

THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

**Spatiotemporal Climate and Atmospheric
Circulation Variability in Asia Inferred from Tree
Rings**

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Abstract

Observed 20th century warming trends accompanied by more frequent weather extremes such as droughts or intense rainfall events have consequences for societies and environments alike. In Asia, where the majority of the population depend on agricultural productivity, recent climate change is likely to increase societal hardships. In order to quantify future climate variability, it is vital to understand past climate variability with respect to its magnitude, frequency and more importantly, its underlying physical processes. Since instrumental data scarcely extends into the pre-1950 era in Asia, annually resolved proxy data such as tree rings provide unique and continuous estimates of past climate and atmospheric circulation variability.

This thesis presents a comprehensive assessment of the relationship between tree growth and environmental factors using local to continental-scale tree-ring networks in Asia. In this regard, new tree-ring chronologies were developed for Central Asia in order to increase the spatial coverage of the existing proxy network. Analyses of five tree-ring width networks were conducted to identify the dominant climate and atmospheric circulation patterns that influence tree growth in Asia.

Based on 38 newly developed juniper (*Juniperus* sp.) tree-ring chronologies including 1069 trees from the northern Pamir-Alay and Tien Shan mountain ranges in Central Asia, the first detailed study of spatial patterns and temporal trends in species- and site-specific climate response was conducted. Our results show that juniper growth at lower elevation sites was significantly limited by drought conditions, which has increased in intensity over the past decades, hence, making those sites highly suitable for drought reconstructions. The majority of juniper trees at high elevation sites, however, showed a distinct growth-climate response shift. In the early to mid- 20th century, juniper growth was favored by warm summer temperatures, while in the most recent decades, it was negatively affected by increasing summer aridity.

By calculating a new index that represents the tree growth relevant circulation pattern at the site during the summer, it was possible to describe leading patterns of the atmospheric circulation for a regional- and a continental-scale tree-ring network in Asia. The main results indicate that pressure anomalies over northwestern Russia had a major impact on tree growth not only in continental regions but also in monsoon influenced parts of Asia. The identified tree growth relevant circulation patterns show a significant spatiotemporal resemblance to leading patterns of pressure anomalies from climate data. Furthermore, the tree growth derived circulation patterns show strong linkages to the North Atlantic sector even further back in time (as far as AD 1600), and can be linked to the Northern Hemisphere atmospheric circulation system.

The findings presented in this thesis enhance our understanding of the influence of environmental factors on tree growth in Asia. Moreover, tree rings are shown to be a highly suitable proxy for reconstructing and investigating past climate and atmospheric circulation variability in Asia.

Keywords Asia, atmospheric circulation, Central Asia, dendroclimatology, growth-climate relationship, objectively classified weather types, teleconnections, tree-ring networks.

List of publications

This thesis consists of a summary (Part I) and of five papers (Part II) referred to with roman letters within the thesis. The published articles are reprinted with permission from the respective journal.

Paper I

Seim A, Tulyaganov T, Omurova G, Nikolyai L, Botman E, Linderholm HW (2015) Dendroclimatological potential of three juniper species from the Turkestan range, northwestern Pamir-Alay Mountains, Uzbekistan. *Trees*:1–16. doi: 10.1007/s00468-015-1316-y

A. Seim initiated the paper, analyzed the data, visualized the results and had the leading role in writing.

Paper II

Seim A, Omurova G, Azisov E, Musuraliev K, Aliev K, Tulyaganov T, Nikolyai L, Botman E, Helle G, Dorado Liñan I, Jivcov S, Linderholm HW (*in press*) Climate change increases drought stress of juniper trees in the Mountains of Central Asia. *PLoS ONE*

A. Seim initiated the paper, analyzed the data, visualized the results and had the leading role in writing.

Paper III

Seim A, Schultz J, Leland C, Davi N, Byambasuren O, Liang E, Wang X, Beck C, Linderholm HW, Pederson N (*in review*) Synoptic-scale circulation patterns during summer derived from tree rings in mid-latitude Asia. *Climate Dynamics*

A. Seim initiated the paper, collected and prepared the tree-ring data, analyzed the ACTI records (provided by J. Schultz using weather types classified by C. Beck), visualized the results and had the leading role in writing.

Paper IV

Seim A, Schultz J, Beck C, Bräuning A, Krusic P, Leland C, Byambasuren O, Liang E, Wang X, Jeong J-H, Linderholm HW (*manuscript*) Evaluation of tree growth relevant atmospheric circulation patterns for geopotential height field reconstructions for Asia.

A. Seim initiated the paper, collected and prepared the tree-ring data, analyzed the ACTI records (provided by J. Schultz using weather types classified by C. Beck), visualized the results and had the leading role in writing.

Paper V

Linderholm HW, **Seim A**, Ou T, Jeong J-H, Liu Y, Folland C (2013) Exploring teleconnections between the summer NAO (SNAO) and climate in East Asia over the last four centuries - a tree-ring perspective. *Dendrochronologia*, 31(4), 297–310

A. Seim collected and prepared the data and contributed to the writing.

Selected publications not included in the thesis

Seim A, Linscott K, Heussner K-U, Bonde N, Baittinger C, Stornes JM, Bartholin TS, Linderholm HW (2015) Diverse construction types and local timber sources characterize early medieval church roofs in southwestern Sweden. *Dendrochronologia* 35: 39–50

Seim A, Kerstin Treydte K, Trouet V, Fank D, Fonti P, Tegel W, Panayotov M, Fernández-Donado L, Krusic P, Büntgen U (2015) Climate sensitivity of Mediterranean pine growth reveals distinct east–west dipole. *International Journal of Climatology* 35(9): 2503–13

Tegel W, **Seim A**, Hakelberg D, Hoffmann S, Panev M, Westphal T, Büntgen U (2014) A recent growth increase of European beech (*Fagus sylvatica* L.) at its Mediterranean distribution limit contradicts drought stress. *European Journal of Forest Research* 133: 61–71

Wolf D, **Seim A**, Faust D (2014) Fluvial system response to external forcing and human impact - Late Pleistocene and Holocene fluvial dynamics of the lower Guadalete River in western Andalucía (Spain). *Boreas* 43(2): 422–449

Wolf D, **Seim A**, Diaz del Olmo F, Faust D (2013) Late Quaternary fluvial dynamics of the Jarama River in central Spain. *Quaternary International* 302: 20–41

Seim A, Büntgen U, Fonti P, Haska H, Herzig F, Tegel W, Trouet V, Treydte K (2012) Climate sensitivity of a millennium-long pine chronology from Albania. *Climate Research* 51: 217–228

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Part II – Papers I to V

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Part I

- Synthesis -

1 Introduction

1.1 Late Holocene climate variability in Asia

Since the beginning of the 20th century, global temperatures have increased at a rate which is unprecedented in the last 1300 years (IPCC 2013). This is caused by changes in the composition of the atmosphere due to increased greenhouse gas emissions such as carbon dioxide. Just over the past century, mean annual temperatures have increased over much of Asia, while the frequency of heat waves have increased since the 1950s in large parts of Asia (IPCC 2013; Donat et al. 2013). Trends and extremes in precipitation are spatially more heterogeneous and have changed since 1950 not only in intensity but also in frequency (Donat et al. 2013). This was partly modified by the weakening of the Asian summer and winter monsoon system after 1970 (e.g., Wang 2001). Overall, the observed trends showed an increase in mean and extreme precipitation along the Yangtze River in China or in northern Asia, while India and northern China recorded a decrease in seasonal mean rainfall (IPCC 2013). It is predicted that temperatures will further rise in the future accompanied by an increase in hot extremes, decrease in cold extremes and more intense hydroclimatic events such as floods or droughts (Field 2012; IPCC 2013). This has serious implications for the population of Asia, where people not only depend on agricultural productivity in monsoon influenced regions such as in India, but where in drought-prone regions such as arid or semi-arid Asia, severe moisture deficits are likely to further contribute to significant societal hardships (e.g., Rao et al. 2015).

To understand and distinguish between natural and human-induced climate variability, it is vital to investigate long climatological records, which can be obtained from instrumental data or from proxy records. In Asia, meteorological observations rarely extend prior to 1950, thus, obtaining a more reliable overview of Late Holocene (i.e. past two millennia) climate variability constitutes a big challenge. Using proxy data, however, significant progress has been made in understanding regional and inter-regional Asian climate variability mainly for the last 1000 but also for the last 2000 years, from documentary evidence, especially from China (Ge et al. 2008) and references therein), physical archives such as speleothems (Paulsen et al. 2003; Ku and Li 1998) or ice cores (Thompson et al. 2003), and from biological archives, e.g. tree rings (Zhang et al. 2003; Liu et al. 2009). Also, different archives have been combined into multi-proxy compilations (e.g., Yang et al. 2002; Shi et al. 2015). Proxy evidence indicate that during the past ~2000 years, climate was at times anomalously warmer, e.g. during the Medieval Warm Period (~900–1350 AD) (Lamb 1965), or anomalously colder, e.g. the Late Antique Little Ice Age (536–660 AD) (Büntgen et al. 2016) or the Little Ice Age (1400–1900 AD) (Grove 1988), than at present. Yet, those long-term climate anomalies caused spatially different regional climate conditions within Asia (Chen et al. 2015; Graham et al. 2011; Shi et al. 2015) and had different temporal manifestations (onsets and durations) around the globe (e.g., PAGES 2k Consortium 2013). This implies that the climate system, i.e. the interaction between the atmosphere, hydrosphere, cryosphere, lithosphere and biosphere, has been changing before

human interference. Graham et al. (2011) showed that regional climate differences during the Medieval Warm Period in Asia and other regions were caused by changes in the large-scale Northern Hemispheric atmospheric circulation that were attributed to a warming of the Indian and western Pacific tropical ocean. However, even with today's existing proxy based climate reconstructions and climate model simulations, the nature and causes of climate change throughout the Late Holocene remains not yet fully understood.

Therefore, further endeavors are necessary to increase the number of annually resolved paleoclimate proxy records to fully elucidate the spatiotemporal complexity and evolution of climate and associated atmospheric circulation variability. Moreover, it is not only important to understand the natural range of historical climate variability but also the response of the climate system to an increased radiative forcing due to greenhouse gas emissions. This is shown to be one of the major source of uncertainty in climate model simulations (Shepherd 2014). It is therefore vital to investigate not only annual but also seasonal variations and associated patterns of climate and circulation variability to improve our understanding of the nature of the processes in the climate system. For example, Horton et al. (2015) were able to partially contribute past temperature extremes during the warm season to an increased occurrence of anticyclonic conditions over parts of Eurasia. Additionally, assessments of the impacts of recent climate change on ecosystems and humans alike, is essential to improve predictions and adaptation strategies (Hansen and Cramer 2015).

1.2 Tree rings and climate in Asia

Tree rings are the most frequently used terrestrial paleoclimate proxy due to their high temporal resolution (annual), broad and dense spatial distribution, and compared to other archives, easy to access. In the extra-tropics, where trees develop annual rings due to the seasonal periodicity of growth processes (Vaganov et al. 2006), the radial increments are strongly influenced by weather conditions during the growing season of previous and current years (Fritts 1976). The science of dendroclimatology makes use of the climate information recorded in tree rings by studying the present growth-climate relationship to reconstruct past climate variability (Kaennel and Schweingruber 1995). This ability, however, relies on the principle of 'uniformity' (Fritts 1976) that assumes that the growth-climate relationship is stable over time. Yet, the climate information stored in the variations of tree growth depends on the sites where the trees are growing. Tree growth at or close to its species distribution limit, is generally limited by a small number of climate variables: low temperature and a short growing season at high altitudes and latitudes, and low precipitation and high temperatures at low altitudes and latitudes (Fritts 1976). Thus, tree rings provide not only a continuous record of environmental factors that influence the tree during its life time but also chronological control (i.e. by matching sequences of wide and narrow tree rings from different trees to assign each ring to its calendar year). Moreover, different parameters can be used from tree rings such as tree-ring width, latewood density or isotopic composition (e.g., Kirilyanov et al. 2008). Thus, our understanding

of temporal and spatial climate variability can be extended further in the past than with instrumental data by using the growth-climate relationship and the development of local site chronologies or even large tree-ring networks.

In Asia, the number of dendroclimatological studies have rapidly increased over the past decades. Climate reconstructions based on tree rings have been developed on different spatial scales, ranging from local (Pederson et al. 2001; Wiles et al. 2015; Liu et al. 2013; Song and Liu 2011), regional (Bräuning and Mantwill 2004; Krusic et al. 2015; Liang et al. 2008; Shao et al. 2005), continental (Cook et al. 2010; Shi et al. 2015) and hemispheric (e.g., Briffa 2000; Wilson et al. 2016). Moreover, the high diversity in climate and topographic features in Asia, has allowed the inference of temperature variability from high altitude (Solomina et al. 2014; Liu et al. 2009; Liang et al. 2008; Davi et al. 2015) and latitude (Hantemirov and Shiyatov 2002; Briffa et al. 1995) regions. Also, numerous reconstructions of hydroclimatic variability including drought were developed from areas, where moisture availability is limiting tree growth in semi-arid to arid environments (e.g., Fang et al. 2011; Pederson et al. 2014).

However, more research is needed, especially for Central Asia, where the impact of climate on juniper, compared to other species, has been shown to be less clear (Graybill et al. 1992; Esper et al. 2003). Also to date, limited attention has been paid on identifying large-scale atmospheric circulation patterns in parts or in the whole of Asia using proxy data compared to Europe and the Atlantic sector (e.g., Luterbacher et al. 2002). These issues will be addressed in this thesis. The recent progress in dendroclimatology as well as the newly developed tree-ring data from this work, provides a solid envelope to study the spatiotemporal climate variability in Asia and to gain a better understanding of the relationship between tree growth, climate and atmospheric circulation patterns.

1.3 Aims and objectives

This thesis presents a comprehensive assessment of climatic and atmospheric circulation variability that influence tree growth in Asia, its spatiotemporal characterization, and its connection to the climate system in the Northern Hemisphere. The overall aim of the thesis is to contribute to an enhanced understanding of the growth-climate relationship and of the climate system in Asia. This would improve the validation of climate model simulations and to make more accurate predictions of future climate. This would allow for the development of suitable adaptation strategies for ecosystems and societies alike.

The specific objectives of the thesis are

- i) to develop new tree-ring chronologies for Central Asia and increase the spatial coverage of the proxy network for Asia;
- ii) to identify local/regional climate signals in juniper trees in Central Asia;
- iii) to identify tree growth relevant synoptic-scale circulation patterns in Asia;
- iv) to assess the spatiotemporal characteristics of the identified climate and atmospheric circulation patterns.

This summary aims at highlighting the main findings of **papers I to V**, which are then placed in a larger context. For detailed descriptions of the methods and discussion of the results, please see the individual papers. Moreover, each of the above mentioned objectives were to a different extent considered in the individual papers.

In **paper I**, species and site-specific climate responses of newly sampled juniper tree-ring data from one region in Uzbekistan were investigated, common extreme growth years were identified, compared, and attributed to climate modes at a regional scale.

Paper II focused on the assessment of the climate sensitivity to current climate change of a newly developed juniper tree-ring network from the northern Pamir-Alay and Tien Shan mountains, Central Asia.

Tree growth relevant synoptic-scale circulation patterns were derived from a multi-species tree-ring network developed for mid-latitude Asia (**paper III**) and for Asia (**paper IV**), which were explored regarding their spatiotemporal characteristics.

In **paper V**, tree ring data and climate reconstructions from eastern Asia were investigated for their potential to extend teleconnection analyses prior to the period of instrumental data (pre-1950).

2 Background

2.1 Study area

Asia is the Earth's largest continent, spanning east from the Ural and Caucasus Mountains and the Caspian and Black Seas to the Pacific Ocean. It is bounded by the Arctic Ocean in the north and the Indian Ocean in the south. Asia comprises 30% of the world's total land mass and 60% of the world's total population (4.4 billion people; World Population Review 2015).

Climate in Asia is diverse and can be divided into three major climate zones: the continental climates of Siberia and Northeast Asia; the arid and semiarid climates of Central Asia and mid-latitude Asia; and monsoon influenced East and South Asia (Köppen 1900; updated by Kottek et al. 2006). Seasonal variations in climate increase from the south (tropical) to the north (high-latitude) in Asia, with the greatest variation in Siberia, due to the unequal distribution of incoming solar radiation. Moreover, regions close to the oceans experience maritime influences. Overall, the local and regional character of Asia's climate is influenced by the atmospheric circulation, i.e. the origin and modulation of air masses as well as their interaction along fronts (Lydolf 1977; Takahashi and Arakawa 1981). An overview of the origin of the dominant air flows is given in Figure 1.

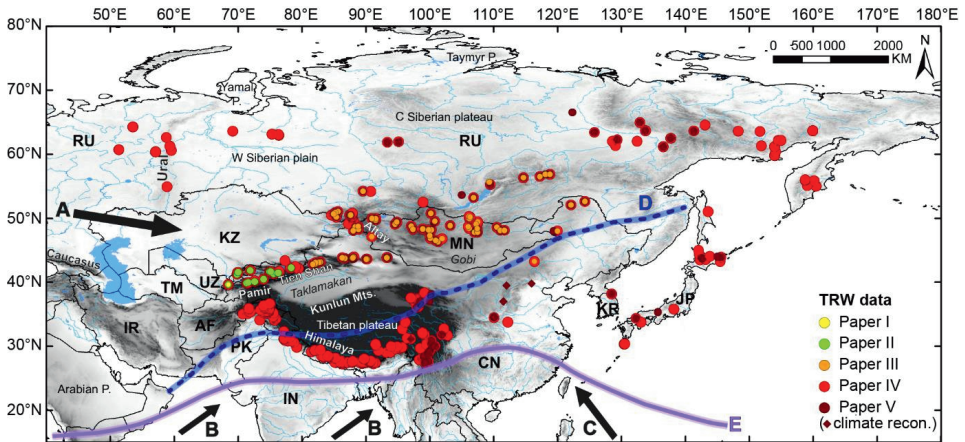


Figure 1 Research area and location of the tree-ring sites used in *papers I to V* (see legend). *A* denotes westerly winds, *B* indicates the Indian summer monsoon, *C* the East Asian summer monsoon, *D* the modern Asian monsoon limit (combined from Chen et al. (2008), Yancheva et al. (2007)) and *E* the summertime location of the Intertropical Convergence Zone (ITCZ). Country names are coded following the international standard.

Weather conditions during winter are closely linked to the Siberian high, which is centered over Lake Baikal, causing strong northerly winds and extreme low temperatures in Eurasia (Perry 1971; Sahsamanoglou et al. 1991; Böhner 2006).

During summer, three major zones of cyclonic activity influence Asia: the Asiatic Polar Front extending in an east-west direction across northwestern Siberia along the 70°N latitude, the Asian Polar Front extending from Central Asia (i.e., Kazakhstan) over Mongolia to northeastern China along the 50°N latitude causing anticyclonic cells between 50°N and 55°N, and the South Asian Intertropical Front (i.e., ITCZ) (Dando 2005). The latter reaches the 25°N parallel in China during summer (Fig. 1) and merges with the by then developed, deep Southwest Asian low-pressure system over Pakistan and northeastern India. Between those fronts, the Polar jet (following often a meandering course) and the Subtropical jet stream are developed, although the latter slowly weakens in May, disintegrates in June, and causes the westerlies to flow north into Central Asia.

Besides a high diversity in regional climates, Asia has a high topographical variety (Fig. 1). The continent comprises numerous mountain systems, such as the Ural, Pamir, Himalaya, Tien Shan, the Altay and associated plateaus (Tibetan or central Siberian plateau), basins (e.g., Tarim), and lowlands (e.g., West Siberian plain). Thus, regional climate is influenced by surface features, which in turn exerts influences on the atmospheric circulation, especially the Tibetan plateau (Duan et al. 2012; Park et al. 2012).

It should be noted that within this thesis, the term Central Asia (used in **papers I, II and IV**) refers to the five post-soviet republics of Uzbekistan, Kazakhstan, Kyrgyzstan, Tajikistan and Turkmenistan. However, in broad geographical terms, it further includes Afghanistan, Mongolia, and parts of Iran, China, Pakistan, India as well as southwestern Siberia.

2.2 Atmospheric circulation, climate and tree rings

Large-scale atmospheric circulation systems (e.g., cyclones and anti-cyclones) and surface characteristics influence local and regional climate (Barry and Perry 1973; Plaut and Simonnet 2001). Generally, climate is defined as long-term average (30 or more years) of short-term atmospheric conditions, i.e. weather. Since topographic features do not change rapidly in space and time, local to regional climate conditions are associated with changes in properties and behavior of large-scale atmospheric circulations; a relationship called synoptic climatology (Barry and Carleton 2001; Yarnal 1993).

Climatologists characterize the large-scale atmospheric circulation by calculating indices that can be related to changes in climate at the surface. For example, one large-scale circulation pattern that influences weather and climate variability in Europe and in the Northern Hemisphere is the North Atlantic Oscillation (NAO) (Hurrell et al. 2003). The corresponding NAO index is based on the pressure difference between the Icelandic low-pressure and Azores high-pressure system. Another important component of the atmospheric circulation is the El-Niño Southern Oscillation (ENSO), which is measured in different ways. For instance, ENSO indices were derived 1) from sea surface temperatures from the east-central tropical Pacific Ocean, e.g. Nino3.4 index (Barnston et al. 1997), or 2) from differences in sea level pressure

between e.g. Tahiti and Darwin, the so-called Southern Oscillation index (Walker and Bliss 1932). However, other approaches are applied in describing and classifying synoptic circulation patterns depending on the spatial (local to global) and temporal scale (1 day to 1 week or more) (Perry 1983). One of the most important approaches is the classification of the position of large-scale pressure systems, i.e. weather types. These weather-type classification schemes can be done subjectively, where meteorological data are manually grouped into distinctive types. Such a classification of large-scale weather patterns was developed for Germany using mean pressure distributions at sea level that remained unchanged over several days (Hess and Brezowsky 1969; Werner and Gerstengarbe 2010) and termed Großwetterlage. Similar work was done by Elliott (1951) for the United States, Vangengeim (Vangengeim 1952) for the Arctic, and Girs (1971) for the Northern Hemisphere. Alternatively, large-scale weather patterns can be classified objectively by using, for example, multivariate methods (i.e. principal component or empirical orthogonal functions analysis) on atmospheric pressure data. It should be noted that subjective weather-type classifications are largely lacking for Asia. We therefore applied an objective classification scheme.

Tree growth is influenced by local to regional climate conditions. However, human impact (e.g., livestock grazing, logging), stand dynamics (i.e. competition) and other abiotic and biotic disturbance factors can affect radial growth and dampen the strength of the climatic signal (Fritts 1976). To maximize the climate information, all those factors need to be minimized. Choice of tree species, sampling site (altitude, species distribution range), replication (number of samples), measured parameter (e.g., ring width, maximum density or isotopic composition) and standardization method need to be considered to successfully extract the climate information. While trees at the site best reflect the local climate, the compilation of sites, i.e. establishment of tree-ring networks, is beneficial for investigating regional climate, and if possible atmospheric circulation patterns. Tree rings and other proxies are frequently used to reconstruct atmospheric circulation indices, e.g. the winter NAO mode (Trouet et al. 2009) and summer NAO mode (Linderholm et al. 2009), ENSO (e.g., Michaelsen 1989; Li et al. 2013) or Pacific Decadal Oscillation (D'Arrigo et al. 2001). Contrary to atmospheric circulation indices, however, the usage of weather types allows for a more comprehensive description of atmospheric circulation patterns. One of the early studies was done by Fritts et al. (1970), who systematically explored the growth-climate relationship using multivariate statistics, i.e. canonical correlation analysis, on a tree-ring network and surface pressure anomalies from western North America, and reconstructed variations in the atmospheric circulation back to AD 1700. Since then, only a few attempts have been made that directly relate tree growth or oxygen isotope ratios from tree rings to continuous records of large-scale weather patterns (e.g., Saurer et al. 2012). More recently, Schultz and Neuwirth (2012) developed a method that links tree growth with large-scale weather patterns to investigate the atmospheric circulation signal in tree rings for Europe and northern Africa. This method was applied in this thesis for trees in Asia.

3 Materials and methods

Different tree-ring width (TRW) datasets as well as climate data were utilized in this thesis ranging from single-species (**papers I and II**) to multi-species tree-ring networks (**paper III, IV, and V**) (see Appendix). Also different climate data were used such as meteorological station data (**paper I**), latest versions of high-quality interpolated grid point data from the Climate Research Unit (CRU) (Mitchell and Jones 2005; Harris et al. 2014) (**papers I, II, IV and V**), and reanalysis data (NOAA-CIRES 20th century; Compo et al. 2011) (**papers III and IV**). In **paper V**, climate reconstructions were additionally used to complement the spatial coverage of the proxy network (see Table 2 in **paper V**). In Figure 1, the individual data tree-ring networks are shown, while Table 1 provides additional information of the individual study areas, utilized data and period of investigation.

Table 1 Overview of the specific objective, spatial scale, covered region, tree-ring width (TRW) and climate data, and time period used in the individual papers.

Paper	Focus of the study	Spatial scale	Spatial domain	TRW sites (n)	Climate data	Period of investigation
I	Species- and sites specific climate response of juniper	Local	Zaamin National Park, UZ (~39.61°N, ~68.50°E)	8	Shahristanskii station; CRU TS3.21	20 th century
II	Climate response of juniper	Regional	Northern Pamir-Alay & Tien Shan Mountains (UZ, KG) (68.49–78.37°E, 39.63–42.24°N)	33	CRU TS3.22	20 th century
III	Weather-type response of a multi-species TRW network	Regional	Mid-latitude Asia (40–60°N, 80–130°E)	78	20 th century reanalysis data	1871–1993
IV	Weather-type response of a multi-species TRW network	Continental	Asia (25–65°N, 50–165°E)	414	20 th century reanalysis data, CRU TS3.23	1871–2010
V	Teleconnection pattern between SNAO and Asian climate	Continental	Asia (27–66°N, 81–145°E)	106 plus 10 climate reconstructions (various proxies)	CRU TS2.1, Nino 3 index from HadSST1; reconstructed SNAO and DJF Nino 3	1601–1978

3.1 Tree-ring data

The majority of the TRW data was obtained from the International Tree-Ring Data Bank (ITRDB; <https://www.ncdc.noaa.gov/data-access/paleoclimatology-data/datasets/tree-ring>). However, sampling was also conducted in Kyrgyzstan (KG) and Uzbekistan (UZ), Central Asia, to 1) improve the existing tree-ring network and 2) extend existing TRW chronologies in Central Asia further back in time and into the most recent period, namely those from Graybill

et al. (1992) and Esper et al. (2002). Main focus was given on juniper (*Juniperus* sp.), since 1) this species can reach ages of up to 2000 years (Mukhamedshin 1977; Esper 2000), 2) it is the dominating species in the Pamir-Alay and western Tien Shan Mountains, and 3) tree-ring data from other species such as spruce (*Picea schrenkiana* Fisch. & C. A. Mey.) or walnut (*Juglans regia* L.) were thoroughly investigated by other research groups. However, two walnut sites were sampled in the Sari Chelek region, KG, and the longer TRW chronology covering the period 1816–2012 is included in **paper IV**. A short description of the sampling and TRW measurements for juniper in Central Asia is given below.

3.1.1 Sampling and ring-width measurements

During 2012 and 2013, 1069 juniper trees were sampled at 38 sites ranging from 1267 to 3020 meters above sea level (m asl) within the 68.49°–78.37°E and 39.63°–42.24°N domain (Fig. 2).

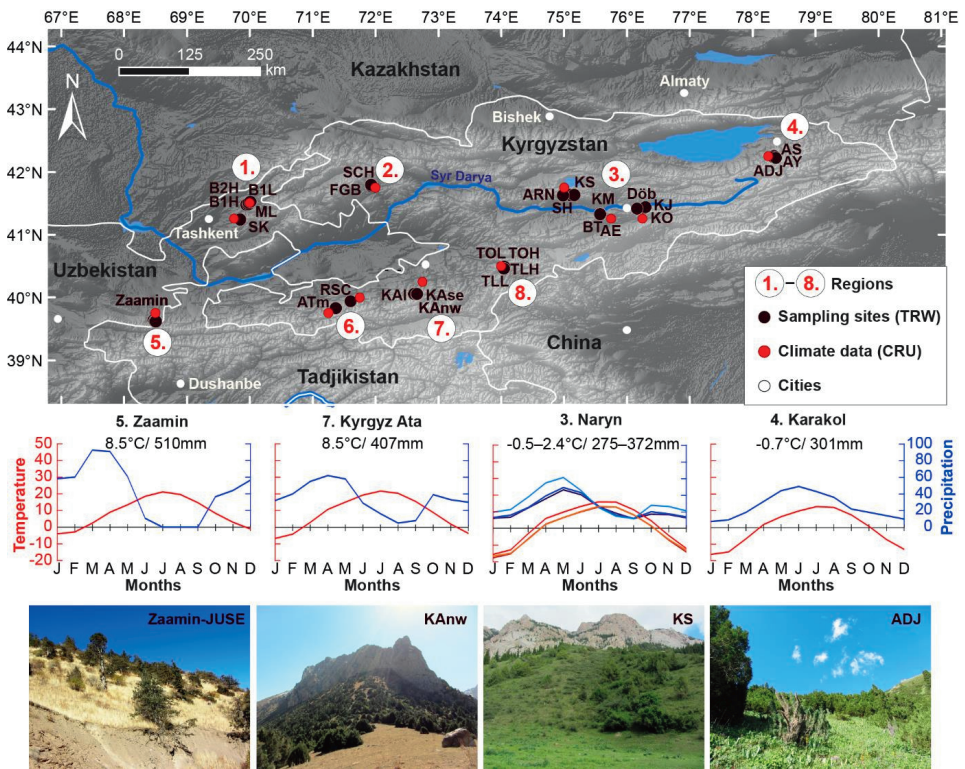


Figure 2 Juniper sampling sites (black dots) and closest CRU grid point data (red dots) from eight regions (1 = Chimgan; 2 = Sari Chelek; 3 = Naryn; 4 = Karakol; 5 = Zaamin; 6 = Khaidarkan; 7 = Kyrgyz Ata; 8 = Karakuldja) in Uzbekistan and Kyrgyzstan. Continental climatic conditions dominate the study area throughout the year as shown for absolute annual (numbers) and monthly temperature means and precipitation sums (red and blue lines), averaged over the period 1961–1990. (Modified Figure 1 from **paper II**)

The sampling was conducted in eight sub-regions located in the northwestern (Zaamin, UZ), northern (Khaidarkan and Kyrgyz Ata, KG) Pamir-Alay, western (Chimgan, UZ; Sari Chelek, KG) and the central (Karakuldja, Naryn and Karakol, KG) Tien Shan mountain systems stretching from west (eastern UZ) to east (all of KG) (Fig. 2).

Juniper sites were selected close to or at the local upper and lower tree lines (supporting information Tab. S1 in **paper II**) to get a better understanding of juniper climate responses along elevational gradients. In the Zaamin National Park, UZ, the juniper subspecies, which largely follow an altitudinal zonation from low to high: *J. seravschanica* Kom. (JUSE), *J. semiglobosa* Regel (JUSM) and *J. turkistanica* Kom. (JUTU), were identified for all trees based on their morphological features (Adams 2011) (**paper I**).

At each site, a minimum of 30 trees were sampled by extracting two cores per tree using 5 mm increment borers (Fig. 3). After preparation of the cross-section of each core and visual crossdating, ring-width variations were measured with an accuracy of 0.01 mm using the LINTAB 5 measuring station and TSAPwin program (Rinn 2003). The quality of the crossdating was statistically verified using the COFECHA software (Holmes 1983).



Figure 3: Sampling of juniper trees at different sites (from left to right): lowest site (SBI) in Zaamin National Park, UZ; steep and rocky site in Shabyr (SH1) in Naryn, KG; sample taken from one of the oldest trees in Kashka Sun, Naryn, KG; humid site Asantur (AS) in Diety-Ogыз, Karakol, KG. Sampling was conducted with support from Kyrgyz colleagues (pictured here Gulzar Omurova (left) and Erlan Azisov (right)) and local foresters.

3.1.2 Tree-ring standardization and chronology development

For the development of the individual site TRW chronologies (data sampled in Central Asia as well as data obtained from the ITRDB), climate unrelated but biological induced growth trends due to age and size of the trees (so-called age trends) were removed. This procedure involves the standardization (detrending) and transformation of each raw TRW series into dimensionless indices. Different statistical models can be applied to detrend raw ring-width measurements using the software ARSTAN (Cook and Krusic 2005), depending on the amount of low-frequency variance aimed to be preserved. In this thesis, cubic smoothing splines (Cook and Peters 1981) with 32-year (**paper IV**), 100-year (**paper I**), 150-year (**paper III**) filter lengths,

flexible age-dependent splines (Melvin et al. 2007; **paper II**), and negative exponential and linear regression curve fits (**paper V**) were applied for preserving inter-annual, decadal and multi-centennial frequencies, respectively.

Additionally, in **papers I to IV** biases caused by temporally uneven sample replication were eliminated by applying a power transformation (Cook and Peters 1997) to each raw TRW series and dimensionless indices of tree growth were computed as residuals prior to detrending. The variance of each final site chronology was stabilized (Osborn et al. 1997) based on the interseries correlation (R_{bar}) (Wigley et al. 1984). The final stabilized and detrended TRW indices were used and chronologies were subsequently generated as robust biweight means.

Each TRW chronology was truncated at a minimum sample size of $n(i) < 5$ series. The R_{bar} , representing the degree of coherency between the series, and the expressed population signal (EPS) (Wigley et al. 1984), a measure for the common signal strength of a chronology, was used to evaluate the quality of each TRW chronology.

3.2 Climate data

To draw robust conclusions about climate and atmospheric circulation variability and how and to which extent trees responded to changes, long time series of climate variables are essential (e.g., Hoy et al. 2013). As stated above, most meteorological stations started operating in Asia in the 1950s and in some regions not until the 1960s, e.g. Tibetan Plateau (Liu et al. 2015). An exception is Central Asia (region defined in chapter 2.1), where quite numerous long, in some cases back to 1879, meteorological station data exists (Williams and Konovalov 2008).

To quantify growth-climate relationships, climate data close to the sampling sites are needed. In **paper I**, the closest meteorological station to the sampling sites (11 km linear distance) was utilized covering the 1950–1992 period. To extend the time period, however, high-quality interpolated data from the Climate Research Unit (CRU) (Mitchell and Jones 2005; Harris et al. 2014), covering the 1901–2012 period, were also included in the analyses (in **papers I, II, and IV**). The CRU data is a high-resolution ($0.5^\circ \times 0.5^\circ$), monthly resolved compilation of gridded climate indices including temperature, precipitation, drought index, cloud cover and other climate variables.

Even longer time periods (1871–2010) can be covered by using NOAA-CIRES 20th century reanalysis data, which are spatial and temporally interpolated data from surface pressure observations (Compo et al. 2011). This dataset also includes different climate variables. In **papers III and IV**, this dataset was used to generate objective weather-type classifications for different 2° by 2° gridded geopotential height data (see **papers III and IV** for further details) and to describe the identified synoptic-scale circulation patterns and surface climate conditions.

3.3 Atmospheric circulation tree-ring index (ACTI)

In **papers III** and **IV**, atmospheric circulation tree-ring indices (ACTI) were calculated using a recently developed procedure by Schultz and Neuwirth (2012). Within this procedure, the associations between weather types and tree growth are modelled for each TRW chronology using Monte Carlo simulation with one million simulation runs, 60 discontinuous selected calibration years (over the period common to the proxy data), and several selection steps (e.g., reduction of outliers etc.). The complex calculation procedure of the ACTI is explained in detail by Schultz and Neuwirth (2012) and in **paper III**.

In this thesis, the extracted weather-type signal from tree rings were computed solely for the summer (June–August) season. Therefore, the values of the ACTI time series are defined as June–August sums of the weighted weather-type frequencies during e.g., the period 1871–1993 (see Figs. 4 and 6 in **paper III**). The weights represent the influence of each weather type on tree growth. Thus, each ACTI record represents growth variations with positive/negative ACTI values denoting favorable/unfavorable tree growth conditions.

3.4 Statistical analyses

To achieve the above mentioned objectives, different statistical methods were used to quantify the relationship between atmospheric circulation, climate and tree growth.

3.4.1 Linear trend analysis

To investigate the relationship between tree growth and climate, Pearson correlation statistics were used (**papers I** to **V**). The correlation coefficient (r) indicates the strength of the relationship, in this case between the TRW data and climate parameters for a given period. Statistically significant growth-climate relationships, exceeding at least the 95% significance level, were evaluated for its temporal stability by applying running correlations of different window lengths (e.g., 31-year windows).

Regression analysis were used to summarize the linear relationship between two variables, for example TRW variations and climate variables (**paper I**) or elevation and climate response (**paper II**).

3.4.2 Multivariate statistics

Principal component analysis (PCA) (Jolliffe 2002), also called empirical orthogonal function (EOF), was used to create a new set of variables (principal components (PCs)) that explain a maximum amount of common variance of a larger dataset (e.g., proxy or climate data). Those components are linearly uncorrelated with each other and are created by using an orthogonal transformation. The transformation rotates the axes of common variation so that they are orthogonally (i.e. perpendicular) aligned and are ordered with decreasing proportion of variance.

Hence, the first PC contains the highest variance and thus, explains most of the variability of the dataset. Generally, PCs with an eigenvalue greater than one were used for further analyses. Additionally, the loadings of each variable (e.g., TRW chronology) on the PC was used because they indicate the strength of variation in a variable that is explained by the component. A PCA was used in **papers III** and **IV**.

In **paper I**, a redundancy analysis (RDA) (Legendre and Legendre 1998) was used, which is based on linear regression and computed using PCA. It shows linear dependencies between the response (TRW chronologies) and explanatory (climate) variables for n samples (years). Each RDA result was tested for statistical significance of the orthogonal (canonical) axes using a Monte Carlo permutation test with 999 random permutations (Legendre et al. 2011). The resulting correlation biplots show different lengths of arrows (vectors), which correspond to the strength of influence of the climate data on the TRW sites, while their direction indicates the sign of correlation.

3.4.3 Extreme year analysis

To investigate causes of extreme growth years, low frequency variations were removed from the time series (here, TRW or ACTI records). This was done using smoothing splines of 10-year filter lengths and years that exceed values of ± 1.5 the standard deviation of the high-pass filtered records were investigated. This method was applied in **papers I** and **III**.

3.4.4 Spatial analysis

The spatial patterns of the identified growth-climate (and growth-weather pattern) relationship was investigated by generating spatial field correlation or composite maps using the KNMI climate explorer (<http://climexp.knmi.nl>; Van Oldenborgh and Burgers 2005). This was done in **papers I, III**, and **IV**.

In **paper II**, the Geographical Information System (GIS) was utilized to map differences in climate, tree growth and climate response between two selected 30-year periods. The ArcMAP 10.1 software (ESRI 2011) was used to estimate areas with no data coverage by an inverse distance weighted (IDW) interpolation technique (Burrough and McDonnell 2011). This method fills missing cell values using a distance-weighted average of neighboring points. The power parameter p defines the influence of the weights. We used twelve neighboring points and $p = 2$, to give higher weights to closer points and a more rapidly decreasing weight to distant points.

4 Results and discussion

4.1 Species- and site-specific climate response of juniper in Uzbekistan

In **paper I**, the species- and site-specific growth-climate relationship of three juniper species from eight sites was investigated from a total of 107 trees including 158 annually dated samples (Fig. 1 and Tab. 1 in **paper I**). This information is vital for the development of TRW chronologies including either solely the same species or different species (i.e., composites) as was done by Esper (2000). Moreover, the influence of topography (aspect, slope) and altitude on the signal strength of the juniper species is important for the development of high quality climate reconstructions. Results showed different climatic responses for the three analyzed juniper species (JUSE, JUSM, JUTU). JUSE, inhabiting lower elevations (Adams 2011; Botman 2008), showed a significant and temporally stable response to April–September drought for the lowest sampling site (SBI) as well as the composite JUSE chronology (Fig. 4a, b). The spatial coverage of the drought signal was regional and covered the southern Central Asian region (Fig. 4c).

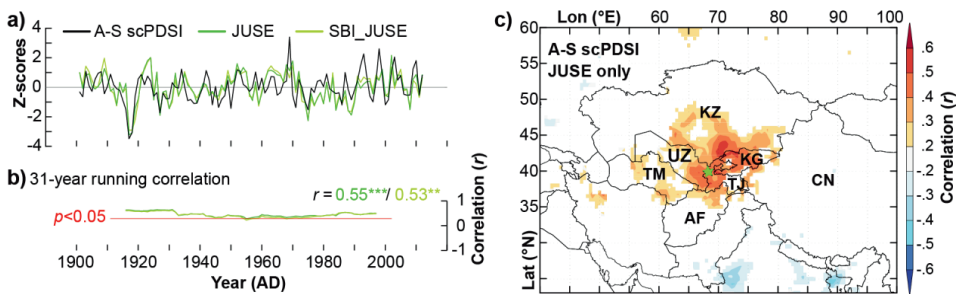


Figure 4 Comparison between **a)** SBI, JUSE and JUSE composite TRW chronology and gridded drought (scPDSI) data (April–September; CRU TS 3.21), its **b)** temporal coherency using a 31-year running correlation and **c)** the spatial extent of the correlation for the AD 1901–2012 period, respectively. The 99% (99.9%) significance level for Pearson correlation coefficients (r) is denoted by two (three) stars. (Modified figure 7 from **paper I**)

This result concurs with the general assumption that drought is the main limiting factor of ring formation at lower elevation (Fritts 1976; Tranquillini 1964). The climate signal for JUSM was more diverse due to its intermediate position between the low-elevation JUSE and high-elevation JUTU zones but JUSM seemed to cluster with JUTU by sharing a positive, though weak, influence of higher summer temperatures on tree growth (Figs. 5 and 6a in **paper I**). The growth of JUTU trees, sampled at the highest elevations in the study area, was favored by warm spring and summer temperatures. Similar findings were obtained for KG (Esper et al. 2002) and high mountain regions in Asia (e.g., Bräuning 1994; Fan et al. 2009). However, a temporally stable relationship between TRW from JUTU and summer temperatures was not found. This could be due to 1) that trees were not sampled at the local tree line, which is generally at 3000 to 3500 m asl in Central Asia (e.g., Botman 2008), 2) closer meteorological station data should

be used, or 3) growth-climate response has shifted as a result of the observed 20th century warming.

The number of identified extreme growth years for the three species reflected the strength of the climate sensitivity, where a high number of extreme years indicate higher climate sensitivity and vice versa. This was the case for JUSE (Tab. 2 in **paper I**). However, extreme growth years that were common to all species, and thus likely controlled by large-scale atmospheric circulation patterns, were found in 1916 and 2002 for positive growth and 1917, 1918, and 2001 for extreme suppressed juniper growth. Synoptic climate conditions for those years was presented and discussed in **paper I**. The year 1917 is interesting, where tree growth was extremely low in the Tien Shan Mountains (Chen et al. 2013; Esper et al. 2002; Solomina et al. 2014) and northern Iran (Pourtahmasi et al. 2007), caused by an anomalous high pressure system over Central Asia and the Mediterranean Basin (Fig. 8b and d in **paper I**). We found that JUSE from low elevations is suitable for April–September drought reconstructions in this area, however, more samples are needed to extend the TRW chronology further back in time. Additionally, our analyses show the importance of the large-scale circulations on regionally expressed extreme growth events and that such events can be connected across the European Mediterranean region, Central Asia and China (Tab. 2 in **paper I**).

4.2 Increased drought stress of juniper in Central Asia in recent decades

In **paper II**, a total of 1882 cores from 1069 trees, sampled at eight regions from the northern Pamir-Alay and Tien Shan Mountain system in Central Asia (Fig. 2; supporting information Tab. S1 in **paper II**), were subjected to a detailed analysis of spatial trends and patterns in recent juniper growth and climate response. This was done to identify 1) the site-specific (along altitudinal gradients) and regional-specific (along an east-west transect from eastern UZ to eastern KG) dendroclimatological potential, and 2) if the temporal instability in the climate signal of JUTU was limited to only a few sites as observed for UZ (**paper I**) and western Tien Shan (Esper et al. 2002).

Over the full 1935–2011 period, the growth-climate relationships of the juniper sites generally showed benefiting effects on tree growth from warm temperatures at high altitudes and abundant moisture supply at low elevation sites (Fig. 2 in **paper II**). This agrees with the general assumption of limiting factors on tree growth (Fritts 1976). Although the temperature signal in the juniper TRW data was not as strong and statistically significant as, for example, in conifers from tree-line sites in the European Alps (Büntgen et al. 2005; Büntgen et al. 2006a) or the Tibetan Plateau (Liang et al. 2008; Bräuning and Mantwill 2004), our results are in accordance with findings from earlier studies in KG (e.g., Graybill et al. 1992) and UZ (Glazirin and Gorlanova 2005).

To investigate the low number of statistically significant temperature sensitive high elevation sites, averages of climate (Fig. 3 in **paper II**), annual increments (Fig. 4 in **paper II**) and

growth-climate responses (Fig. 5) between 1935–1964 and 1982–2011 were compared. Period differences were mapped for the entire region and as a function of elevation.

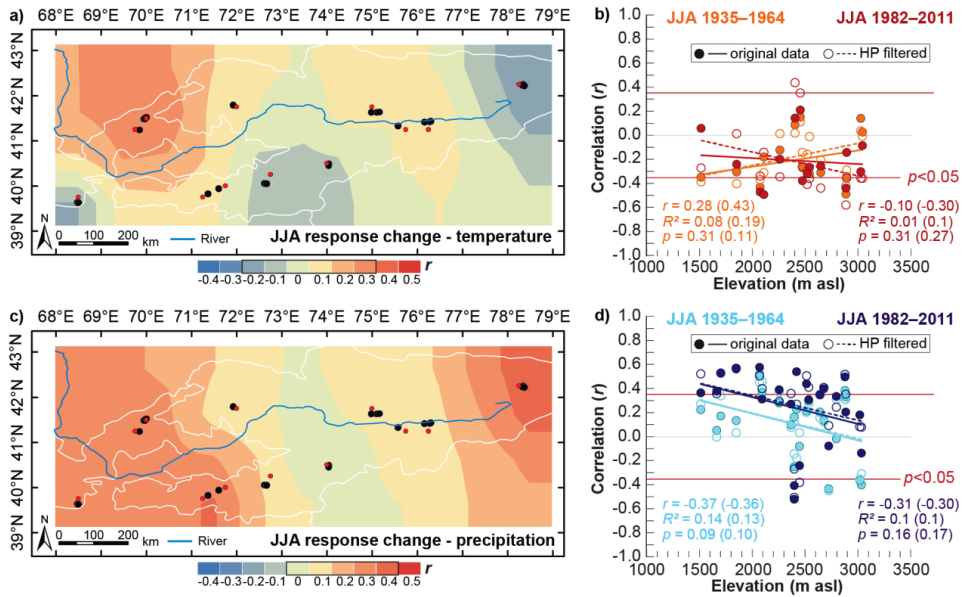


Figure 5 Changes in climate response for the June–August (JJA) season of all 33 sites (black dots) with its closest CRU grid point dataset (red dots) from the 1935–1964 to 1982–2011 period. Differences in **a**) temperature and **c**) precipitation response were spatially interpolated. TRW sites with significant correlations for one of the periods are shown as a function of elevation for **b**) temperature (15 sites) and **d**) precipitation (22 sites) with the unfiltered and filtered (see legend and numbers in brackets) data. (Figure 5 from **paper II**)

From 1935–1964 to 1982–2011, we found a maximum temperature increase of 2.4°C for winter and 1.1°C for summer in eastern KG. Winter rainfall increased by 56 mm in eastern UZ whereas smallest changes were observed in summer. These findings are in accordance with previous studies (Aizen et al. 1997; IPCC 2013). However, juniper growth varied from site to site and overall growth trends were less obvious and uniform. This could be related to different climate regimes across the study area, where our easternmost and humid sites in KG even benefited from increasing temperatures and decreasing precipitation amounts during summer (Fig. 3b and d in **paper II**). However, regarding the importance for reconstructing past climate variability, we were able to show that junipers at low elevation sites increased their climate sensitivity to drought during summer and the entire growing season (Fig. 5). At the highest elevation sites, however, juniper growth was favored by high summer temperatures during the early 1935–1964 period, but was limited by increasing drought conditions during the past 30 years (Fig. 5). Shifting growth-climate responses have also been detected at high elevation conifer sites in Europe (e.g., Büntgen et al. 2006b; Carrer and Urbinati 2006), restricting the development of temperature reconstructions, and in North America (Salzer et al. 2014).

4.3 Tree growth relevant synoptic-scale circulation patterns in Asia

We tested the application of the new ACTI method developed by Schultz and Neuwirth (2012) for a smaller TRW network located in mid-latitude Asia (**paper III**) and for the whole of Asia (**paper IV**) (Fig. 1) for the summer season. The objective weather-type classification showed that during summer, the most frequent weather types at lower levels (i.e. 1000 hPa) had in common a low pressure system of varying intensity and spatial extent over northwestern China and southern Mongolia (Fig. 3 in **paper III** and supporting information Fig. S3a in **paper IV**). Thus, resulting type-specific synoptic configurations lead to varying prevailing wind directions over the target region between North, Northeast and Southeast. At upper levels (700 to 500hPa), however, westerly winds prevailed over the study area caused by a high pressure system over Central and Southwest Asia (supporting information Fig. S3d in **paper IV**). This is in accordance with the general climatology described for Asia (see chapter 2.1). The resulting ACTI time series, which incorporated the prevailing weather-type frequency on tree growth, showed clear results for both the smaller and larger TRW network.

For mid-latitude Asia, we found that three major atmospheric circulation modes (or patterns) reflected the climatic influence on tree growth at sites with distinct biogeographic characteristics (Figs. 5 and 7 in **paper III**). The dominant mode (70% explained variance in the ACTI network of 25 sites) represented tree growth of mainly drought sensitive sites and enhanced growth was associated with below-normal pressure anomalies at 500 hPa geopotential height developed over northwestern Russia. A similar circulation pattern, although more westwards displaced, was associated with tree growth of primarily temperature sensitive trees at mid-elevation sites that benefited when anticyclonic climate conditions over Mongolia and northeastern Europe/northwestern Russia prevailed (Figs. 5 and 7 in **paper III**). By extending the spatial coverage of the TRW network as well as the weather-type classification to pressure anomalies including four geopotential heights (**paper IV**), we found similar circulation patterns for the leading ACTI modes for tree growth across entire Asia (Fig. 6). For example, high growth rates for trees at 226 sites in ACTI_1 (42% variance explained) were associated with above-normal sea level pressure (SLP) anomalies over western and northern Asia (Fig. 6a). At 200 hPa geopotential height, a tripole pattern emerged with a high pressure center over northwestern Russia, low pressure center over Central and mid-latitude Asia, and a high pressure system over southern China (Fig. 6b).

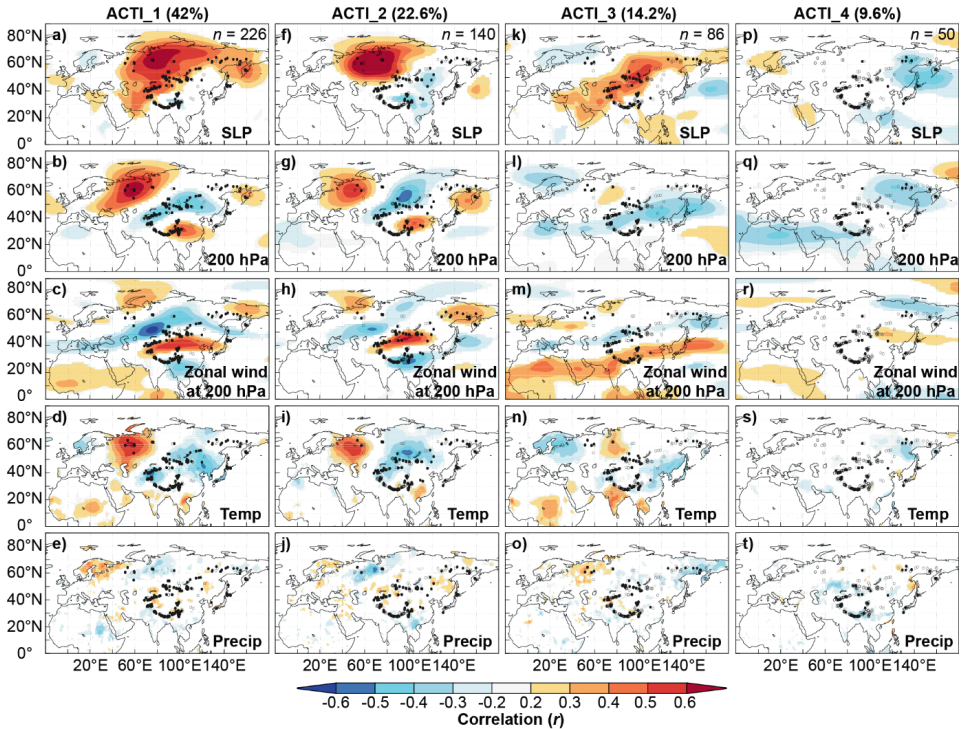


Figure 6: Spatial correlations of the four ACTI components (from left to right: ACTI_1 to ACTI_4) and June–August mean sea level pressure (SLP), pressure anomalies and zonal wind at 200 hPa geopotential height from the 20th century reanalysis dataset, and temperature and precipitation from the CRU TS3.23 dataset for the period 1901–2010. Data were high-pass filtered (year-to-year difference). Black dots represent sites (n) with loadings exceeding ± 0.45 on the principal components. (Figure 2 from [paper IV](#))

Since jet streams are one of the important factors affecting synoptic-scale weather conditions in the mid-latitudes (Bluestein 1993; Holton and Hakim 2012), spatial field correlation maps for 200 hPa zonal wind were computed. Along the northern edge of the Tibetan plateau, the subtropical jet stream enhances and cyclonic conditions prevail around Lake Balkhash (Kazakhstan), Central Asia causing higher than normal rainfall amounts and enhanced tree growth (Fig. 6e). Conversely, the prominent negative correlations for 200 hPa zonal wind indicated that enhanced westerlies extending from the Mediterranean to mid-latitude Asia (Fig. 6c), caused dry climate conditions and thus, growth limiting conditions in Central and mid-latitude Asia (Fig. 6d). Influences of atmospheric circulation, i.e. incoming air masses from the Atlantic via the Mediterranean, on climate in Central Asia were found for extreme growth years of juniper in UZ ([paper I](#)).

It should be noted, that the ACTI modes derived in [paper III](#), have an inverse relationship to the modes derived in [paper IV](#). By definition of the ACTI, positive ACTI values denote enhanced tree growth (i.e. wide tree rings) and vice versa, so that every TRW chronology is

positively correlated with its corresponding ACTI record (Schultz and Neuwirth 2012). Therefore when using the PCA, the dominant climate signals of the TRW chronologies of the input dataset define the sign of the growth-circulation response relationship. For the mid-latitude Asian network, the majority of the trees showed drought responses, while the majority of the trees in the larger Asian domain responded positively to temperature (supporting information Fig. S2 in **paper IV**). Although the final PCA outcome in terms of the sign of the loadings might seem complicated, the PCA is a highly suitable method to extract common large-scale signals from the proxy network.

The high spatiotemporal agreement between leading synoptic-scale circulation patterns derived from tree rings and those obtained from a PCA on 500 hPa pressure data can be seen in Figure 7. Here, the first four modes, although not following the same order as the ACTI modes, are to a high degree captured by the ACTI, i.e. tree-ring data.

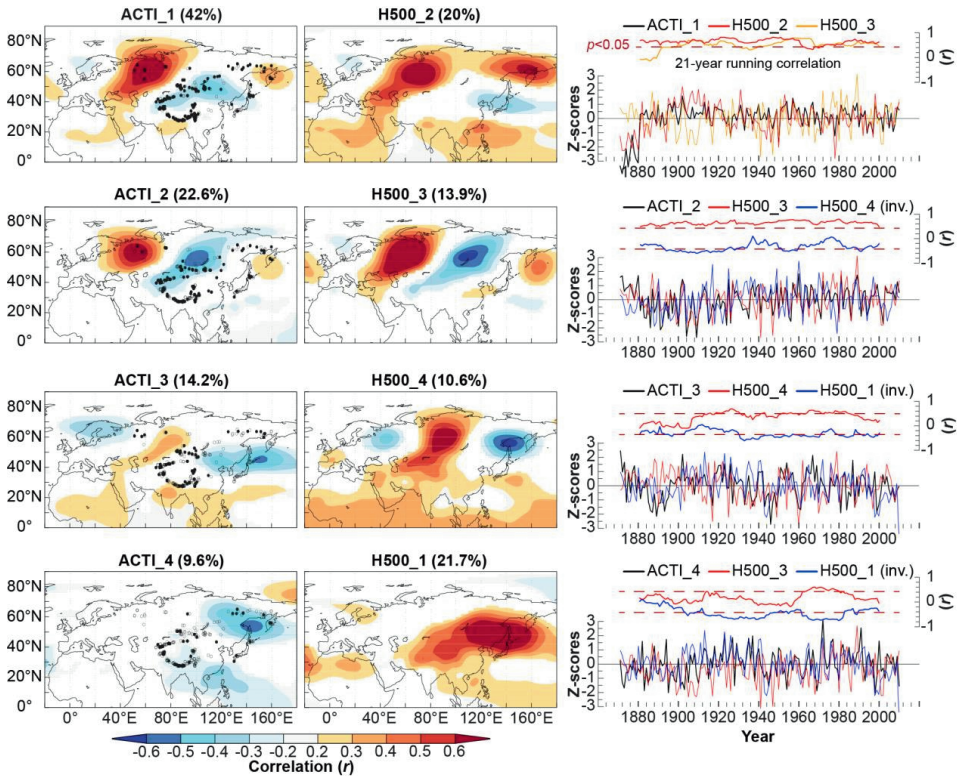


Figure 7 Spatial field correlations of the four leading ACTI modes (left) derived from tree-ring sites (black dots) and corresponding EOF modes (center) for pressure anomalies at 500 hPa geopotential height over the period 1901–2010. Right: Temporal coherency between the leading ACTI and 500 hPa heights EOF scores using 21-year running correlations (Pearson correlation coefficients (r)) (upper panel). Colors for the EOF scores (inv. stands for inverted) correspond to colors for the 21-year running correlation. Red dashed lines indicate the 95% significance level. (Figure 3 from **paper IV**)

In detail, ACTI_1 highly corresponded to H500_2 ($r = 0.67$; $p < 0.001$), ACTI_2 to H500_3 ($r = 0.63$; $p < 0.001$) and ACTI_3 to H500_4 ($r = 0.24$; $p < 0.01$), whereas ACTI_4 was negatively associated with H500_3 ($r = 0.18$; $p < 0.05$). The first three ACTI modes showed temporally stable associations to leading H500 modes over the last century (Fig. 7, right panel). Although H500_1 mode exhibited the highest amount of explained variance (21.7%), trees showed a negative but significant association to this pressure pattern. This was observed especially for the ACTI_3 and ACTI_4 modes, which together contained 84% of the circulation variability of H500_1 (Tab. 1 in **paper IV**). Interestingly, also the other ACTI modes captured to different extents the leading circulation patterns, for instance, ACTI_1, ACTI_2 and ACTI_3 almost fully represented the H500_3 mode (Tab. 1 in **paper IV**).

Overall results from the spatial field correlation analysis, for instance obtained with temperature data (e.g., Fig. 6d) were in accordance with results found by Shi et al. (2015) who reconstructed spatial patterns of summer temperature anomalies from a multi-proxy network for Asia. Moreover, with the application of the ACTI procedure (**papers III and IV**), we are finally able to provide a comprehensive overview of synoptic-scale circulation patterns that causes the spatial patterns of temperature and hydroclimatic variability in Asia as reconstructed by Shi et al. (2015) and Cook et al. (2010), respectively.

4.4 Spatiotemporal variability of teleconnections between Europe and Asia

In **paper V**, we investigated the potential of the tree-ring proxy to extend teleconnection analyses back in time (before 1950) using atmospheric circulation indices, i.e. the summer NAO and ENSO, and East Asian climate as demonstrated by Linderholm et al. (2011). Results showed that tree rings can be used to derive large-scale atmospheric circulation variability further back in time. However, not all utilized TRW sites showed a strong response to NAO and ENSO. This was also found in the analyses using the ACTI method, where some site chronologies did not show a significant response to weather types (**papers III and IV**). We tested the group (i.e. composite) TRW chronology for each ACTI mode for SLP and found that the overall SLP pattern were similar but less distinctly defined (shown in supporting information Fig. S4 in **paper III**). After removing variability in the TRW chronologies caused by ENSO (for details see Linderholm et al. 2011), the strongest summer NAO signals were found in and around Mongolia (mid-latitude Asia) and at the eastern edge of the Tibetan Plateau. Firstly, trees in both regions grow under harsh climate conditions, i.e. semi-arid/arid Asia and at high elevations in the Tibetan Plateau, and strong climatic signals are expected. Secondly, for mid-latitude Asia influences from both westerlies modulated by the NAO and East Asian monsoon are found that effect regional climate (An et al. 2008; **papers III and IV**), and climate variability in the Tibetan Plateau has also been linked with the NAO (e.g., Zhu et al. 2011; Liu and Yin 2001). Moreover, our results showed a high spatiotemporal variability in the teleconnections for both the summer NAO and ENSO among the regions and throughout

the past 400 years (Fig. 7 in **paper V**). This result was not surprising since temporally instable associations in atmospheric circulation across Eurasia have been reported for instrumental data (Sun and Wang 2012; Liu and Yin 2001). Moreover, as recently demonstrated for the North Atlantic/European sector by Schultz et al. (2015), the climate sensitivity of the proxy can be affected by non-stationarities in the climate system.

Nevertheless, by using two different approaches, once the ACTI (**papers III and IV**) and correlations with the summer NAO and ENSO index (**paper V**), teleconnection patterns across Eurasia were found that influences climate in Asia. As shown for extreme growth (i.e., ACTI) years for the mid-latitude Asian network (Fig. 8), tree growth is strongly influenced by large-scale circulations originating from the North Atlantic sector as found for studies using climate data on shorter time scales (e.g., Zhu et al. 2011).

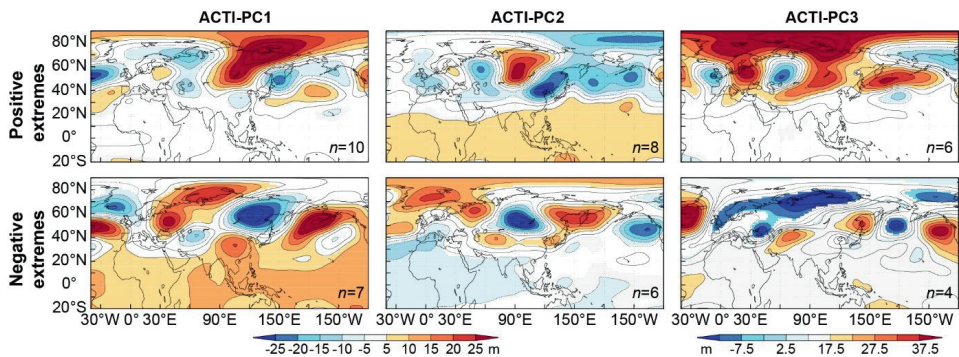


Figure 8 Composite maps of 200 hPa geopotential height anomaly fields for positive (upper panel) and negative (lower panel) ACTI years (n) that exceeds ± 1.5 standard deviation for the 1901–1993 period. ACTI records were high-pass filtered using a 10-year spline. Shadings are significant at the 90% significance level. Please note changes in legend for negative extreme years of ACTI-PC3. (Figure 8 from **paper III**)

It can be seen that local climate is modulated by wave train like patterns, expressed as alternating high and low pressure anomaly fields (Fig. 8), in the upper troposphere linking the North Atlantic and Eurasia in summer. This cross-Eurasian teleconnection pattern, so-called summer circumglobal wave train, modulates precipitation and surface air temperature in western Europe, Eurasia, India, east Asia and North America (Ding and Wang 2005; Saeed et al. 2014; Zhu et al. 2011), which is strongly linked with the Indian summer monsoon and ENSO (Ding and Wang 2005). Saeed et al. (2014) identified, using precipitation data from Europe an opposite response for the summer NAO than for the circumglobal wave train. Our results showed both the north-south dipole like pressure patterns of the summer NAO (Folland et al. 2009) for mid-latitude ACTI-PC1 and negative extreme years for ACTI-PC2 (Fig. 8), and an east-west dipole like pattern of the circumglobal wave train (Saeed et al. 2014) for positive extreme years for ACTI-PC2 and ACTI-PC3 (Fig. 8).

5 Conclusions

The overall aims of the study were to contribute to the assessment and understanding of the effect of environmental factors on tree growth in Asia. By developing new TRW chronologies from Central Asia and testing the application of a recently developed method that directly links atmospheric circulation variability to tree growth (see chapter 1.3), the scientific contribution of this thesis can be summarized as follows.

- i) A new and extensive tree-ring network consisting of 1069 juniper from 38 sites covering the northern Pamir-Alay and Tien Shan mountain ranges in Central Asia was developed.
- ii) Species- and site-specific climate responses of three juniper species in Uzbekistan were investigated. It was shown that intensity and magnitude of the growth-climate relationship depends on juniper species and sites, where JUSE at low elevations showed the highest potential for growing season drought reconstruction.

Investigating juniper tree-ring chronologies from Central Asia, developed within this thesis, and possible impacts of recent 20th century climate change, we found that junipers growing at lower elevations showed an increased sensitivity to summer drought. Although a few high elevation juniper sites showed a temporally stable response to temperature, the majority of juniper trees at high altitudes showed a growth-climate response shift. During the mid-20th century, juniper growth was favored by warm summer temperatures but increasing summer aridity was detrimental in recent decades.

- iii) Using a recently, and for Asia yet untested method of extracting atmospheric circulation variability directly from tree rings, we were able to identify tree growth relevant synoptic-scale circulation patterns from mid-latitude Asia and the whole of Asia. The ACTI method revealed leading modes of atmospheric circulation patterns that highly corresponded in space and time to leading modes of pressure anomalies for the same spatial domain. Thus, a high potential for reconstructing past atmospheric circulation variability is provided.

- iv) Overall linkages to the large-scale Northern Hemisphere atmospheric circulation system were found that persist even further back in time, i.e. covering the past four centuries.

6 Future perspectives

The five studies presented here, provide a valuable basis for several future projects.

Regarding the juniper network developed for Central Asia (**papers I and II**), further endeavors are necessary to develop millennial-long and robust TRW tree-ring chronologies from well-selected sites, especially drought sensitive juniper from low elevations in Central Asia. Firstly, the existing tree-ring chronologies need to be compared and connected with the newly sampled material. Secondly, it would be highly beneficial to incorporate also subfossil or even archaeological and historical material. Moreover, since the density parameter from juniper did not provide a strong interseries correlation nor additional climatic information than the TRW proxy, future efforts should focus on the analysis of the isotopic composition in the tree rings. In this regard, the newly developed and well-replicated juniper network provide a solid base to study the site-specific (i.e., along altitudinal gradients) and regional-specific (i.e. along an east-west transect from eastern UZ to eastern KG) dendroclimatological potential.

Our findings in **papers III to V**, provide a basis to reconstruct atmospheric circulation variability using tree rings in Asia, however, not by using conventional methods with atmospheric circulation indices. It is possible to reconstruct the individual ACTI records utilizing the full length of the TRW chronologies and also to use spatial field reconstruction approaches to obtain spatially resolved reconstruction of pressure patterns for different geopotential heights as done, for instance, by Schmutz et al. (2001), Casty et al. (2007) or Luterbacher et al. (2002) for the Atlantic/European region. This would allow the investigation of the spatiotemporal evolution of key climate variables and the assessment of the leading patterns of recent and past climate variability for Asia. Furthermore, by combining tree-ring data from Europe and Asia, we would be able to explain past and present large-scale atmospheric circulation patterns for Eurasia.

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