Thesis for the Degree of Doctor of Philosophy

Tree Rings and Climate

Standardization, Proxy-development and Fennoscandian Summer Temperature History

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To my Father (1946-2007) for his love and support, I always carry it with me

ABSTRACT

Instrumental meteorological observation are too short for trying to estimate climate change and variability on multi-decadal and centennial time-scales, *and* when trying to evaluate the response of the climate system to human influence, such as raised concentrations of green house gases (GHG), altered land-use, black carbon etc. To access information about the climate system predating instrumental observations, reliable proxy records (natural archives) are necessary. These proxies include for example tree rings, ice cores, fossil pollen, ocean sediments, corals and historical documentary data.

Tree rings is one of the most widely used proxy for high-resolution growing season temperature reconstructions during the last millennium, and in Fennoscandia some of the best-calibrated records in the world exist. Yet, in this available body of work, there is limited homogeneity on decadal to centennial scales. Since this tree-ring data is targeting growing-season temperatures and growing-season temperatures in this region are very well correlated on annual to decadal scales this is unexpected. This thesis is concerned with trying to address this issue by 1) developing existing standardization-tools in order to display centennial scale variability and at the same time reduce noise arising from internal and external disturbances and mismatches in actual growth trends compared to the expected growth trend. 2) By developing the new un-exploited ΔDensity and ΔBlue Intensity proxies (the difference between the latewood and earlywood for density and blue intensity respectively) to act as complement or quality control to the established maximum latewood density (MXD) which is the state of the art proxy for high latitude temperature reconstructions, and also to the Blue Intensity measurement scheme, that potentially could be an inexpensive complement to the radiodensitometric methodology.

Results showed that using the Δ parameter for both density and Blue Intensity, give added value in a more focused annual scale summer temperature signal, and an improved coherence between different chronologies on decadal to centennial scales. Methodological protocols such as data analysis and standardization seem to be critical when trying to attain adequate low-frequency signals from tree-ring data. A more coherent view of the summer temperature history for the last 900 years in Fennoscandia is provided using the methodological improvements outlined in this thesis. Future challenges include trying to extend this excellent network back in time to not only cover the Little Ice Age (1450-1900 CE) but also to cover the debated Medieval Climate Anomaly (850-1250 CE).

Keywords: Tree rings, Fennoscandia, summer temperature, maximum latewood density (MXD), blue intensity (BI), standardization

PREFACE

This doctoral thesis consists of a summary (Part I) followed by four appended papers (Part II), referred to in the text by Roman numerals. The papers are reprinted with permission from respective journal.

I. Paper I
Björklund J A, Gunnarson B E, Krusic P J, Grudd H, Josefsson T, Östlund L and Linderholm H W (2013) Advances towards improved low-frequency tree-ring reconstructions, using an updated *Pinus sylvestris* L. MXD network from the Scandinavian Mountains. *Theoretical and Applied Climatology,* 113: 697-710 With kind permission from Springer Science and Business Media

JB sampled and prepared parts of the data, designed the analysis, visualized the results and contributed to the bulk of the writing.

II. Paper II
Björklund J A, Gunnarson B E, Seftigen K, Esper J and Linderholm H W (2014) Blue intensity and density from Northern Fennoscandian tree rings, exploring the potential to improve summer temperature reconstructions with earlywood information. *Climate of the Past*, 10: 877-885

JB sampled and prepared the data, designed the analysis, visualized the results and contributed to the bulk of the writing.

III. Paper III
Björklund J A, Gunnarson B E, Seftigen K, Zhang P and Linderholm H W The merit of using adjusted Blue Intensity data to attain high-quality summer temperatures information - a case study from Central Scandinavia (Submitted to *The Holocene*)

JB contributed in sampling and prepared the data for the updated part of the Jämtland density chronology and the full BI chronology, designed the analysis, visualized the results and contributed to the bulk of the writing.

IV. Paper IV
Linderholm HW, **Björklund J A**, Seftigen K and Gunnarson B E Fennoscandia revisited – A spatially improved reconstruction of summer temperatures for the last 900 years (Submitted to *Climate Dynamics*)

JB provided parts of the data, helped to design the analysis and contributed to the writing.

Table of Contents

I. Summary

II. Papers I-IV

Part I

Summary

1. Introduction

Meteorological measurements, such as air temperature, precipitation and air pressure, began in the 17th century as a result of inventions such as the thermometer (Galileo 1593) and the barometer (Torricelli 1643). Nevertheless, systematic instrumental observations rarely predate the mid 19th century (c.f. Chen et al., 2006) with some noteworthy exceptions (e.g. the Uppsala and Stockholm meteorological records) (Bergström and Moberg, 2002; Moberg et al., 2002). These records are fundamental for our understanding of the climate system such as trends, extremes and averages of the weather on different time-scales. Yet, they are too short for trying to estimate climate change and variability on multi-decadal or centennial time-scales, *and* when trying to evaluate the response of the climate system to human influence, such as raised concentrations of green house gasses (GHG), altered land-use, black carbon etc. (Masson-Delmotte et al., 2013). To study the climate system predating instrumental records, reliable proxy records (natural archives) of past climate histories are necessary. These proxies include tree rings, ice cores, fossil pollen, marine sediments, corals and historical documentary data, etc. (Tab. 1)[1].

Table 1. Range and resolution of different climate proxy archives

Archives for climate information	**Resolution**	**Approximate Range (years)**
Documentary data	~Daily to seasonal	~10^3
Tree rings*	***Seasonal***	***~10^4***
Coral reefs	Annual to decadal	~10^4
Ice cores	Annual to centennial	~$5x10^5$
Lake sediments	Annual to >decadal	~10^5
Peat sequences	>Decadal to centennial	~10^4
Glacier movements	>Decadal to centennial	~10^4
Boreholes	>Decadal to centennial	~10^4
Speleothems	>Annual to centennial	~$5x10^5$
Pollen	>Decadal to centennial	~10^5
Tree-limit fluctuations	Centennial	~10^4
Marine sediments	Annual and up	~ 10^8

*Absolute dating with cross-dating techniques

Palaeoclimatological studies in Norway, Sweden and Finland (henceforth referred to as Fennoscandia) (Fig. 1) have been based on fluctuations of glaciers (e.g., Karlén, 1976), tree-limit variations (Karlén, 1976; Kullman, 1995; Kullman, 2013), pollen/macrofossil analysis (e.g. Bjune et al., 2009), speleothems (Lauritzen and Lundberg, 1999; Sundqvist et al., 2009), peat sequences (e.g. Nilssen and Vorren, 1991; Vorren et al., 2007), lacustrine sediments (e.g. Bjune et al., 2005) marine sediments (Cunningham et al., 2013 and references therein). These proxies sometimes cover the whole of Holocene[2]. The dating of the information from these records is usually obtained with radiocarbon methodologies (Freidrich et al., 2004) accompanied

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[1] US National Oceanic and Atmospheric Administration NOAA). (http://www.ncdc.noaa.gov/paleo/primer_proxy.html)

[2] Time past since the last glacial during the current Ice age, ~11700 years (Walker et al., 2009)

by a confidence interval rather than absolute calendar dates. In combination with limited sampling resolution, usually decadal to centennial scale climate information is inferred from these records (Tab. 1). To access well replicated, absolutely dated climate information with annual resolution in this region, the study of tree rings is the most viable method (Linderholm et al., 2010a) (Tab. 1). This scientific field is called dendroclimatology.

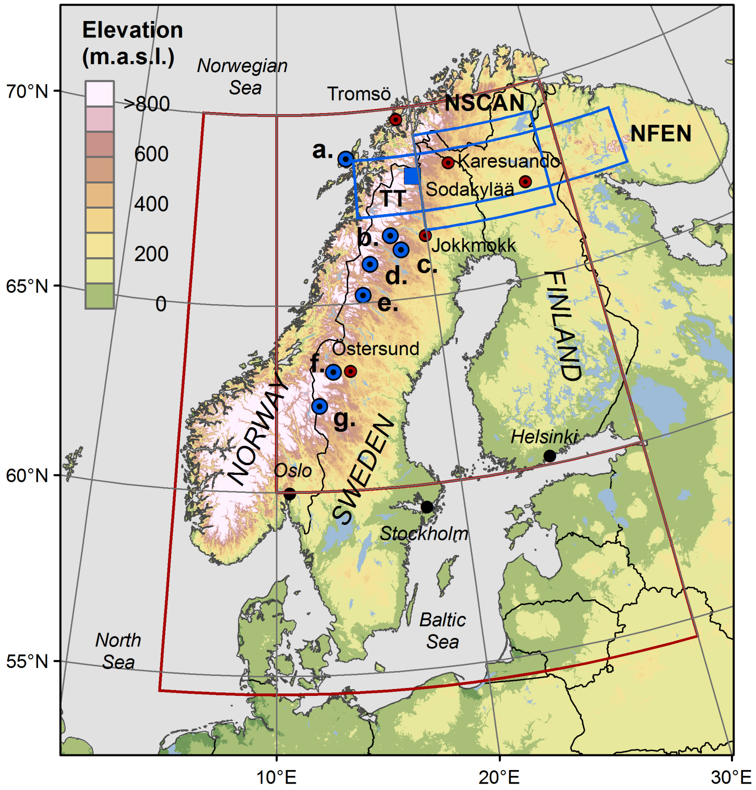

Figure 1. Map of the studied domain (open red box) Fennoscandia. Blue markers indicate the tree-ring data used in this thesis: a) Forfjorddalen, b) Tjeggelvas, c) Arjeplog, d) Ammarnäs, e) Kittelfjäll, f) Jämtland and g) Rogen. The N-Scan (Esper et al., 2012), NFEN (McCarroll et al., 2013) and Torneträsk (Melvin et al. 2013) (in blue boxes, size of the box indicate size of the sampling areas). Open brown square indicate the mean of the gridded reconstructions from paper IV (H14).

1.1 Temperature history the last millennium

On a hemispheric to global scale, climate variations are mainly caused by the variability in the earth system's absorption of energy from the sun and the redistribution therein by ocean and atmospheric circulation (Masson-Delmotte et al., 2013). The absorption depends on the output from the sun, driven by cyclical solar irradiance (Wenzler et al., 2005), and the earths' distance and axial tilt in relation to the sun, the orbital forcing (Laskar et al., 2004). Furthermore, volcanic eruptions can cause widespread, even global, cooling events through the radiative dimming impacts of atmospheric sulphate aerosols dispersed into the lower stratosphere (Robock, 2000). Also, human activity, such as fossil fuel burning and agricultural usage has raised the atmospheric concentrations of gases such as CO_2 CH_4 and N_2O. These gases are relatively transparent to incoming short-wave radiation from the sun but effective absorbers of outgoing long-wave radiation emitted from the earth (Harvey, 2000) and lead to increased heat content in the earth system.

There are three periods that are frequently used to describe the centennial scale temperature variations of the last millennium, although the timing and amplitude of these periods may vary somewhat geographically (Ljungqvist et al., 2012; Pages 2K Consortium, 2013). First, the Medieval Climate Anomaly (MCA), a.k.a. Medieval Warm Period (MWP), described as a warmer period ca. 800-1250 CE, second, a cooler phase around the 14th to 19th centuries called the Little Ice Age (LIA), and third, the warm post-industrial 20th century (Fig. 2) (e.g. Masson-Delmotte et al., 2013). The MCA coincides with the medieval solar maximum and is relatively free of large volcanic eruptions while LIA could be triggered by the massive eruptions in the 1200’s followed by major eruptions in 1400’s, 1600’s and 1800’s, in combination with the solar minima of Wolf, Spörer, Maunder and Dalton (Fig. 2) (Steinhilber et al., 2012; Crowley and Untermann, 2013). The modern warm period coincides with a raised level of GHG’s and the Modern solar maximum. Reconstructions of forcing (ibid.) and reconstructions of temperature variations (e.g. Christiansen and Ljungqvist, 2012) as well as simulations covering the last millennium broadly agree on a global scale, but it is important to note that there is also an internal variability driven by atmospheric and oceanic circulation, that perhaps dampen the more regional expressions such as the expression of the debated MCA (Fernandez-Donado et al., 2012).

In Fennoscandia, various proxy based reconstructions of warm season temperatures describes the MCA as relatively warm, for example in compilations of: pollen-stratigraphies targeting July temperatures (Bjune et al., 2009), marine sediment-cores reconstructing either warm season sea surface temperatures (Cunningham et al., 2013) and tree-ring records calibrated with summer temperatures (McCarroll et al., 2013) (Fig 2). The low-resolution proxies display a slow cooling after MCA transitioning into the LIA, and that this cold period ended around the turn of the 20th century. All proxy records show a warming trend into the modern period of the 20th century. The forcing expressed in hemispheric temperature reconstructions, are thus supposed to also be expressed on this smaller regional scale.

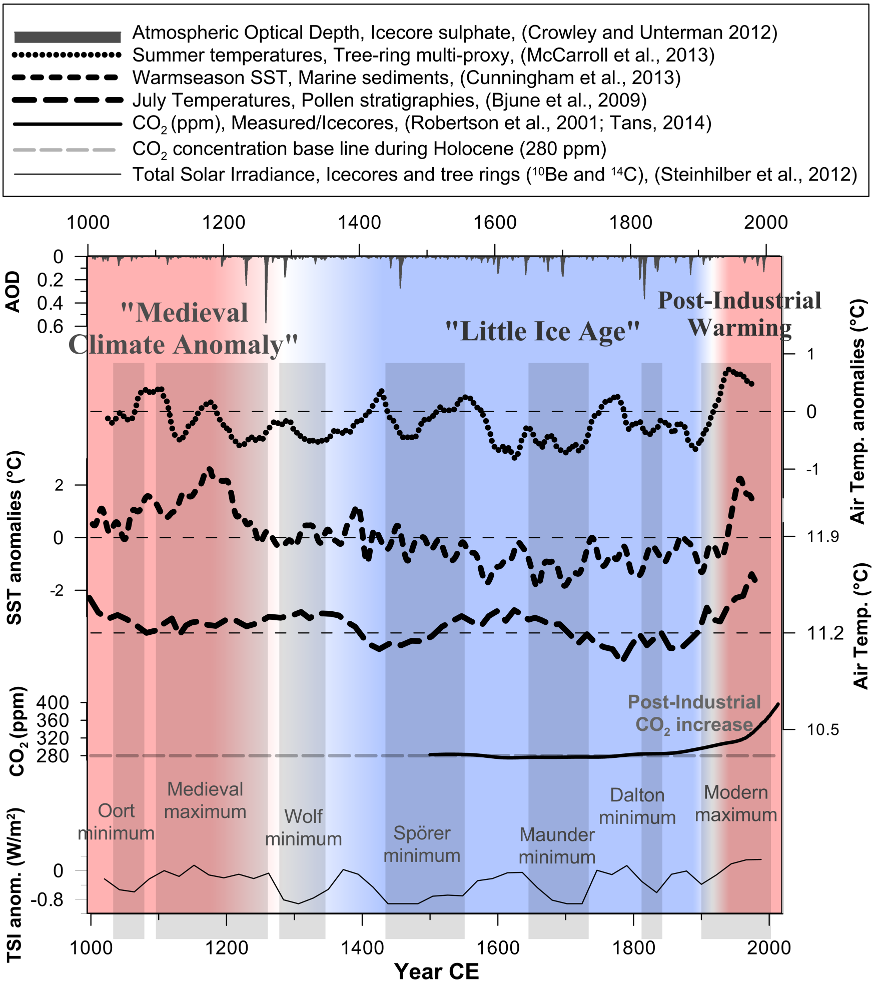

Figure 2. Three different reconstructions of temperature for the Northern Fennoscandian region based on tree-rings, marine sediments and pollen. Medieval climate anomaly (MCA) is indicated with light red colour, the little ice age is indicated with light blue colour and the modern warm period is indicated with light red colour. The pollen record consists of 11 sites encompassing the northern part of Fennoscandia, all 11 records have different sampling resolution and reconstruct temperature at different places. All records were z-scored and compiled into one dataset where after it was smoothed with a moving average, (n = 10). The marine sediments were smoothed by the authors with a 25 years Gaussian filter. The tree rings were smoothed with a 50 years moving average. The pollen, marine sediments, volcanic and solar forcing datasets were downloaded from (http://www.ncdc.noaa.gov/paleo/primer_proxy.html, US National Oceanic and Atmospheric Administration NOAA). The tree rings were shared with the kind permission of the lead author of (McCarrol et al., 2013) Danny McCarroll. Also plotted are reconstructions/measurements of CO_2, volcanic sulphate (atmospheric optical depth) and total solar irradiance (TSI) for global to hemispheric scale. Solar minima and maxima are indicated with light grey areas.

1.2 Statement of the problem

The coldest periods during the LIA occurred, according to the pollen data, around the 1400's and 1800's, and according to marine sediments it was consistently cold from 1500 to early 1900 CE, while the tree-ring records display cooler phases around 1200-1350, 1600-1720 and 1800 to early 1900 CE (Fig. 2). Although the different reconstructions' multi-centennial scale features fairly agree, the multi-decadal to centennial scale variations are difficult to match, perhaps as a result of imprecise dating and different resolution, as suggested by Bjune et al. (2009). However, examining some of the latest and best-calibrated tree-ring records (Forfjorddalen and Laanila in McCarroll et al., 2013; Jämtland in Gunnarson et al., 2011; N-Scan in Esper et al., 2012a; Torneträsk in Melvin et al., 2013) used for warm-season temperature reconstructions in this region more closely, the picture remains complex despite the absolute dating (Fig. 3, records are smoothed with cubic smoothing spline with at 50% cut-off at 50 years).

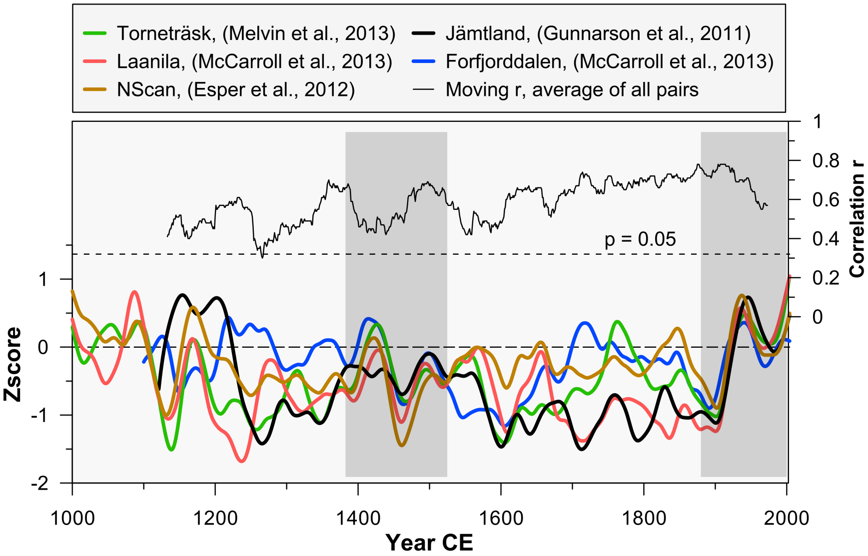

Figure 3. Existing maximum latewood density (MXD) records used in reconstructions of summer temperatures for the Fennoscandian region. The records are scaled for mean and variance during the period 1900-2000 CE. The records are smoothed with cubic smoothing splines with a 50% cutoff at 50 years. The grey areas indicate when the records are converging. Top panel is the average moving window correlation between all pairs (n =50, first differenced data).

Both cold and warm conditions are varying in timing and magnitude among the records and it is only the 1400's and 1900's that are convergent in this collection (note that all records were scaled for mean and variance during 1900-2000 CE). It is unexpected that tree-ring records, so closely spaced, within a radius of 500 km (Fig. 1), reflect so different versions of the temperature history, because the target, growing season temperatures, is in this region quite homogenous, (correlation decay distance of 500-800km at r = 0.71 for June-August (Fig. 4)).

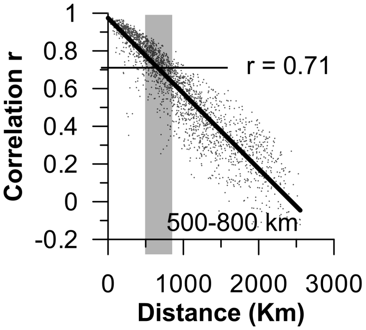

Figure 4. Correlation decay distance for June-August temperatures from all the stations in the Nordklim data base (Toumenvirta et al., 2001), meteorological stations comprising Iceland, Denmark, Norway, Sweden, Finland and Kola Peninsula.

Further, studying the instrumental summer temperatures in Fennoscandia, specifically from five different stations with >100 yearlong records corresponding in geographical location to the tree-ring records: Jokkmokk, Karesuando, Sodankylä, Tromsø, Östersund (Toumenvirta et al., 2001) (Fig. 1), the observed annual scale correlation is at $r_{\text{annual}} = 0.71$ (an average of the first differenced correlations between all possible pairs). Performing the same exercise without removing positive autocorrelation, reveals an average correlation at $r_{\text{unfiltered}} = 0.78$, and at $r_{\text{smoothed}} = 0.77$ when a 5 year moving average is applied, also suggesting spatially homogenous temperatures, and with no observed loss in homogeneity in the decadal scale variability.

Hence a great deal of similarity would be expected among the different tree-ring based reconstructions. In fact, in the overlap with instrumental observations, this *is* observed $r_{\text{annual}} = 0.67$, $r_{\text{unfiltered}} = 0.71$ and $r_{\text{smoothed}} = 0.77$. However, performing the same exercise for the full length of the tree-ring data ($r_{\text{annual}} = 0.58$, $r_{\text{unfiltered}} = 0.49$ and $r_{\text{smoothed}} = 0.37$) gives another view: the common annual scale variability is still strong, but a decoupling seems to occur in the lower frequencies, further suggested by the smoothed data in figure 3. If the tree-ring data over these distances have a strong annual scale association during the entire network's length (indicated by the moving window correlation in figure 3), and a decadal scale association in the instrumental era, the decadal and arguably the centennial scale association should stay coupled also during the pre-instrumental era. Thus, the lack of homogeneity in lower frequencies suggests that the tree-ring data is affected by additional non-temperature related factors that make them diverge. If this is the case, relatively little is actually known about the temperature history in this region even if some of the best-calibrated temperature reconstructions in the world originate from here (Esper et al., 2012b).

So although it is important to extend tree-ring archives back in time, it is equally important to make sure that the climatological information therein is of as high quality as possible. Addressing diverging mid- and low frequencies, defined here as decadal and centennial scale variability, in tree-ring records that arguably ought to display convergence should therefore be prioritized. The information at these timescales is also, as will be subsequently discussed, greatly dependent on site selection, replication, data analyses and standardization techniques. Methodologies need to be revisited and new ones developed, before making improved tree-ring based temperature reconstructions (Frank et al., 2010).

1.3 Aim and objectives

The overall aim of this thesis work is to improve estimates of Fennoscandian warm-season temperature variations over the last millennium, and to provide a more coherent view of the pre-instrumental temperature history than has previously been portrayed by various tree-ring archives, especially when it comes to decadal to centennial scale variability. To achieve this, tree-ring data from Fennoscandia will be utilized, and various new dendroclimatological methodologies will be explored.
The main objectives are to:

1) *Explore and develop new high-quality tree-ring proxies*
    - by developing previously un-exploited tree-ring parameters to provide tools of identifying systematic biases in established density parameters. This includes modifying the inexpensive optical measurement scheme called 'Blue Intensity' to also attain adequate centennial scale information and thereby increase the potential for a denser network of high-quality tree-ring data (paper II and III)

2) *Improve existing standardisation methods used for long time-scale reconstructions*
    - by adding simple modifications to the Regional Curve Standardization (RCS) methodology introduced by Briffa et al., (1992) to give added value in the decadal and centennial scale variation in tree-ring based multi centennial reconstructions (paper I and IV)

3) *Provide a new and improved reconstruction of Fennoscandian summer temperatures within the last millennium*
    - by contributing new tree-ring data (density and Blue Intensity) to add to an increasingly denser network of high quality proxy-data in Fennoscandia (paper I, II, III, IV)
    - by using modified standardization techniques and newly developed proxy parameters on existing and newly developed tree-ring data from the region, addressing both the spatial and temporal summer temperature history in Fennoscandia (paper III and IV)

The first objective is addressed in paper II where the previously unexploited tree-ring parameter ΔDensity is presented. This parameter is developed to examine if maximum latewood density (MXD) measurements are biased by non-structural components in the wood that are non-exclusive for each tree-ring increment. Latewood and earlywood measurements are assumed to be equally biased by these components, and the earlywood density is used as a baseline for the MXD, thus creating ΔDensity.

Also relating to the first objective, development of the measurement scheme for Blue Intensity (BI) is made in papers II and III. In paper II the Δ parameter is also used, and in paper III it is further developed.

The second objective is realized in paper I, where the concept of Regional Curve Standardization of tree rings is relaxed. Instead of only removing the expected growth trend represented by the average pith year growth-rate from every tree-ring measurement, data-adaptive signal free curves are adjusted to the average of the overlapping segment of the expected growth trend, to address other unwanted variability in dendroclimatic data than just age-trends. In paper IV, this methodology is expanded upon further.

Together papers I, II and III lay the groundwork for paper IV of providing new methodologies to produce new high-quality tree-ring data which is required to refine the Fennoscandian temperature history, which is the third objective, both in a temporal and spatial sense. At least one new tree-ring chronology is presented in each paper, either as completely new (Kittelfjäll paper I, Arjeplog paper II, Rogen paper IV) or as a new parameter that has been measured in a previously published chronology (Jämtland BI paper III). Paper IV combines ΔBI and ΔDensity parameters from multiple sites distributed throughout a latitudinal transect in Northern Fennoscandia, standardized with novel methodologies to produce a reconstruction of JJA temperatures over the past nine centuries.

Before data and methods are presented in section 3, a brief introduction to the scientific field of dendroclimatology follows in section 2 to give the reader a comprehensive understanding of the concepts. Section 4 provides a summary of the papers, and a more in-depth account of the newly developed methodologies. Section 5 contains a synthesis, where the findings are connected to address the overall aim of the thesis.

2. Dendrochronology and Dendroclimatology

Dendroclimatology is defined as the study of climate and weather conditions through the observations *of*, and the empirical linkage *with*, features in annual growth bands of trees (Fritts, 2001). A tree ring in a conifer (needle tree) is a result of differentiated cell sizes and cell-wall thickness laid down inside the bark as the growing season progresses. The abrupt shift from small and thick-walled cells (latewood) laid down just before the tree is entering the dormant phase (the winter) to large and thin-walled cells (earlywood) when the growing season starts again in the spring, clearly demarcate an annual increment (Fig. 5). The prerequisite for annual ring formation is that the tree is growing in an area characterized by pronounced seasonality. The size, density and isotopic compositions of tree rings are largely determined by the weather and climatic conditions in the environment in which it grows (Douglass, 1914; Polge, 1970; McCarroll and Loader, 2004).

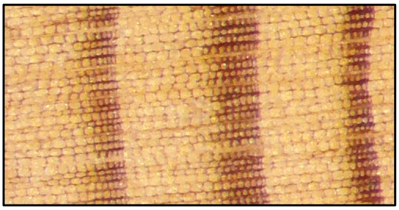

Figure 5. Radial section of a Pinus sylvestris were the cell-structure is clearly visible. The direction of growth is from left to right in the image, and the growing seasons are separated by the sharp contrast between latewood and earlywood.

The link between weather and the annual growth of trees in Fennoscandia has been the subject of scientific study for about 300 years. Already in the 18th century, Carl Fredric Broocman (1709–1761) related the annual growth of trees, in the eastern part of southern Sweden, to favourable summer conditions (Broocman, 1760) and Carl von Linné (1707–1778) viewed ring-width patterns from an oak in southern Sweden as a record of winter severity (Linné, 1745). Ulric Rudenschöld (1704–1765) compared pine trees in northern and southern Finland finding both differences and similarities, which he attributed to regional climate and soil conditions (Rudenschöld, 1899). Although tree rings and climate have strong traditions in the Nordic countries, it was the American astronomer Andrew Ellicott Douglass (1867–1962), who in the beginning of the 20th century recognized the significant benefit of tree rings as a climate proxy archive; the possibility of absolutely dating the information contained in the tree rings, dendrochronology.

2.1 Dating of tree rings

Dating is achieved by counting rings from the outermost ring (which has a known date) to the centre of a radial cross-section assigning each ring a calendar date of formation. However, sometimes the radial growth structure for various reasons resemble a finalized annual growth ring but be instead a “false growth band” or intra-annual density fluctuation (Fig. 6). Merely counting growth bands, including false rings, results in an overestimation of the tree age and tree rings formed prior in time to the false ring will be incorrectly dated. Furthermore, an analysed tree sample might not show physical evidence of a ring even though a growing season has passed between two clearly visible rings. These rings are called locally absent growth bands or missing rings (Fig. 7). These usually occur when conditions for the tree are difficult and the growth is not able to occur throughout the stem in its entirety, and results in an underestimation of the tree age, and hence incorrect dating. It is important to note that physical evidence of a locally absent ring can be found in other places of the tree if searched for (Fig. 7).

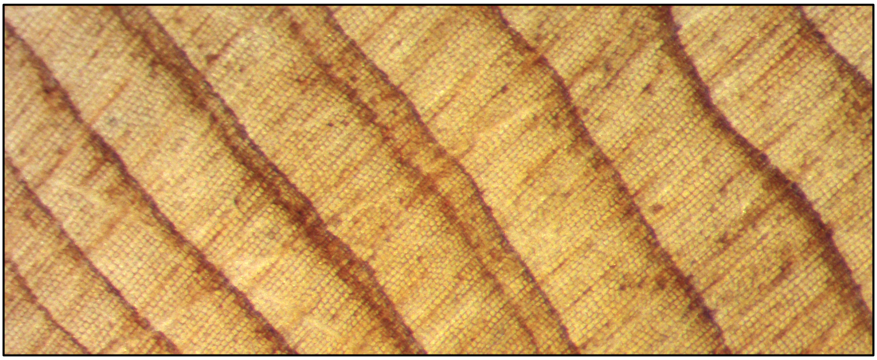

Figure 6. Two false growthbands in a *Juniperus communis* (common juniper).

Figure 7. Locally absent growth band to the right in the photo of a *Pinus sylvestris* L. but visible in the left in the photo.

By comparing ring sequences obtained from multiple samples within a tree, and multiple trees from the same stand/climatological region, these sources of dating-errors can be rectified. This is because trees in a confined area respond similarly to the environmental and climatological conditions around them. Extreme weather-conditions, good or bad, induces similarly “extreme” wide and narrow rings in those years for most trees; distinct sequences of “pointer years”. Establishing a sequence of pointer years in the “easiest” trees (samples that likely have no missing rings and few density fluctuations), more and more difficult trees (samples that probably have missing rings and suspicious density fluctuations) can be dated using these pointer years. It is very unlikely that all trees have synchronously false bands or locally absent growth bands (Anchukaitis et al., 2013), and eventually an absolute dating of each tree ring can be made, the methodology is referred to as ‘cross dating’. Applying the sequence of alternating narrow and wide rings in common among all the dated trees, even dead trees (stumps, snags, beams etc.) with unknown date of the outermost ring, can be dated by matching their narrow and wide ring-sequences with the dated trees.

Figure 8. Data sampling with increment corers top panels, and sawn discs from deadwood on the ground, bottom panel.

Only when all tree rings investigated are dated correctly can analyses of ring properties such as measurements of width, density or other sources of information be conducted and be meaningful. These quantities can subsequently be averaged for every calendar year to construct a *chronology* of ring widths or ring densities. If a forest contains a large amount of preserved dead trees either on the ground (Fig. 8) or in lakes (Fig. 9), successively longer tree-ring records can be built by matching dated samples with older undated samples, sometimes several thousands of years back in time, reaching almost as far back as the entire Holocene, around 7000 to 8000 years ago (Grudd et al., 2002; Helama et al., 2002; Linderholm and Gunnarson, 2005). This despite the fact that maximum lifespan of Fennoscandian trees is <1000 years[3]. Most chronologies in Fennoscandia are usually as long as the oldest living trees included, around 300-400 years long[4] because dead trees are removed by humans, or have decomposed.

Figure 9. There is a huge databank in mountain lakes that is explored to extend tree-ring data series almost as far back as the last glacial when the Scots pine migrated in after the glacial 7000-8000 years ago.

2.2 Climatic and non-climatic factors expressed in tree growth

As was previously mentioned, trees exposed to the same weather share this as one of their growth-influencing factors: the more extreme the climate is, the more the weather will be reflected in the tree growth. If growing season temperatures generally are very low, so low that a further cooling cannot support tree growth, such as around the tree line in Fennoscandia, the growth will largely be a function of growing season temperature (e.g. Erlandsson, 1936). Similarly, if growing seasons generally are very dry, the variations in growth will again largely be a function of water availability,

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[3] Sveriges äldsta träd (http://www.norgig.com/national/se/old_trees.html)
[4] International Tree-ring Data Bank (http://hurricane.ncdc.noaa.gov/pls/paleox/)

such as arid southwestern US (Douglass, 1914) or well-drained locations in otherwise temperate regions (Seftigen et al., 2013). But, even when tree growth is dominated by a single meteorological variable, the growth is simultaneously controlled by continuously present non-climatic factors like the age and the size of the tree, or sporadically by the presence or absence of disturbances, that are either non-synchronous or synchronous on local to sub-regional scales, and also other unexplainable factors (Cook and Kairiukstis, 1989). The shape of the resulting measures of annual growth, which is an aggregate of all the above-mentioned factors, is usually dominated by the age trend, but frequent exceptions can occur. For later discussions, already here it is useful to make the distinction between the shape of the *expected growth trend* and the shape of the *actual growth trend*, where the expected growth trend is considered only to be dependent of age and is represented by the average of all trees included aligned by their pith age, and actual growth trend is here defined to be represented by the local average-growth in every individual tree. The actual growth trend may be in conflict with the expected growth trend for various reasons, further discussed below.

The age trend: a young tree with little foliage has of course not the ability to produce as much wood as a mature tree with extensive foliage, so with increasing age, an increase in growth and ring width can be observed on average. When a tree reaches maturity or dominance, the foliage does not continue to develop as much in size. Roughly the same amount of wood is produced every year, but has to be distributed around an increasingly larger stem; therefore measurements of tree-ring width (TRW) are observed to display an exponential decrease in size. Furthermore, other processes, like increasing transport distances for assimilates, hormones and water, and limitations of exploitable resources (e.g. nutrients), and reduced foliage with age, likely also results in persistent decreases in densities and TRW (Schweingruber et al., 1978; Warren, 1980; Bräker, 1981; Melvin, 2004).

The size: the relative size of a tree within a stand depends on micro site conditions such as soil type, water-holding capacity, slope aspect or life history (dominance/suppression) etc. and generally, a larger tree with extensive foliage can produce more wood than a smaller tree even though they are experiencing the same weather and are of similar age. It thus expected that a large tree continue to produce large amounts of wood while a smaller tree continues to produce smaller amounts of wood, it thus useful to also distinguish between *slow-growing* and *fast-growing trees.* Furthermore, considering one large and one small tree that are for arguments sake only a function of age and size. The large tree necessarily exhibits a more rapid growth decline than the smaller tree because of the geometrical constraint and the increasing transport distances etc. mentioned above, and the shape of the actual growth trend may thus vary with size.

Disturbance pulses: the sporadic disturbances are divided into two categories dependent on if they are random events in time and space acting on single trees, or if they are random events in time acting on the whole stand. The term random is used in a broader sense, because these events are not truly random. These two types of disturbances are henceforth referred to as *internal* and *external disturbances* respectively. Both these types create pulses of release or suppression of tree growth (White, 1979) from annual scale to multi-decadal scale and perhaps even longer. Disturbances may affect growth to such a degree that also here the actual growth trend deviates significantly from the expected growth trend. Examples of internal disturbances include gap dynamics, such as when a tree dies and falls; it will leave space and nutrients for its immediate neighbours. Disturbance pulses can also have external origins, for example fires, wind throw, pathogens, or human influence from pollution, low intensive thinning, dwellings, or ditching.

In dendroclimatology the factors that cause variability, which are not related to climate variability, are considered to be *noise.* If tree-ring data is going to be used to infer climate history, it is desirable to minimize the non-climatic expressions. This is done in the sampling stage with careful consideration of site selection and replication, and later with various data-treatment processes (standardization). The discussion above is directed to the expressed growth in trees, but it is also important to keep in mind that this growth is going to be measured and also at this stage, non-climatological bias of variance and mean can be introduced, discussed in section 3.

2.3 Fieldwork and sampling bias

At the sampling stage, it is important to minimize the non-climatological response in the trees of the forest, discussed above, and to design the sampling to yield as representative sample of the forests climatological response as possible. The former is reduced by maximizing the expression of variability caused by weather, found in sites with extreme climatic conditions. Furthermore, it is important to minimize impacts that have commonly started synchronously with instrumental measurements, that is, external disturbances associated with human influence. Other external disturbances also affect the trees but these are arguably time-independent features, not concentrated exclusively in the modern parts of tree-ring chronologies.

In Fennoscandia, human impacts have arguably altered the overall dynamics and structure of the forest ecosystems over the course of the past centuries (Brumelis et al., 2011). Commercial selective logging was introduced in the 19th century, aiming at the largest (and often the oldest) trees in the forest. Logging on a larger scale (Fig. 10) began throughout Sweden in the late 19th century. Selective logging may deplete older generations of dominant trees and lead to an uneven age-class distribution in the remaining forest stand. Any logging or thinning cause positive disturbances in the remaining trees much like in natural dynamics (Fraver et al., 2004) but more systematically. Indigenous Sami people have utilized trees for food; bark peelings (Fig 10). Gunnarson et al., (2012) showed that low intensity dwellings of indigenous people could have negative impacts on Scots pine growth when settlements were abandoned and more opportunistic species like birch started to compete for space and nutrients. A careful choice of location can minimize these factors, and one of the best examples of a forest with natural dynamics and structure, and a minimum amount of human influence, is included in the thesis: namely the Tjeggelvas nature reserve (ibid.) (Fig. 11). However, these sites are now very rare.

Figure 10. Human impact on forests, to the left a clearcutting, with a few saved over-mature Scots pine trees, that subsequently became a planted *Picea abies* forest. To the right, scar from harvesting of inner bark by Sami people. Human impact may be much more subtle than this but still have influence on tree-growth.

When a forest is chosen for sampling, additional biases can arise from how it is sampled. Trees are living organisms and their growth is, as mentioned, a response to many different things and manifest in varying magnitude in each tree. The tree growths in a forest thus display a natural range, and if an average growth is going to be calculated, a more robust mean is achieved with more trees. However, increasing replication, here defined as the amount of trees included in a chronology extensively, tends to reduce chronology variance while the opposite is true for low replication (Frank et al., 2007), and so it is good practise to make sure that replication does not change too much through time.

Furthermore, generally, dendroclimatological sampling practises are biased towards old trees because they provide more data and longer chronologies with the least amount of effort. This typically leads to high tree-ages in modern parts of chronologies and low tree ages in older parts of chronologies, potentially introducing an age-class bias (Linderholm and Linderholm, 2004; Esper et al., 2008). But even if the forest is sampled with a randomized strategy (Nehrbass-Ahles et al., 2014) or by making sure that all available age classes are included, the deadwood and older generations may not contain the structure and natural variation in trees that it used to.

For example, trees that have had a tough life history usually have higher resin content and grow older and when they die they are preserved more readily. The older part of the chronology may thus be biased towards suppressed slow-growing trees or damaged trees with higher noise level. A chronology that has this constitution will thus be biased by the 'date' of the sampling, a modern sampling bias (Melvin, 2004). Human use and colleting of deadwoods for fire or tar production etc. (Östlund et al., 2003; Holmgren, 1959) have further depleted the information back to older times.

To conclude, sampling bias is a real concern and external disturbances as well as the sample not being entirely representative of past forest growth patterns may seriously affect resulting chronologies.

Figure 11. Tjeggelvas Nature Reserve, one of the last un-logged old-growth boreal forests in the Fennoscandia.

2.4 Tree-ring data

TRW from the most commonly used conifer in Fennoscandia *Pinus sylvestris* L. (Scots pine) have, using trees growing at the altitudinal or latitudinal tree line, historically been shown to have significant correlation with growing season temperatures, from Erlandsson (1936) to Linderholm and Gunnarson (2005). However, there are other features in annual increments that can be measured. Polge (1970) reported about advances in the techniques of measurements of wood density, where he used x-ray densitometry or radiodensitometry. Wood density is an integrated measure of several variable wood properties, including cell-wall thickness, lumen diameter, size and density of vessels or ducts, proportions of fibres etc. The density, specifically the density in the latewood of the annual increment, maximum latewood density (MXD), is tightly coupled to growing season conditions (McCarroll et al., 2003). Schweingruber et al. (1978) refined the methodology introduced by Polge (1970), and later noticed that the MXD potentially possess a more pronounced sensitivity to growing season temperatures than TRW (Schweingruber et al., 1988), later corroborated by numerous colleagues (e.g. Wilson and Luckman, 2003; Grudd, 2008; Linderholm et al., 2010b; Melvin et al., 2013). However, even though significant advances have been made since the 70s regarding the methodologies of how to measure density, expensive instrumentation and trained personnel is still needed. Hence only a few laboratories around the world are presently able to perform this type of analysis (e.g. Swiss Federal Institute for Forest, Snow and Landscape Research, Birmensdorf, Switzerland; Bolin Centre for Climate Research Stockholm, Sweden; Sukachev Institute of Forests, Krasnoyarsk, Russia). The cost of a ring-width chronology is a fraction of the cost required to produce a density chronology. Even though the potential climatic signal in a density chronology is of higher quality, the cost affects the amount of replication and the average value of each year in a chronology may be less robust because of this.

In the last decades, alternatives to radiodensitometric measurements have been studied. Numerous works to find a substitute for the excellent but expensive and laborious x-ray methodology have been made. Park and Telewski, (1993) experimented with ultra thin micro-sections of wood and transmitted visible light. Yanosky et al., (1987) and Sheppard et al., (1996) used photographic equipment to capture images of visible light. These methodologies produce comparable results to x-ray densitometry but are also quite expensive and/or laborious, and have systematic biases like optical image distortion in edges of images. McCarroll et al. (2002) utilized optical flatbed scanners and the expressed reflected blue light from tree rings, a methodology later termed Blue Intensity (Campbell et al., 2007). In this scheme, optical distortion is eliminated, no difficult micro-thin section need to be cut and cheap commercial scanners for analysis can be bought anywhere. The cost of an optically scanned chronology is very similar to the cost of a ring-width chronology, and if the information from this alternative is comparable in quality to density, then replication (both in terms of spatial coverage and amount of samples for every chronology) can be significantly enhanced, resulting in more robust mean annual estimates of pre-instrumental climate variability. Limitations and systematic biases regarding both density and Blue Intensity will be further discussed in section 3 and 4.

2.5 Standardization – a necessity with limitations

Standardization is the step where all the factors that compromise climate signals in tree-ring data for the last time can be mitigated. Tree-ring standardization can be defined as estimating the noise with an algorithm that subsequently is used to convert tree-ring measurements to a common average and at the same time remove age trends and possibly disturbance pulses (Cook, 1985). This is commonly done by fitting an ordinary least square (OLS) function to a tree-ring measurement that is subsequently subtracted or divided from the measurement. Chronologies generated in this way commonly preserves variability on timescales significantly shorter than the mean indexed series lengths, because all data is scaled to a common mean, and overall trend is usually neutralized. This lack of variability in lower frequencies is termed the "segment length curse" in tree-ring data (Cook et al., 1995).

In an attempt to minimize the loss of information on longer timescales, a method called Regional Curve Standardization (RCS) was developed (Briffa et al., 1992). With RCS, all trees in a sample are standardized using a common function of age. All individual tree-ring series are aligned by their pith year[5] and averaged. When tree-ring series are aligned and averaged by pith year instead of calendar age, climate, disturbance pulses and varying sizes among the trees are cancelled out to improve the signal in the age-trend. A curve is fitted to the regional average growth, termed regional curve (RC) or expected growth trend, and is subsequently subtracted or divided from each tree-ring series. The advantage is that potentially, climatic signal exceeding index series length can be preserved. The limitations include 1) that all the variability that was cancelled out deriving the RC or expected growth trend will be manifested in the resulting chronology: disturbance pulses and non-climatological differences in growth rate. 2) The shape of the expected growth trend may be an inappropriate match of the shape of the actual growth trend. 3) If most samples in the chronology are even-aged living trees, then the climate signal will not be entirely cancelled out in the RC and is actively removed from the chronology (Briffa and Melvin, 2011). 4) If a modern sampling bias is present in the chronology, distant time periods are then associated with slow growing trees and more modern periods with fast growing trees. Then, the RC will be an average of these, and thus underestimate growth in distant periods compared to the modern period. In this particular case, two or more RCs' for a chronology can be made. Nevertheless, given the above reasons, RCS chronologies need a sample depth roughly three times that of a chronology standardized with individual curve-fitting, to have similar standard deviations (Melvin, 2004).

An attempt to increase the removal of noise and at the same time try to keep as much signal as possible in resulting chronologies was made by Melvin and Briffa (2008) with their signal-free approach to standardization (SFS). The theory behind this methodology is that variance in common within a group of trees is signal that is wanted (climatically induced). This is of course a simplification, because there are as stated before, non-climatological common variance (external disturbance pulses; coinciding age-trends etc.) that also will be interpreted as desirable. Nevertheless, practically, SFS is done by first, standardization as described above. Then the resulting chronology is used to remove the common variance from each and every tree-ring measurement by series of calendar-aligned division to produce a set of "signal- free" indices. OLS curves are then fitted to these signal-free measurements, which are representations of the signal-free growth in each tree. These curves are subsequently used to detrend the raw tree-ring measurements to derive a chronology with more noise removed, and more common variance preserved. This procedure is iteratively repeated until a specified maximum difference between the successive chronologies is met. The potential for retaining variation on timescales closer to the

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[5] The innermost ring at the sampled height. If a sample lack rings close to the pith (due to heart-rot or sampling) an estimation of the amount of years missing to the centre is made (pith offset) to avoid gross misplacements of ring ages in the regional average growth.

entire age of the tree-ring series increases since indices generated with SFS can have an overall trend. This is because the OLS curves are fitted to the signal free indices and not to the raw tree-ring data that would otherwise remove the trend. Nevertheless, variability on timescales longer than the mean series length is lost since all individual series have similar means, i.e., the “segment length curse” remains.

With the above methodologies it thus not possible to retain climatic variability exceeding mean index-length and at the same time reduce noise-levels from size, miss-match in shape between expected and actual growth-trends and external and internal disturbances.

2.6 Estimating the performance as climate predictor

Standardized tree-ring measurements can subsequently be averaged to build chronologies that can statistically be compared to various climate variables to explore the direction and strength of the tree ring/climate relationship. This comparison is usually referred to as calibration. It is important to stress that these records are not perfect gauges of meteorology, but since they are annually resolved, with absolute calendar dating, a quantitative estimation of their performance can be given. The signal is evaluated with simple or multiple regressions against the target climate parameter, and verified with independent data. Typically the instrumental observations are split in half, calibrated on one part and validated on the other (Gordon et al., 1982). This procedure comes with the assumption that the same physical and biological processes that link current environmental processes with current patterns of tree growth must also have been operated in the past. That is, if the data is verified in the independent period, the assumption is made that the data is also valid in the period when instrumental observations are unavailable. By estimating the climate-tree growth relationship in the instrumental period, reconstructions of climate from tree rings can thus be made for times well before weather records were ever kept.

3. Data and Methods

3.1 Climate setting

The geographical, climatological and topographical setting of this thesis work is exclusively Fennoscandia, with focus on Northern Sweden. With the overall aim of providing a more robust version of summer temperature history for the Fennoscandian region, it is critical to find trees to sample that are growing in cool climate as to make sure that changes in temperature will clearly manifest in the annual growth increments. The cooler areas in this region have a clear latitudinal and altitudinal component. The Scandinavian Mountain range, that crosses Norway and the central and northern parts of Sweden in a SW-NE direction, largely determine this. The Scandinavian Mountains divide Fennoscandia into two climatically different zones: a more maritime in the west and a more continental in the east of the mountain range.

The climate in the region is greatly influenced by the adjacent North Atlantic Ocean, more so on the western side of the mountain range. The spatial variation in precipitation and runoff is tightly linked to the passage of cyclones, typically following westerly - easterly tracks across the region (Ångström, 1974), implying that the highest total annual rainfall amount, mostly of orographic origin, occur along the west coast and in the Scandinavian mountain range. East of the divide, where the bulk of the tree-ring data used in this thesis work is sampled, have a lower annual rainfall amount of around 500-700 mm. It is natural to target trees on the rainfall lee side of the mountains since the trees otherwise can be negatively affected by too much precipitation (Seftigen et al., 2014). The fine roots of many tree species will not operate below the water table and a high water table can produce considerable restrictions in tree growth (Nicoll and Ray, 1996). The temperatures at the study sites of this thesis work are below zero in the winter-season and usually well into April, and falls below the zero threshold again in October. Hence, the growing season in these areas are very short. This means that these trees take advantage of warmer growing seasons and suffer from colder growing season. The area around the Scandinavian Mountains is thus ideal for tree-ring based retrospective temperature studies, due to the abundance of old-growth forests in proximity to the altitudinal tree line in the mountainous areas. Also, the region offers several long and excellent meteorological records (in several cases >100 years, in mostly operated by the Swedish Meteorological and Hydrological Institute SMHI), which is a pre-requisite for a successful statistical investigation of limiting climatic factors for the trees.

3.2 Fieldwork

Principal investigators Björn Gunnarson, Mauricio Fuentes, and myself collected most of the tree-ring data used in this thesis work, together with other members of the Gothenburg University Laboratory for Dendrochronology (GULD). Table 2 and figure 1 provides an overview of the tree-ring data used in papers I-IV. I sampled two sites for this thesis work: Arjeplog and Kittelfjäll, both located in the northern part of Sweden (Fig. 1, Tab 2). Trees with the oldest looking exterior were selected in order to extend the living part of the tree-ring data as far back in time as possible (Fig. 12). After this, successively younger trees were sampled to account for the potential age-class bias. Finally, all deadwood lying on the ground was sampled to extend the tree-ring chronology as far back in time as possible, beyond the period covered by the living trees (Fig. 8). The structure of the Scots pine stands in Arjeplog and Kittefjäll differ markedly. The Kittefjäll chronology extends barely more than five hundred years and is mostly a result of old living trees with successively younger cohorts mixed in (Fig. 13). Probably this forest has been extensively scavenged for firewood because little deadwood was found. The forest is sparse and of low productivity, suggesting that it has not been logged on either smaller or larger scales. The Arjeplog pine stand density is varying from open to closed, and most ages of pines are represented but very few over-mature trees (>300 years) can be found. Only three living specimens exceeded a dating of 1500 CE and one a dating of 1360 CE (Fig. 12).

Figure 12. The oldest known specimen of Scots pine in the Arjeplog site (perhaps 750 years of age), sampled and photographed by Petter Stridbeck.

These trees were extremely slow growing and if determining a date of germination by the root collar on the oldest one, an age of 700 years, perhaps even 750 years is not unlikely. The deadwood found in Arjeplog can roughly be divided into two sub-categories: (1) either distant death-dates in the 1600-1700s, or (2) recent death dates in the 20th century. The Arjeplog chronology extends more than 1000 years back in time but there are two distinct cohorts of samples: living trees from 1700-2000 CE and dead trees from 1200-1500 CE (Fig. 13). The deadwood class that is missing (death dates around 1700-1900) would also coincidently be corresponding to very old living trees (>300 years). This suggests that the forest in Arjeplog has at some point in the past probably been harvested for large dominant trees (high-grading of timber that was more merchantable), but with little amounts of collected firewood.

3.3 Production of Tree-ring data and analysis biases

Used and produced tree-ring data in this thesis work is exclusively derived from Scots pine. In the laboratory, the tree samples were dried, mounted, and sanded to enhance the appearance of ring boundaries and cell structure (Stokes and Smiley, 1968). Annual tree-ring widths were measured to the nearest 0.01 mm using a stereomicroscope connected to a Lintab measurement table and the Time Series Analysis Program (TSAP) software (Rinn, 1996) using the cross dating as a guide. The cross dating was verified statistically in the software COFECHA (Holmes, 1999).

The ring widths were later used as references when measurements of density and blue intensity were analyzed.

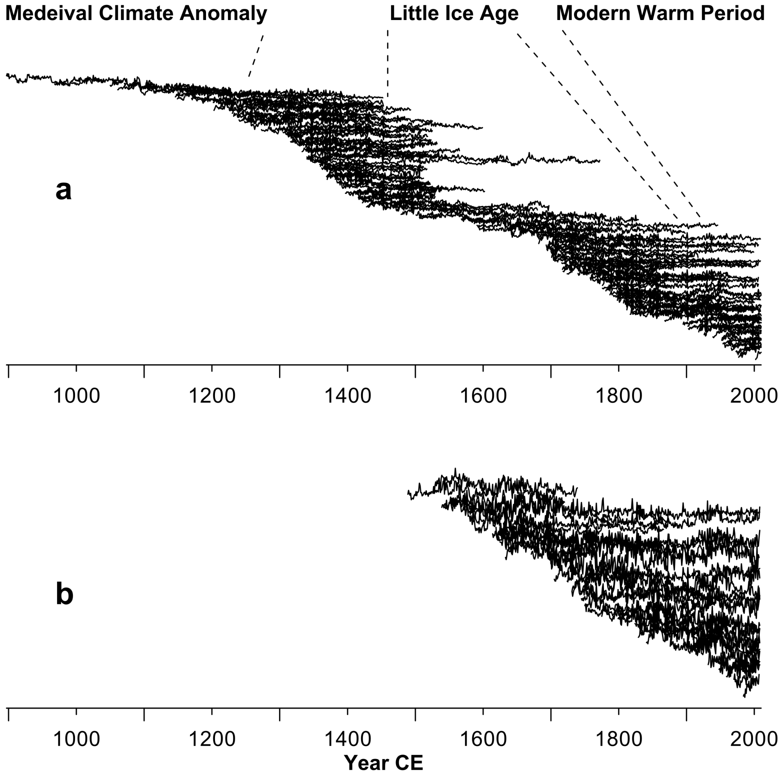

Figure 13. a) All Arjeplog samples through time. b) All Kittelfjäll samples through time. In Arjeplog, there was little deadwood or living wood to be found that germinated between 1550 and 1650 CE. Kittelfjäll is almost exclusively a "modern" chronology, very little deadwood.

3.3.1 Radiodensitometry

The mounted samples from Arjeplog and Kittelfjäll were then prepared according to protocols outlined in Schweingruber et al. (1978) and methodologies in Gunnarson et al. (2011). Most of the data that was produced for this thesis and used with the permission and in collaboration with other researchers were analyzed on the ITRAX multiscanner from Cox Analytical Systems (www.coxsys.se) situated at Bolin Centre for Climate Research, Stockholm University. Yet other data, like the older parts of the MXD data from Torneträsk (Schweingruber et al., 1988) and the massive dataset of N-scan (Esper et al., 2012b) was developed with an analogue methodology, the DENDRO2003 X-ray instrumentation from Walesch Electronic (http://www.walesch.ch). More detailed descriptions of the specific settings and methodologies of the two techniques are given in paper I.

Table 2. Overview of the datasets used in the thesis work. The data include both newly sampled and existing tree-ring records, instrumental observation and reconstructed climate data as well as reconstructed forcings. P.I. stands for principal investigator.

Sitename	**P.I.**	**Time span**	**Analysis/Proxy**	**Reference**	**Papers**
Newly sampled tree-ring chronologies					
Ammarnäs	Gunnarson B.	1277 - 2010	Density/MXD and ΔD	-	I, IV
Arjeplog	Björklund J.	897 - 2010	Density/MXD, EWD and ΔD. Blue Intensity/ MXBI, EWBI and ΔBI	-	II, III, IV
Jämtland	Björklund J.	1192 - 2008	Blue Intensity/ MXBI, EWBI and ΔBI	-	III, IV
Kittelfjäll	Björklund J.	1488 - 2007	Density/MXD, EWD and ΔD	-	I, IV
Rogen	Fuentes M.	985 - 2012	Blue Intensity/ MXBI, EWBI and ΔBI	-	IV
Existing tree-ring chronologies used for analysis and comparison					
Forfjorddalen	Gunnarson B.	925 - 2007	Density/MXD, EWD and ΔD	McCarrol et al., 2013	II, IV
Jämtland	Gunnarson B.	1291 - 2008	Density/MXD, EWD and ΔD	Gunnarson et al., 2011	II, III, IV
N-Scan	Esper J.	(-215) - 2006	Density/MXD, EWD and ΔD	Esper et al., 2012a	II, IV
Tjeggelvas	Gunnarson B.	1455 - 2010	Density/MXD, EWD and ΔD	Gunnarson et al., 2012	I, IV
Torneträsk	Schweingruber FH. Grudd H.	441 - 2004	Density/MXD	Grudd 2008, Melvin et al., 2013	I, IV
Laanila	-	800-2005	Density/MXD	McCarrol et al., 2013	Summary
Existing temperature histories used for comparison					
Northern Fennoscandia	-	Last 2000 years	Pollen data	Bjune et al., 2009	Summary
Northern Fennoscandia	-	Last 1000 years	Marine sediments	Cunningham et al., 2013	Summary
Europe Gridded	-	1500 - 2004	Multiproxy + Instrumental	Luterbacher et al., 2004	Summary
Europe Gridded	-	600 - 2007	Multiproxy (Treerings, documentaries, pollen, icecores	Guiot et al., 2010	Summary
Fennoscandia Gridded	-	442 - 1970	Tree rings/ TRW MXD	Gouirand et al., 2008	IV
Northern Fennoscandia	-	800 - 2005	Tree rings/TRW, MXD, Height and MXBI	McCarroll et al., 2013	III, IV
Forcing records					
Global Solar	-	1000 - 2001	^{10}Be and ^{14}C icecores and tree rings	Muscheler et al., 2007	Summary
Carbon Dioxide concentrations	-	1500-2013	Measurements and icecores	Robertson et al., 2001;Tans, 2014	Summary
Global Volcanic	-	500 - 2000	Sulphate aerosols from icecores	Crowley and Unterman, 2013	Summary
Instrumental climate records					
Jokkmokk, Stensele, Östersund	-	1862-	Temp. Calibration	SMHI	I
NordKlim	-	1890-2001	Correlation decay distance	Toumenvirta et al., 2001	Summary
CRUTEM.4.2.0.0, Gridded 5x5	-	1850-2014	Temp. Calibration	Jones et al., 2012	III
CRU TS3.1, Gridded 0.5x0.5	-	1901-2014	Temp. Calibration	Harris et al., 2013	II, III IV

In principal, x-ray radiation is emitted through a tree sample of known depth and the same is also performed with a reference where both density and depth is known. Using the measurements of the reference, calculations of radial profiles of density can be made on the wood samples (Fig. 14). It is critical that samples are prepared with great accuracy to avoid systematic errors in the analytical step. When cutting the samples into laths, resulting thickness can vary in the range of almost 0.1 mm why every sample is measured with the accuracy of 0.01 mm afterwards. A low accuracy in input thickness will have consequences on the mean value of density that is calculated for each sample. After cutting the samples, they are refluxed with alcohol to remove resins and other components that otherwise are distributed freely over ring boundaries. After approximately 24 hours the extraction rate of these compounds is so low that it is impractical to continue. It has to be assumed that samples are extracted to a point where it has no significant effect on the density measurement.

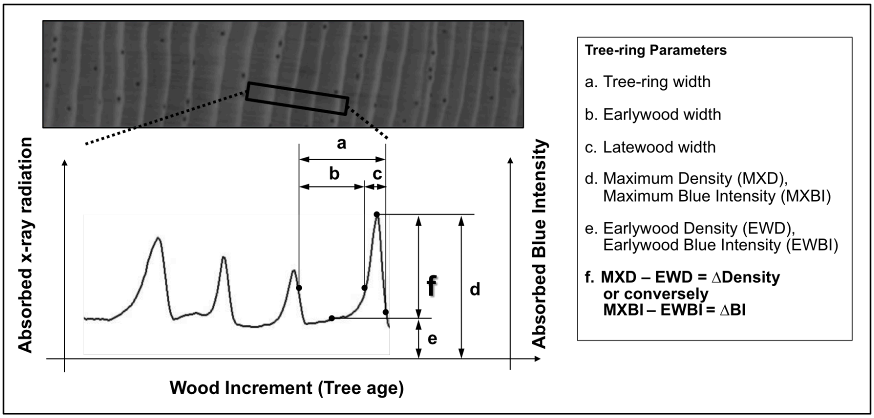

Figure 14. Density and Blue Intensity profiles of a radial section wood. f) indicates the new parameters introduced in this thesis ΔDensity and ΔBlue Intensity.

The fiber angles in the samples need to be exactly parallel to the angle at which the x-rays are transmitted. Even small deviations in angle will yield a loss in focus. This is because fiber sizes, radially, typically are significantly smaller than the 1.2 mm thickness of the sample, and significantly longer in the longitudinal direction. A "smeared" sample, when for example the core is not sampled perpendicular to the growth direction, will give lower peak values of latewood density and higher values of earlywood density because they borrow structures from each other. A twisting of the cores will be less critical, but still result in a loss in focus, and can give problems when analyzing narrow rings. The samples and the x-ray device are stored in a room with controlled humidity and temperature as to make sure that all samples are x-rayed when the wood has a specific water content, typically 12%. If deviations from this occur, density values will be changed according to water content.

Wood density measurements are laborious and all these factors can in the worst case introduce a systematic bias in the low-frequency domain. As much care as possible have been given to these details when preparing the Arjeplog and Kittelfjäll chronologies. Unfortunately, it is likely that Arjeplog has a problem of incomplete extraction, not due to negligence, but probably due to a type of modern sampling bias discussed above. This problem is briefly described in paper II, (see also Fig. 15a Arjeplog MXD). Density chronologies produced by me and other researchers were used in all papers.

3.3.2 Blue Intensity

Campbell et al. (2011) outlined all the necessary steps to produce Blue Intensity measurements in an easy to follow protocol, and these were followed but with some minor modifications (Paper II). The digital images were produced with a flatbed scanner at 1600 dpi resolution (Epson Perfection V600 Series) calibrated with SilverFast Ai professional scan software using the Calibration Target (IT8.7/2). In contrast to the x-ray technique, the BI technique is based on the detection of *reflected* visible blue light instead of transmitted x-rays, and there is no reference available to calibrate the BI measurement into wood density. McCarroll et al. (2002) argued that the variation in BI is mainly caused by the lignin content in the wood, which is a very effective absorber of short wavelength energy (deStevens and Nord, 1951; Schubert, 1965). Even if this is a simplification, the structural components of wood (lignin, cellulose, hemi-celluloses etc.) all occur in similar mass ratios across an annual increment (Dr. Michael Jarvis, Pers. Comm., 2013), and BI should thus be highly correlated with wood density. Furthermore, there is a documented strong relationship between x-rayed wood profiles and scanned wood profiles (McCarrol et al., 2002; Campbell et al., 2007; paper II and III).

Radiographic images are inverted so that the transmitted x-rays represent the absorbed x-ray radiation to be positively correlated with wood density. This thesis introduces a similar protocol to BI by inverting BI images and redefining BI as the absorption of blue light rather than the reflection of blue light; it uses the maximum latewood blue absorption intensity (MXBI) as the more intuitive counterpart to MXD and to make the proxies positively correlated. Consequently, both MXD and MXBI measurements represent the peak values in the latewood each year (Fig. 14). Likewise, measurements of Earlywood Density (EWD) or Earlywood Blue Absorption Intensity (EWBI) can be calculated as the mean value over the earlywood width.

The technical difficulties with the BI technique involve meticulous sanding-preparation of the scanned surface, as well as extraction of movable compounds such as resin that stain the wood. The sensitivity to thickness and fiber angles is much less pronounced than for density analysis, but thicknesses of samples should be kept to less than 4 mm in order for extraction with ethanol to be effective (in-house recommendations). A more exhaustive description of the problems of extractives and BI is given in the summary of paper II, where the low-frequency signal in BI measurements is evaluated. Paper III builds on the results from paper II and tries to resolve issues therein. In the thesis, Arjeplog and Jämtland, two multi-centennial chronologies were used, where parallel BI and x-ray measurements were made. In paper IV, yet another almost-millennium-long BI chronology from Rogen was used with the permission of Mauricio Fuentes, but without parallel density measurements.

3.4 Statistical tools in reconstructions of summer temperature

In papers I and II, response function analysis was applied on first differenced tree-ring and instrumental data to test for climate association. The technique is a variant of principal component regression, which is designed to overcome the problem of co-linearity in the climate predictors. Monthly variables of temperature and precipitation are stripped of common variance and subsequently correlation analysis is performed between the variables and the tree-ring data. This allows an estimation of the period in time that is most influential upon tree-growth. The analysis was performed in software DENDROCLIM2002 (Biondi and Waikul, 2004). In paper III and IV including the actual reconstructions, the growth-climate response from the previous papers was relied upon.

Linear regression is the most widely used method in dendroclimatology for developing models to reconstruct climate variables from tree-ring series. In papers III and IV a simple linear regression was performed where tree-ring data of the current year was the only predictor of the predictand summer temperature (mean JJA temperature). In paper IV, a nested approach (Meko, 1997) was employed to account for the varying temporal coverage of the tree-ring predictors. Regression models were built in a sequential manner for progressively longer periods back in time (so called nests), to account for the changing tree-ring chronology coverage back in time. The calibration period mean and standard deviation of each individual reconstruction nest was scaled to have the same mean and standard deviation as the instrumental temperature data over the calibration period. The nests were then put together to produce a complete full-length temperature reconstruction.

The potential of using Fennoscandian tree-ring data to produce a spatial temperature reconstruction was tested using a point-by-point regression approach (PPR) (Cook et al., 1999). Also here the principal component regression is utilized, in which the PPR is used to reconstruct a single predictand in this case JJA temperatures, from one or more principal component predictors. PPR is built on the assumption that only tree-ring chronologies from sites *proximal* to a given grid point are likely to be the true predictors of climate at that specific point. A circular search radius is centered over the grid point that is reconstructed. All tree-ring data from sites that fall within the circle are retained as candidate predictors for the reconstruction. A search radius of 1500 km was used. All tree-ring chronologies within the search radius were additionally screened (two-tailed 95 % screening probability) in order to eliminate predictors poorly correlated with temperature at the given grid point. All above outlined PPR steps were executed in the Matlab environment following the protocol outlined in Seftigen et al., (2014).

The reconstructions in papers III and IV were calibrated and validated by means of a split-sample strategy. The full-length instrumental climate data (predictand) was split into segments of roughly equal length. Calibration was performed on one half of the data, and the other half was withheld for the validation of the model. The procedure was then repeated with the calibration and validation periods exchanged. In case satisfactory validation statistics were obtained for both validation periods, a final model was constructed using the full available predictand dataset. The skills of the reconstructions presented in papers III-IV were assessed by root mean squared error (RMSE), reduction of error (RE), coefficient of efficiency (CE) (National Research Council, 2006).

Further, in paper III coherence analysis was used to reveal the frequency association between different tree-ring chronologies and between tree-ring chronologies and instrumental data. Coherence analysis is a kind of squared correlation coefficient that depends upon frequency (von Storch and Zwiers, 2004). It is important not to analyze lower frequencies than the diminishing number of degrees of freedom allows, typically frequencies that are less than 30% of the length of the data. The analysis was made with the Anclim software (Štěpánek, 2008). Since the analysis can be associated with large biases in estimates of coherency, and potentially also in the location of coherency peaks (von Storch and Zwiers, 2004), coherency analysis is only used to analyze the impact of different analysis techniques on the same datasets. Additional validation of the reconstructions was made by comparison with independent climate reconstructions (Tab. 2).

4. Summary of papers

4.1 Paper I

Björklund J A, Gunnarson B E, Krusic P J, Grudd H, Josefsson T, Östlund L and Linderholm H W (2013) Advances towards improved low-frequency tree-ring reconstructions, using an updated *Pinus sylvestris* L. MXD network from the Scandinavian Mountains. *Theoretical and Applied Climatology*, 113: 697-710. With kind permission from Springer Science and Business Media

In paper I, an attempt to relax the methodology surrounding the RCS was made to try to retain low-frequency variability and at the same time remove as much of the unwanted variability as possible inherent to the RCS methodology. Five 500-year long MXD chronologies (whereof Ammarnäs and Kittelfjäll being new), with warm season temperature response was employed to test standardization methods based on the assumptions that (1) warm-season temperature variability is spatially homogeneous throughout the studied transect (Fig. 1) and (2) that summer temperature is the main driver of tree-ring variability across the area, which should result in the fact (3) that the low-frequency variability in the tree-ring data should be in common for all five chronologies. The design of the methodology included a simple modification to the RCS methodology by also implementing the signal-free approach. This was done by, first performing a signal-free data-adaptive curve fitting. The curve fitting was done with a spline that becomes progressively less flexible with tree age, the time-varying response smoother (Melvin et al., 2007). The signal-free curves were subsequently aligned by pith-age, and forced to have the same mean as the overlapping segment of the RC or expected growth trend. These modified age-dependent signal-free splines were then used in series of subtraction from the raw tree-ring data; resulting in the "regional curve adjusted individual signal-free approach" termed RSFi, here referred to as RSFi #1 to distinguish it from the further modified version in paper IV termed RSFi #2.

Results showed that using the original signal-free data-adaptive curve fitting yields a more homogenous set of chronologies than the RCS chronologies but without overall trend: that is, less low-frequency variability, and also with the limitation of compressed local mean values if segment lengths are short. The RSFi #1 approach seemed to yield chronologies that displayed both the advantages of the two former approaches without the limitations. No tests were performed to quantify the improved performance, nor are there any conclusive evidence that increased amount of low-frequency variability in the RCS and RSFi #1 chronologies has a climatological origin. The enhanced convergences among chronologies do however suggest a regional-scale common response, likely from temperature, and comparisons with previous reconstructions and solar forcing also suggest that the increased variability has a value to it.

4.2 Paper II

Björklund J A, Gunnarson B E, Seftigen K, Esper J and Linderholm H W (2014) Blue intensity and density from Northern Fennoscandian tree rings, exploring the potential to improve summer temperature reconstructions with earlywood information. *Climate of the Past*, 10: 877-885

In Paper II, the low-frequency information in the tree-ring proxy Blue Intensity is explored. The incomplete extraction of non-structural compounds such as oils, gums, resins and tannins can offset the radiographic density/structural wood density by adding mass to the cell-wall structure (Schweingruber et al., 1978) and can also offset the BI/"lignin-content" by staining the cell-walls (Fig. 15). The contributions from the extractives to MXD or MXBI are not related to photosynthetic activities allocated to specific increments, but rather they represent a response to environmental stress and are freely distributed across ring boundaries (ibid.). This potentially becomes a problem because of the fact that the woody tissue of many coniferous tree species is divided into heartwood and sapwood due to the differential allocation of extractives towards the heartwood (Raven et al., 2004), and if this is not accounted for then a systematic bias is introduced. Moreover, some trees within the same species may produce more extractives than others due to stress or just natural variability. If such trees are not distributed randomly in time, then a similar systematic bias in a climate proxy chronology can occur.

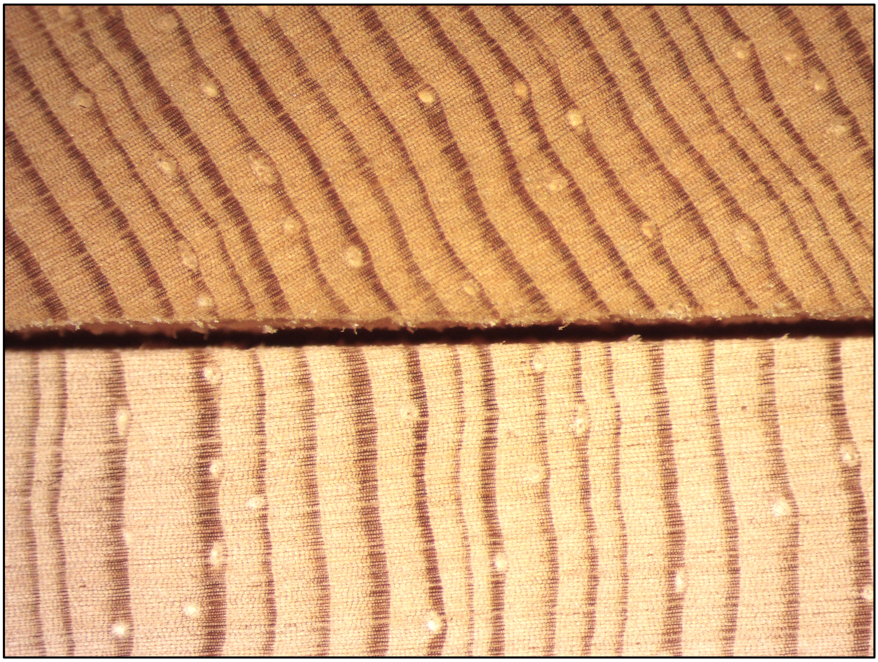

Figure 15. Typical difference in color nuance between dead preserved wood and living-tree wood after extraction with alcohol for 24 hours. It is possible to imagine that even though the density in these wood pieces are very similar the reflected blue intensity from these differ markedly. One can also imagine that the BI values in the latewood have not changed as much as the ones in the earlywood, suggesting the need for a contrast adjustment if used as climate proxy.

To address the issue of biased radiodensitometric/optical measurements, a newly sampled, highly replicated, multi-generation, more than 800-year long Scots pine chronology from Arjeplog, Northern Fennoscandia, was utilized. Both optical and radiographic measurements are made on the *same* cores to directly evaluate their relationship and their climatic signals. A novel approach designed to address the brightness and potential wood density bias in the heartwood/sapwood boundary and among samples is introduced. This method relies on the assumption that the biasing effect is of equal magnitude in the increments of earlywood and latewood. The difference between latewood and earlywood is calculated to give the latewood measurement a baseline, here termed ΔDensity for radiographic measurements and ΔBI for optical measurements.

Based on the Arjeplog Scots pine samples, our results suggest that differential staining is a critical obstacle when trying to create a high-quality climate reconstruction based on Blue Intensity. Furthermore, radiodensitometric measurements can likely also be biased due to the insufficient extraction of movable compounds even though recommended protocols are followed. The Δ-parameter can be used to identify problems with radiodensitometric measurements, and as an alternative or complement to MXD if a shorter target season is required. A noteworthy feature of the new ΔDensity-parameter is that it includes information from the whole ring (also the earlywood), which is more intuitive and informative than only using the maximum latewood density (MXD). This has the benefit of improving the JJA temperature signal on average with 20%. The Δ-parameter only partly works for Blue Intensity. Using ΔBI, high quality decadal- to centennial-scale climate reconstructions can be obtained but >centennial timescales appear to have additional biases. These biases are further addressed in paper III.

4.3 Paper III

Björklund J A, Gunnarson B E, Seftigen K, Zhang P and Linderholm H W The merit of using adjusted Blue Intensity data to attain high-quality summer temperatures information - a case study from Central Scandinavia (Submitted to *The Holocene*)

Paper II showed that it is a marked improvement using the ΔBI parameter in favour of the MXBI parameter. However, the persistent trend in ΔBI does not fully match the trend in ΔDensity that is assumed to be the best estimate of summer temperatures on >centennial timescales. Our hypothesis is that there is not an *equal* contrast between earlywood and latewood BI, shown in paper II, as the degree of staining changes, but there is still *proportionality* in contrast as the degree of staining changes that can be exploited. Section Proxy development in paper III gives a detailed account for how this is done.

Our overall aim is to investigate if RCS-based ΔBI chronologies that take this potential proportionality into account can be a new source of excellent summer temperature information, also on >centennial scales. Results showed that the contrast between earlywood and latewood (the Δ) decreases when samples are more heavily stained by extractives. The phenomenon is quite robust, and a methodology of how to adjust the contrast as degree of staining changes was constructed using parallel radiodensitometric measurements. By exploiting the systematic difference in contrast between earlywood and latewood, we showed that RCS-based contrast-adjusted Scots pine ΔBI chronologies have potential as adequate predictors of past summer temperatures in the Scandinavian region. When combined into a regional composite, the chronology has comparable skill with existing MXD records. We present the first RCS based summer temperature reconstruction using only BI, from multi-generation data from Arjeplog and Jämtland. The introduced approach can likely be applied to BI measurements from other sites in Scandinavia for Scots pine when parallel density measurements are not available. However, we recommend that a small subset of the BI produced also be density-analyzed to contribute to a community-sample used to derive a constantly improving contrast adjustment. This small subset of samples should be encompassing the entire span of the mean brightness in the different sample's earlywood. This would enable maximum leverage in a potential regression against corresponding density measurements.

4.4 Paper IV

Linderholm HW, Björklund J A, Seftigen K and Gunnarson B E Fennoscandia revisited – A spatially improved reconstruction of summer temperatures for the last 900 years (Submitted to *Climate Dynamics*)

In paper IV an updated reconstruction of summer temperatures was made using the novel approaches outlined in paper I, II and III.

Several millennial and multi-millennial reconstructions of various climate parameters (temperature, precipitation, drought etc.), have furthered our knowledge about past climate change, where some of the data has been included in many recent hemispheric to global temperature reconstructions. However, despite the homogenous summer temperature pattern in the region, there are large spreads among the reconstructions, resulting in an uncertainty in the timing and amplitude of past changes.

In an attempt to provide a more spatially coherent view of summer (June-August, JJA) temperature variability within the last millennium, we utilized 7 density and 3 blue intensity Scots pine chronologies collected from the altitudinal (Scandinavian Mountains) and latitudinal (northernmost part) treeline. To attain a strong as possible JJA temperature signal, as well as preserving > century-scale variability, we used the new Δ parameter (Paper II and III), and the RSFi methodology for standardization, introduced in paper I with some further refinements outline below.

Even though summer temperature is the short-term dominating meteorological forcing upon this group of trees, the forcing on longer time-scales may not be as clear on local scales. For this reason it can be useful to include signals from other forests to compare with. Trees that, in the Fennoscandian region grow within the summer temperature correlation decay distance of 500-800 km, arguably share the temperature signal in the lower frequencies. It can then be argued that data from different locations can be run in the same signal-free batch, and later be separated again to use the regional signal-free curves to improve the lower frequencies in each chronology separately. This extended modifications to the RSFi methodology was employed in this paper termed RSFi #2.

The new reconstruction comprises 5 nests of different length and included number of chronologies, but no loss in validation occurred back in time. The average chronology for the region explained over 70% of the variance in mean Fennoscandian summer temperatures, and over 50% for a large part of the same region. Comparing with previous point reconstructions the spatial validity is improved, and comparing with previous gridded reconstructions like Gouirand et al., (2008) the new reconstruction brings added value in terms of skill back in time and it reproduces low-frequency variability, which ibid. did not do.

5. Synthesis

5.1 Density and Low-frequency noise

The great advantage with tree rings as climate proxy is the annual resolution with absolute dating, the possibility of high replication and the quantifiable estimation of the performance as climate archive on annual scales. The limitations include the relatively short length of records (Tabs. 1 and 2), and the skill in the centennial-scale variability. Here the focus is on limitations in the lower frequencies and they include as mentioned above, uncertainties from the sampling, the analysis and from the standardization stages.

Even in Fennoscandia, where many highly replicated, high quality tree-ring chronologies exist; there are large spreads among the published reconstructions of growing season temperatures (Fig. 3), resulting in uncertainty in the timing and amplitude of past climate changes. Studying the MXD records from the sites used in paper IV, also standardized with RCS, the picture is not much clearer (Fig. 16a). The chronology overlap in figure 3 and figure 16 is N-Scan (Esper et al., 2012a), Jämtland (Gunnarson et al., 2011) and Forfjorddalen used in McCarroll et al., (2013), the rest are different. In fact, the spread is even larger for this collection; note the difference between Arjeplog and Tjeggelvas, that are only 40 km apart and very well correlated on annual scale ($r_{annual} = 0.86$, $n = 460$). Since the Arjeplog and Tjeggelvas chronologies diverge so dramatically, where it is assumed that temperatures are identical, it is likely that the sampling, the measurements or standardization or all, causes this divergence. Since the newly sampled chronologies display similar degree of divergence as the established chronologies, little if any improvement at the sampling stage has been achieved.

As discussed in section 3, there are many factors that can compromise density measurements also noted by Helama et al., (2010). However, the novel tool, which is introduced in paper II, could possibly address some of the biases that are associated with the analysis. Using the Δ parameter a more focused annual scale summer temperature signal is attained, where on average, 20% more variance is explained in target temperature. But more importantly, applying the Δ parameter to the density data (Figure 16b), which perhaps can correct for incomplete extraction of resins etc. or degradation of wood, clearly results in a more coherent set of chronologies. One striking result of the Δ transformation is seen in the Arjeplog chronology, where the pronounced negative trend is neutralized. However, Tjeggelvas still stands out as the chronology with the most positive trend. Nevertheless, there are still inconsistencies among the records.

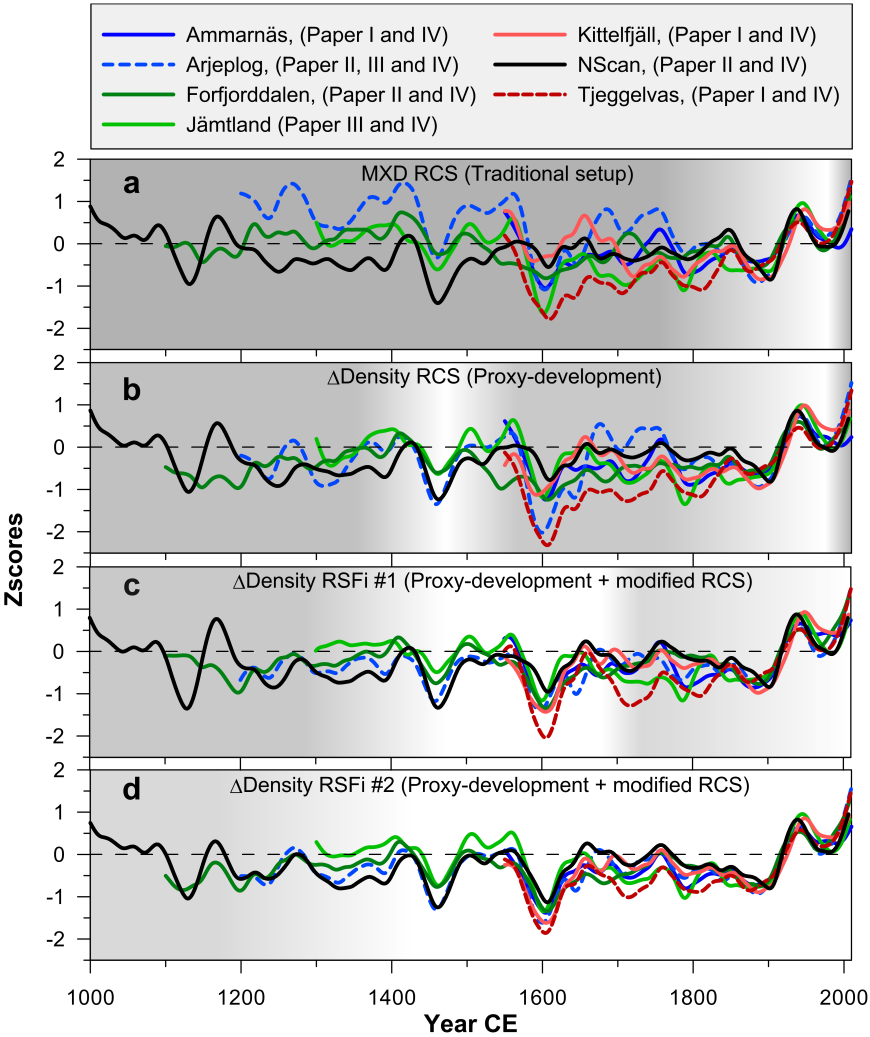

Figure 16. a) MXD chronologies standardized with RCS (Briffa et al., 1992). b) The same sites but with the new parameter ΔDensity. c) The new ΔDensity parameter standardized with the modified RCS protocol from paper I termed RSFi #1, that aims to remove internal disturbances and miss-matches in expected growth and actual growth. d) Same as in c) but with the added modification of running all samples in the same signal-free batch and subsequently averaging chronologies separately, termed RSFi #2. This allows standardization to address also external disturbances. The records are smoothed with cubic smoothing spline with a 50% cutoff at 50 years. Grey areas indicate when records are divergent, and white areas when records convergent and thus provide a more reliable estimation of historical local to sub-regional temperature variations.

Trying the modified standardization technique, the regional curve adjusted individual signal-free approach introduced in paper I (RSFi #1), the chronologies display a greater degree of similarity (Fig. 16c). This methodology was designed to address, internal disturbance pulses as well as inappropriate matches between the shapes of actual growth trends and the shape of the expected growth trend. The results suggest, that these factors do play an important role when trying to reconstruct temperature variability, and that the traditional RCS methodology can give quite large bias in decadal scale variability. Applying the further modified RSFi #2 introduced in paper IV, there is yet again a small improvement (Fig. 16d). This modified version was designed to also be able to address external disturbance pulses that are expressed as common variance in trees at local scales. The original signal-free approach is designed to preserve common variance regardless of the cause, and for this reason it is useful to employ tree-ring data that presumably have similar temperature response but are outside the external disturbance zone. If such a collection of chronologies are run in the same signal-free batch and subsequently separated and averaged, this increases the chance of identifying external disturbances as something non-climatological. This is because the common variance from external disturbances in each chronology is not common variance in such a large group. The external disturbances in a single chronology can thus be identified and removed more effectively. Studying the improvement from figure 16c to 16d, it is suggested that the external disturbances are not as important as the internal disturbances and potential miss-matches in shape between expected growth trends and actual growth trends. Figure 17a and b display the increased coherency in lower frequencies using RSFi #2 instead of RCS, and suggests that there is an added value in addressing also disturbances and miss-matches between the expected growth trend and the actual growth trends when standardizing tree rings for centennial scale climate reconstructions.

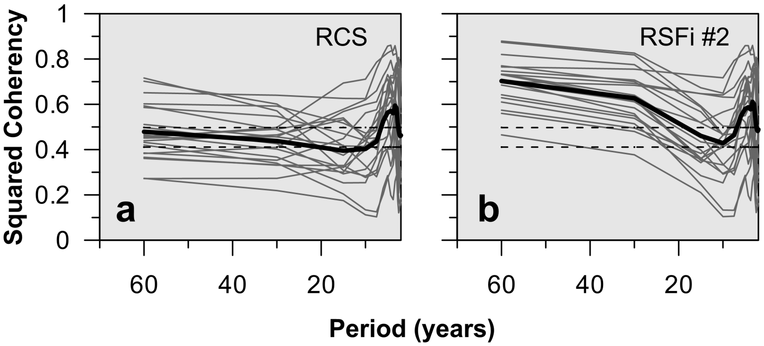

Figure 17. Coherence analysis between all pairs of ΔDensity chronologies (from figure 15), standardized with RCS in a) and with RSFi #2 in b). An increased coherence is evident in decadal scale periods when using the slightly modified RSFi approach instead of RCS. Thin grey lines are coherence between all pairs of the chronologies, and thick black line is the average of these. Dashed lines are significance levels $p = 0.01$ and $p = 0.05$.

A note of caution using RSFi #2: if the actual temperatures at these locations have differed through time, this methodology *will* dampen the effect of this to some degree and before using this methodology, it is important to stress that the dominating factor that is reconstructed should be in common to the sites that are pooled. Since this is a set of chronologies produced with the aim to reconstruct temperatures, and that temperature is demonstrable homogenous in the instrumental period (Fig. 4), the pooled approach RSFi #2, is justifiable.

Still there are some differences in overall trends among the chronologies. These differences can likely be attributed to biased “size” distribution through time (a heterogeneous distribution between slow-growing and fast-growing trees). In each chronology the different growth rates in each tree cause a spread around average values and the modifications and new methodologies has contributed little to reduce this spread. This is because size bias has not been addressed by adjusting for slow-growing or fast-growing cohorts. However, the problem of biased size distribution is small compared to the addressed biases, suggested by the improvement from figure 16a to figure 16d compared with the room for additional improvements. To conclude, the divergent collection of published summer temperature reconstruction in figure 3 is thus likely not a reflection of a more heterogeneous summer-temperature regime back in time, but more likely a reflection of the methodological difficulties associated with 1) attaining a representative sample of the forest from both the modern and the older part, 2) eliminating significant analysis bias, and 3) applying appropriate standardization techniques. The temperature response in tree-line trees in the Fennoscandian region is convergent, but the applied techniques make them appear divergent.

5.2 Blue Intensity and Low-frequency noise

The Blue Intensity proxy, constructed as an inexpensive alternative to MXD (McCarroll et al., 2002), has been shown to be very promising even in the lower frequencies provided that the new methodologies outlined in this thesis work are followed. In Figure 18a, it can be seen that a very steep negative trend will be produced, which is a result of staining from substances like resin (extractives) if MXBI is used. Applying the Δ parameter, by subtracting the staining in the earlywood from the latewood, yields a remarkable improvement. Still, it was shown to be inadequate (paper II) when aiming at retaining information on lower frequencies (see figure 18a, where the ΔBI has a slightly more positive trend than the ΔDensity in figure 18b). Applying some simple adjustments of the contrast, using the contrast between earlywood and latewood in density measurements, improved the results slightly on local site level. By averaging the ΔBI_{adj} chronologies from Arjeplog and Jämtland comparable results to ΔDensity was achieved (Fig. 18b). In Figure 18b it can also be seen that while the ΔBI_{adj} composite chronology (Arjeplog and Jämtland) is very similar to its counterpart, ΔDensity, with 100% data overlap, it is also very similar to a composite ΔDensity chronology with 0% data overlap, constituted by Ammarnäs Forfjorddalen, Kittelfjäll, Tjeggelvas and N-Scan. This means that using this new methodology, it is possible to produce these high-quality chronologies at a significantly lower cost and higher production rate. This new method will make it possible to increase sample replication in individual chronologies and to spatially extend networks of chronologies and this likely lead to more confident reconstructions of temperature in the Boreal belt. Even if the Blue Intensity has slightly higher low-frequency noise-level than density, the amount of replication that can be achieved with BI compared to density for the same cost, would likely lead to more confident reconstructions in future work.

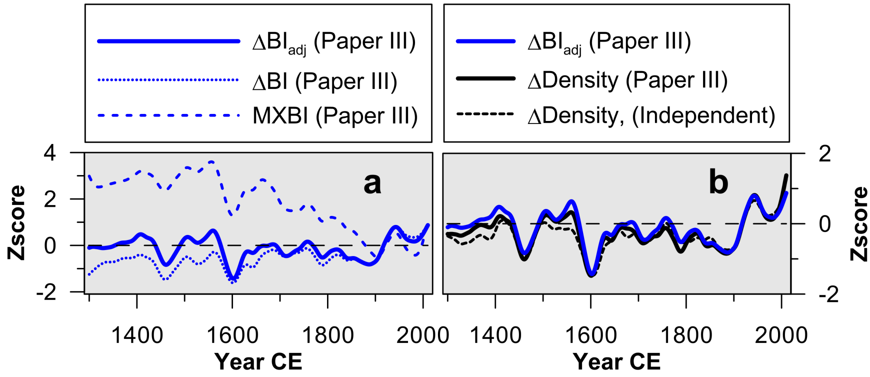

Figure 18. a) The three Blue Intensity Arjeplog and Jämtland composite chronologies from the parameters MXBI (dashed blue), ΔBI (dotted blue) and ΔBI_{adj} (solid blue). b) ΔBI_{adj} (solid blue line) together with the corresponding ΔDensity chronology (solid black line) and also a completely independent ΔDensity chronology consisting of Ammarnäs, Forfjorddalen, Tjeggelvas, Kittelfjäll and N-Scan. The records are smoothed with cubic smoothing spline with a 50% cutoff at 50 years.

As a note of caution, it should be kept in mind that these tests were only performed on two chronologies, and more tests are needed to firmly establish the usefulness of the contrast-adjusted BI parameter. The next step will be to aim for a large number of BI measurements and perform a few parallel measurements with density, to add to the pool of parallel measurements already started in this thesis, to further evaluate this methodology.

5.3 Comparison with Fennoscandian summer temperature reconstructions

The reconstruction presented in paper IV (H14) constituted by both ΔDensity and ΔBI_{adj}, is not the first reconstruction of summer temperatures in the region and therefore comparisons with other reconstructions can be made. The H14 and the low-resolution reconstructions based on marine sediments and pollen (Cunningham et al., 2013; Bjune et al., 2009) perhaps have the LIA and modern warm period in common, but it is difficult to make the comparison more detailed than this due to dating issues and the different sampling resolutions of the reconstructions.

Comparing with annually resolved reconstructions like Gouirand et al. (2008) (G08); Guiot et al. (2010) (G10); Luterbacher et al. (2004) (L04) that are also gridded and cover the Fennoscandian region much like (H14), is however easier. Even though the G10 reconstruction for the Fennoscandian region contains a large amount of tree-ring data, it does not correlate at all with H14 (Fig. 19a) and is also poorly correlated with the instrumental temperatures for the region. The reconstruction is based on tree-ring data but exclusively TRW, and some of this data is poorly correlated with growing season temperatures. Also the more suitable TRW data included in G10, is mainly correlated with a shorter time window; the month of July, because TRW from the northernmost part of Fennoscandia is mostly formed during this month (Seo et al., 2008).

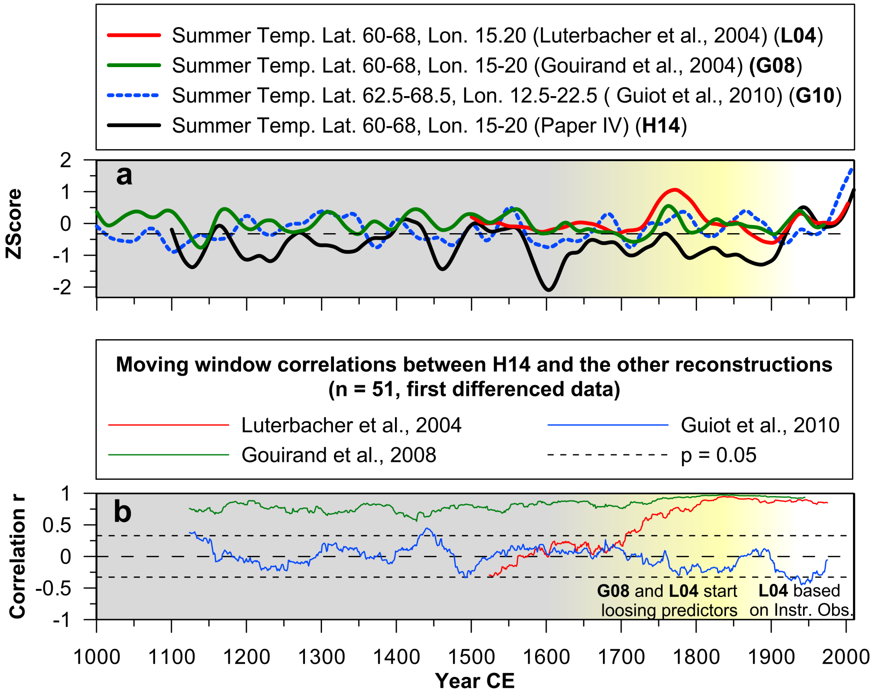

Figure 19. Four gridded reconstructions of summer temperature for the Fennoscandian region, L04, G08 and G10 together with the new reconstruction from paper IV, H14. a) The records are adjusted for means and scaled for variance in the period 1900-2000, also they are smoothed with cubic smoothing spline with a 50% cutoff at 50 years. b) Moving window correlations between the H14 and the other records, all records were first differenced before correlation and (n=50 years).

The L04 reconstruction however, is mainly based on instrumental temperature measurements the last 150 to 200 years and should be highly correlated with H14. Figure 19a shows the two reconstructions smoothed with a 50-year spline, and they display similar variations during 1900-2000 (all records are scaled for mean and variance during this period). Before this, they diverge. The main difference is that H14 does not display the pronounced warm period around 1800 CE seen in the L04. Examining the individual chronologies in H14, none of them display this pronounced positive period (Fig. 15). Examining the long instrumental records that cover this period in Europe, also included in L04 (Stockholm, Trondheim, Central England, Geneva, Berlin, St. Petersburg and De Bilt) they all have more or less positive summer temperature anomalies during this very period (Shabalova and Weber, 1998), why L04 naturally display this. However, regarding instrumental temperatures during this period, insufficient radiation protection were likely used, and this is thought to have biased measurements positively by up to 0.7-0.8°C (Luterbacher et al., 2004).

Moberg et al. (2003) concluded that it is very likely that both the long Stockholm and Uppsala records (the only instrumental predictors in L04 prior to 1802) are positively biased and that this bias concern the period before 1858. If this is the case, the L04 and H14 would converge during this time and better reflect the high annual scale correlations between the two records in figure 19b. The very high moving window correlations between H14 and L04 during 1800-2000 CE is replaced prior to this by gradually lowered correlations being insignificant between 1500 and 1700 CE. Since the L04 predictor-configuration changes from instrumental data to exclusively TRW and documentary data earlier than ca. 1750 CE and the H14 predictor-configuration remains unchanged, it is suggested the H14 is more to be trusted prior to 1750 CE, and perhaps even prior to 1860 CE due to potential inconsistency in the early instrumental data.

Focusing only on Fennoscandia, Gouirand et al. (2008) showed that it is possible to provide a reliable reconstruction of summer temperatures for the whole of this region provided that also data from its central parts is included. Comparing H14 with the G08 record, the moving window correlations are very high throughout their lengths, but with slightly lower correlations before 1750 CE. This is also the time when G08 start to loose most of its tree-ring predictors. The G08 is exclusively made out of tree rings as is H14 (principal components from MXD and TRW from scots pine and Norway spruce), but there is no overlap in data. The records' similarity on annual scale thus highlights the skill of tree rings to reflect temperature variability in higher frequencies. The G08 is standardized with data-adaptive curve fitting, which largely disables comparisons of changes on centennial scales, as can be noted in the low variability in the record compared to the H14 composite. However, on decadal scales, positive and negative up and downturns are quite synchronous, suggesting that should G08 be standardized in a similar manner as H14, the records would be very similar. The H14 thus contribute with a more robust view of how the temperature history during the last 900 years have evolved because of G10 not being appropriate, L04 having lower performance when instrumental data is not included in the reconstruction and G08 unable to reflect centennial scale variability due to standardization technique, but also due to lower quality in predictors prior to ca. 1700 CE. Records such as Torneträsk (Melvin et al., 2013), Jämtland (Gunnarson et al., 2011), N-Scan (Esper et al., 2012b) and the multiproxy record NFEN presented by McCarroll et al. (2013) have comparable skill to H14, but lack the spatial component offered by the gridded reconstruction in paper IV, and the added value of being a coherent dataset.

5.4 Remaining challenges and future outlook

This thesis work is certainly not the first study to try to reconstruct summer temperature with tree rings in Fennoscandia, but it is one of the first to try to review and address the limitations and divergences that occur in the literature. As Esper et al. (2012b) put it "despite the high number of high-resolution proxy records in northern

Fennoscandia, which are individually well calibrated against observations, the summer temperature evolution during the last millennium is still not well understood". This thesis work has provided a little more understanding about the temperature evolution from the period 1100 CE to today. It has been made clear in this thesis that to also have a better understanding about the "Medieval Climate Anomaly" this period also need to be covered by an extended number of density chronologies, and they need to be treated with improved methodologies, such as the ones outlined in this thesis. The records that are available today are excellent on their own (Melvin et al., 2013; Esper et al., 2012b), but to some degree contradictive. Therefore the remaining future challenge is to continue to verify the adjusted Blue Intensity scheme and by making longer and more such chronologies as well as more density chronologies to cover MCA, to better understand this debated periods' temperature expression (Fernandez-Donado et al., 2012; Ljungqvist et al., 2012; PAGES 2k Consortium, 2013) in this region, and also elsewhere.

6. Major Conclusions

1) The previously un-exploited Δ parameters can provide a test for long MXD chronologies of identifying systematic biases, and it also has the benefit of providing added focus to the summer temperature signal with on average a 20% increase in signal strength (paper II)

   The modifications of the inexpensive optical measurement scheme adjusted ΔBlue Intensity enables tree-ring data to also contain comparable centennial scale information. These findings potentially enable a denser network of high-quality tree-ring data since Blue Intensity is much less expensive than density measurements (paper II and III)
2) The modifications to the existing standardization methods have been shown to provide a more coherent set of tree-ring data on decadal to centennial scales, because of the ability to address biases arising from internal and external disturbances, and miss-matches in the shape of the expected growth trend compared with the actual growth trend (paper I and IV)
3) Applying the modifications outlined here to newly-developed and existing tree-ring data in the Fennoscandian region generates chronologies with higher coherence: the temperature history back to at 1550 CE is here covered by 10 coherent chronologies both on annual scale and centennial scales. The temperature history back to 1100 CE is also better known than before, both in a temporal and spatial sense, but since fewer chronologies cover this period less can be said for the coherence (paper III and IV)

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