine chronologies can bias the resulted chronology to some degree, thus it is always better to consider the necessity of using several RCS curves for different old series. The strongest climate signal obtained by “AVE” method is characterized for PM-Sm1490 site, site with the largest sample coverage. It support the assumption that quality of the signal obtained by such methods as “RCS” or “AVE” is dependent on the number of samples from the given area (Büntgen et al. 2012).

8 Conclusion

The research has been carried out on the samples of *Pinus mugo* shrubs in Krkonoše Mountains. Four sites in different elevations of Sněžka Mountain and Smogornia ridge have been chosen for analysis. It has been found, that growth of *Pinus mugo* in the vicinity of closed spruce stands differs from *Pinus mugo* growing in higher elevations. While the climate signal at upper elevations has been quite strong, the signal at lower ones has been weak pointing out that the growth there is not fundamentally regulated by climate.

The growth of shrubs at upper sites is mainly determined by temperatures of May – August period. Temperature signal at lower sites is quite mixed and unclear. The influence of precipitation differs from site to site. The importance of July precipitation has been shown at all sites except PM-Sn1500. The positive influence of snow cover during January has been shown mainly at PM-Sm1490 site where snow is easily blown away to lower parts. The positive role of April precipitation has been pronounced at PM-Cr1300 and PM-Sn1500 sites.

The important link between growth of mountain pine and PDSI has been revealed at upper sites, indicating the decline of growth in these areas in case of continuing climate warming.

Though it is assumed, that mountain pine shrubs are less sensitive to extreme cold event, it is obvious that in case of warming with the availability of precipitation the increment of TRW will increase. It can be beneficial to make some research in testing the changing of shrub TRW sensitivity with time.

If to compare the growth of prostrate *Pinus mugo* with growth of *Picea abies*, it will be seen that climate signal in pine shrubs is weaker than in spruce trees.

Climate signal obtained by usage of four different standardization methods reveal the best suitability of RCS and AVE methods for maximizing climate signal in shrubs while in spruce trees the satisfactory result has been obtained by spline detrending.

It is supposed that mountain pine as well as other shrubs species in alpine environment is well adapted to the harsh altitudinal conditions. *Pinus mugo* are less susceptible to frost event, pollution, different climate oscillations than spruce or some deciduous species. A big damage however can be made by some external disturbances as, for example, insects' outbreaks.

A lot of questions remain uncovered in the strategies of *Pinus mugo* to survive in harsh alpine conditions thus making this plant very prospective for further high altitude shrubs investigations. For example it can be very useful to make some research in temperature limits for growth of more adapted individuals as it can open some new facts in shrub strategies to withstand unfavorable growth conditions.

9 Literature

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