Thesis for the Degree of Doctor of Philosophy

Late Holocene spatiotemporal hydroclimatic variability over Fennoscandia inferred from tree-rings

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This dissertation is dedicated to my family, for their love, support and understanding.

ABSTRACT

There is a broad scientific consensus that the global climate is changing, and that human activity is a significant factor contributing to the change. The response of the hydrological cycle to the warming is far reaching, including increases in the intensification and frequency of extreme hydroclimatological events. The underlying physical mechanisms driving this changes are poorly understood, and the observational record, which rarely predates the 20th century, is too short to resolve the full range of natural moisture variability or make predictions of longer-term hydroclimatic patterns. Tree-rings provide precisely dated and annually resolved paleoclimatic archives, which can be used to infer climate in the pre-instrumental era. Focused on the Fennoscandian region, the core efforts of this dissertation work are (1) to examine the potential of Fennoscandian tree-ring data as proxies of past moisture variability, (2) to increase the network of moisture sensitive tree-ring chronologies in the region, and finally (3) to combine the newly sampled data with already existing dendrochronological material to develop a first spatiotemporal reconstruction of Fennoscandian hydroclimatic variability spanning over the past millennium.

A unique network of twenty-seven moisture sensitive chronologies was provided for southern and central Scandinavia. A subset of the network, combined with existing tree-ring data, was used to produce the first regional hydroclimatic reconstruction, as expressed by the Standardized Precipitation Index (SPI), for southeastern Sweden, spanning the last 350 years. The reconstruction revealed decadal scale alterations in wet and dry regimes, and proved xeric-site tree-ring data from the region to contain valuable hydroclimatic information. Moreover, a pilot study using Scots pine tree-ring carbon ($\delta^{13}C$) and oxygen ($\delta^{18}O$) measurements from the central Scandinavian mountains assessed the potential of each record as a proxy of local moisture conditions. Results showed that both isotope ratios recorded the moisture signal strongly enough to be used as a proxy of past hydroclimatic conditions. Based on these results, the potential of using multi-parameter tree-ring data (including ring-width, maximum latewood density, stable isotopes) from Fennoscandia to make spatiotemporal reconstructions of past moisture variability was first tested, and then applied to produce an “atlas” of past hydroclimatic conditions, defined by the Standardized Precipitation-Evapotranspiration Index (SPEI), spanning back to 1000 CE. The resulting reconstruction gave a unique opportunity to examine the frequency, severity, persistence, and spatial characteristics of Fennoscandian climate variability in the context of the last 1000 years. The reconstruction highlighted the 17th century as an epoch of frequent severe and widespread hydroclimatic anomalies, and the 15th-16th centuries as surprisingly free from any spatially extensive droughts/pluvials. No explicit shifts towards more frequent and intense extremes over the region were observed in the reconstructed data over the most recent century. Moreover, the analysis suggests that the spatial hydroclimatic patterns over Fennoscandia may be divided into two major modes, remarkably stable over the past seven centuries, and that the controls on these patterns may come from the summer North Atlantic Oscillation.

Keywords: Tree-rings, Fennoscandia, hydroclimate, SPEI, SPI, ring-width, maximum latewood density, stable isotopes, field reconstruction, Point-by-point regression.

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
Seftigen, K., Linderholm, H.W., Loader, N.J., Liu, Y., Young, G.F.H, 2011: The influence of climate on $^{13}C/^{12}C$ and $^{18}O/^{16}O$ ratios in tree ring cellulose of Pinus sylvestris L. growing in the central Scandinavian Mountains. Chemical Geology 286, 84-93.

   K. Seftigen prepared the data, conducted the data analysis (mass spectrometry work was conducted by N.J. Loader), visualized the results, and contributed to the bulk of the writing.

II. Paper II
Seftigen K., Linderholm, H.W., Drobyshev, I., Niklasson, M. 2013: Reconstructed drought variability in southeastern Sweden since the 1650s. International Journal of Climatology 33, 2449-2458.

   K. Seftigen initiated the paper, collected and prepared the data, conducted the analysis, visualized the results, and contributed to the bulk of the writing.

III. Paper III
Seftigen K., Cook, E.R., Linderholm, H.W., Fuentes, M., Björklund, J.: The potential of deriving tree-ring based field reconstructions of droughts and pluvials over Fennoscandia. (In review, *Journal of Climate*).

   K. Seftigen initiated the paper, collected and prepared the data, conducted the analysis, visualized the results, and contributed to the bulk of the writing.

IV. Paper IV
Seftigen K., Björklund, J., Cook, E.R., Linderholm, H.W.: A field reconstruction of Fennoscandian summer hydroclimate variability for the last millennium. (Manuscript).

   K. Seftigen initiated the paper, collected and prepared the data, conducted the analysis, visualized the results, and contributed to the bulk of the writing.

Peer reviewed papers not included in the thesis:

Liu, Y., Linderholm, H. W., Song, H., Cai, Q., Tian, Q., Sun, J., Chen, D., Simelton, E., **Seftigen, K.,** Tian, H., Wang, R., Bao, G., An, Z. 2008: Temperature variations recorded in Pinus tabulaeformis tree rings from the southern and northern slopes of Qinling Mountains, central China. Boreas 38, 2: 285-291.

Linderholm, H.W., Björklund, J., **Seftigen, K.,** Gunnarson, B.E., Grudd, H., Drobyshev, I., Jeong, Liu Y. 2010: Dendroclimatology in Fennoscandia - from past accomplishments to future potentials. Climate of the Past 6: 93-114.

Drobyshev,I., Niklasson, M., Linderholm, H.W., **Seftigen, K.,** Hickler, T., Eggertsson, O. 2011: Reconstruction of a regional drought index in southern Sweden since AD 1750. The Holocene 21: 667 - 679.

Seftigen, K., Moldan, F., Linderholm, H., 2013: Radial growth of Norway spruce and Scots pine: effects of nitrogen deposition experiments. European Journal of Forest Research 132: 83-92.

Björklund, J., Gunnarson, B., **Seftigen, K.,** Esper, J., Linderholm, H.W.: Introducing ΔMXD and ΔBI, a dendroclimatological case study in Northern Fennoscandia. (In review, *Climate of the Past*).

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I. Summary

II. Papers I-IV

Part I

Summary

1. Introduction

1.1 Motivation

The Intergovernmental Panel on Climate Change (IPCC) states that the frequency and intensity of extreme climatic events, such as droughts and floods, are likely to increase in a warmer future climate [IPCC AR5]. Northern Europe has experienced an overall increased annual mean precipitation over the last decades (fig. 1), and projections indicate that extreme precipitation events are likely to become more frequent and intense by the end of the this century [Meehl et al., 2005]. Hydrological extremes often have severe social and economic consequences, such as shortage of food, water, and energy. It has also the potential to cause severe direct and indirect impacts to the environment, e.g. by affecting soil and water quality, wildlife habitat, and increasing the stress on endangered species [EEA, 2004]. Major uncertainties and gaps in knowledge still exist when it comes to understanding and modeling the climate related to the hydrological cycle, hampering the ability to quantify future changes in hydrological variables and their impacts on systems and sectors. Hence, to overcome this problem, the IPCC has recently called for a refined and extended research related to the components of the hydrological cycle [IPCC AR5].

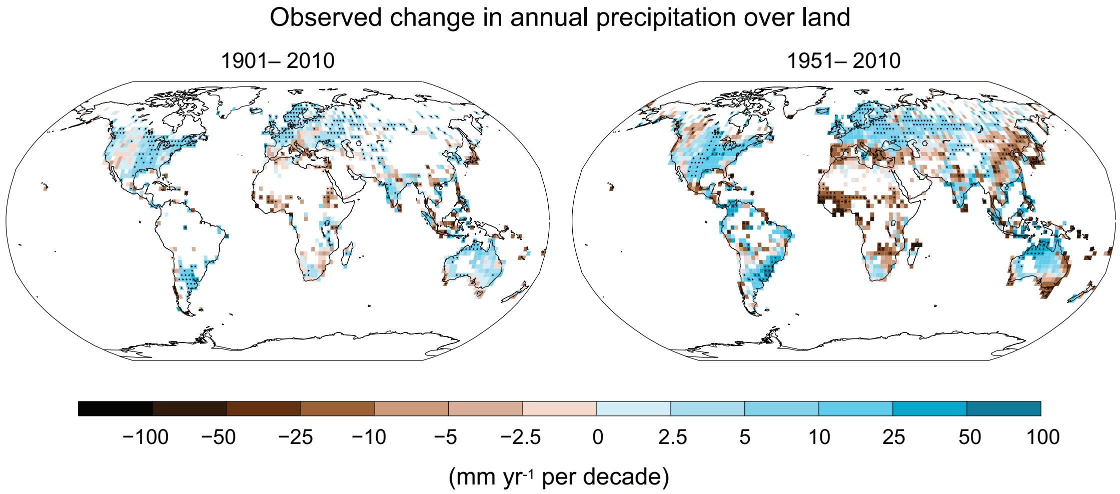

Figure 1. Observed precipitation changes recorded between (*left*) 1901-2010, and (*right*) 1951-2010. Figure taken from IPCC AR5 [2013].

Understanding the causes of extreme moisture events, especially the severe multi-year events, are essential if reliable strategies of prediction and mitigation are to be developed. Yet, the instrumental record of climate is too short to capture the full range of natural climate variability and to elucidate the underlying physical mechanisms for changes in the hydrological cycle. Tree-rings can help alleviate this problem, by providing continuous annually resolved records of past hydroclimatic variability for regions or periods with no instrumental climate data; however, dendrochronological reconstructions of past moisture variability are thus far mostly limited to arid and semiarid regions of the world.

1.2 Background

1.2.1 High-resolution reconstructions of past variations in hydroclimate

When it comes to temperature, there exist a plethora of studies reconstructing past variability on local to global scales, with a decent global coverage [e.g. PAGES 2K Consortium, 2013]. However, due to a lack of highly resolved proxies outside arid or semi-arid regions, it is difficult to achieve a global, or hemispheric, view on past hydroclimate fluctuations. Efforts are now being made to increase the spatiotemporal information of past variability, for instance within the PAGES 2K network [http://www.pages-igbp.org/workinggroups/2k-network], to better understand how hydroclimate changes are related to climate forcings and internal variability in the climate system, but also to provide information to near-term climate predictions.

The most successful high-resolution reconstructions of past moisture variability have been based on tree-ring derived climate proxy indicators. Tree-ring data has not only the advantage of having annual resolution, allowing it to be calibrated against instrumental data, but offers the hydrological sensitivity and spatial availability that are crucial to reconstruct past moisture patterns. A variety of hydroclimatic variables, including precipitation, drought, streamflow, salinity, and snowpack have previously been estimated from tree-ring parameters [e.g. Stahle et al., 2001; Woodhouse 2003; Büntgen et al., 2009]. Although the majority of this work has involved single point climate reconstructions, providing information over limited geographical areas, network of tree-ring chronologies have also been shown to offer the potential of spatial climate reconstructions. Presently, several successful attempts have been made to reconstruct “atlases” of past moisture variability, based in tree-ring data, for dry to semi-dry regions across the globe: North America [Cook et al., 1999, 2004], Monsoon Asia [Cook et al., 2010], central High Asia [Fang et al., 2010], arid to semihumid East Asia [Hua et al., 2013], Northwestern Africa [Touchan et al., 2011], and the Mediterranean region [Nicault et al., 2007]. These studies have not only provided a long-term context for 20th century hydroclimatic variability that is crucial for climate modeling, prediction, and attribution studies, but have also revealed the occurrence of past, previously unknown, droughts in ways never before possible.

1.2.2 Holocene hydroclimatic changes over Fennoscandia

Holocene hydroclimatic fluctuations in Fennscoandia are and have long been an important research focus for paleoclimatologists. The substantial body of research that exist has mainly focused on terrestrial and marine sediments, peat stratigraphy and peat initiation as records of long-term moisture variations. Consequently, we now know that significant fluctuations in climate have occurred in Northern Europe through the last 10.000 years. The early stage of the Holocene (approx. 11.500–8.000 calibrated years BP), and especially the 8.300-8.000 cal. BP interval, is generally considered to have been wet in the North Atlantic region. The so-called 8.200-year event, which is present in many of the regional moisture reconstructions, was originally identified as a distinct depletion in $\delta^{18}O$ of Greenland ice cores [Johnsen et al., 1992; Grootes et al., 1993; Alley et al., 1997], and was attributed to a major meltwater discharge that retarded the North Atlantic thermohaline circulation [Barber et al., 1999; Renssen et al., 2001]. The consequence of such an event was a 200-400 year period of cooling over the North Atlantic region, and related decreases in evaporation, leading to elevated lake-levels throughout Scandinavia [e.g. Korhola, 1995; Hammarlund et al., 2003 and 2005] and re-advances of mountain glaciers in the Scandinavian mountain range [Dahl and Nesje, 1996; Nesje et al., 2001]. Evidence points towards a generally dry and warm mid-Holocene (approx. 8.000-4.000 cal. years BP). The period coincides with a major reduction in the glacial activity in southern Norway [Dahl and Nesje, 1996; Nesje et al., 2001], elevated tree-lines, increased abundance of several warmth-demanding species [Digerfeldt, 1977; Lagerås, 1996] as well as a general lowering of the Scandinavian lake levels [Barnekow, 2000; Seppä et al., 2005; Hammarlund et al., 2005]. Over the late Holocene (approx. 4.000 cal. BP-present) the climate in Fennoscandia shifted once again towards wetter conditions [Harrison and Digerfeldt, 1993; Korhola, 1995; Bjune et al., 2004; Hammarlund et al., 2003 and 2005; Seppä et al., 2005]. A major change in the atmospheric circulation pattern over Northwest Europe seems to have taken place at about this time, perhaps as a result of a weakening of North Atlantic thermohaline circulation, as shown by declining sea-surface temperatures and salinity [Duplessy et al., 1992; Ko**c** and Jansen, 1994].

Many of the proxy records (e.g., lake sediments, peat stratigraphy) that have been used to infer past large-scale humidity fluctuations over Fennoscandia are not accurate on an absolute timescale. The time resolution of these data varies, and depends on the accuracy of the stratigraphic age control. While the records provide unique perspective on millennial- to centennial-scale variations and trends, most of these types of paleo-proxies are not resolved at annual timescales. Complementing these records with highly resolved and absolutely dated hydroclimatic proxy data, such as tree-rings, is therefore vital if information on a wider range of past moisture variability is to be obtained.

1.2.3 Prior studies of tree-ring moisture records in Fennoscandia

Tree-ring data from the Fennoscandian region has previously been considered of limited use in reconstructing past hydroclimatic conditions [Erlandsson 1936; Eklund 1954]. This is because the geographical location of Fennoscandia does not, in general, provide the dry conditions needed for trees to be strongly limited by moisture availability, which is the case in many semi-arid and arid regions. Thus, the growth of trees in cool and moist climates of high latitude regions is rather dependent on the thermal conditions of its surrounding environment, especially during the growing season, than moisture availability. It is therefore not surprising that most dendroclimatological research conducted in the Nordic countries mainly has been focused on developing temperature-sensitive tree-ring width, maximum latewood density, and, to a lesser extent, tree-ring $\delta^{13}C$ and $\delta^{18}O$ chronologies, to infer past temperature variability [Linderholm et al., 2010], and that comparatively few efforts have been made to explore the potential of the Fennoscandian tree-ring data in hydroclimatic reconstructions. The handful attempts that have been made have all been conducted either in the southern and central parts of Sweden [Linderholm et al., 2004; Linderholm and Molin, 2005; Linderholm and Chen, 2005; Jönsson and Nilsson, 2009; Drobyshev et al., 2011] or in the southeastern Finland [Helama and Lindholm, 2003; Helama et al. 2009]. No tree-ring based hydroclimatic reconstructions have up to this point been conducted for Norway.

The longest two reconstructions were provided for the southeast of Finland [Helema and Lindholm, 2003; Helama et al., 2009]. Helema and Lindholm [2003], used ring-width data of Scots pine (*Pinus sylvestris* L.) to reconstruct early summer (May-June) rainfall variability in the southeast of Finland back to A.D. 874, capturing approximately 30% of the variance in the instrumental record. Scots pine in these areas seldom lives more than a few hundred of years. Hence, in order to extend the reconstruction beyond the past millennium, the ring-width data from the living trees were complemented with data from dead wood material from historical buildings and from tree logs preserved in lacustrine sediments at the bottom of small lakes. The chronology was later updated with more tree-ring records and used to extend the precipitation history of southeastern Finland back to 670 CE [Helama et al., 2009]. Perhaps the most striking feature of this reconstruction was the distinct and persistent drought, "megadrought", from the early 9th century to the 13th century, supporting the concept of a Medieval Climate Anomaly.

In Sweden, the first attempt to infer information of past moisture variability from trees was made by Linderholm et al. [2004]. The authors presented a 300-yr long xeric-site Scots pine ring-width chronology from Tyresta National Park, east-central Sweden, and compared it to long observational precipitation and temperature records from Stockholm. May-June precipitation was identified as the overall main limiting factor for the tree-growth in the area, explaining roughly 30% of the variability in the radial tree-growth. However, it was also noted that this relationship was temporally unstable, and that the tree-growth was occasionally responding to summer temperatures rather than precipitation, especially during exceptionally dry spells. In a subsequent study Linderholm and Molin [2005] used the Tyresta chronology to reconstruct past summer drought, as defined by the Standardized Precipitation Index (SPI). By combining the reconstruction with historical written records from the area, moisture variability over the past 250 years was assessed, and the 1806-1832 period was identified as the longest continuous drought interval over the last centuries. Another study from the eastern parts of central Sweden was provided by Jönsson and Nilsson [2009], who demonstrated that Scots pine growing on shingle fields could be used to infer information of past precipitation. Rather than only using annual ring-width data, they based their reconstruction model on the widths of early and late wood, as well as the entire ring width. The resulting calibration model was able to capture more than 45% of the early summer (May-June) precipitation, and allowed a reconstruction back to 1560 CE. Hence, using a multi-proxy tree-ring approach, Jönsson and Nilsson [2009] were able to improve the precipitation signal provided by previous studies in Fennoscandia. The reconstruction, being in good agreement with previous proxy based hydroclimatic reconstructions from the region, identified the 1694-1751 period as a rather marked spell characterized by overall low variability and below average precipitation. The period was tentatively associated with the Late Maunder Minimum, the coldest phase of Little Ice Age.

Tree-ring derived precipitation/drought reconstructions in Fennoscandia have almost exclusively been restricted to tree-ring parameters obtained from Scots pine. The main reasons for this are the sensitivity of the species to moisture availability, as well as its wide spatial distribution and rather long longevity. However, quite recently Drobyshev et al. [2011] was able to demonstrate that also Pedunculate oak (*Quercus robur* L.) can be used in hydroclimatic reconstructions. The authors developed regional drought reconstructions, defined as the ratio of actual to equilibrium evapotranspiration, for two areas in the northeastern and southwestern parts of southern Sweden, respectively, from a network of eight Pedunculate oak chronologies and one Scots pine chronology. The reconstructions explained between 30 and 45% of the variance in the observed data, respectively, and were able to extend the regional drought history roughly to the mid-18th century.

Most attempts to gain climate information from tree-rings in Fennoscandia have focused on the warm season. However, Linderholm and Chen [2005] showed that temperature sensitive Scots pine tree-ring width data from west-central Scandinavia also could provide information on cold season precipitation on semi decadal time scales. They developed a 400-year long winter (September-April) precipitation reconstruction with a 5-year resolution, explaining 45% of the instrumental precipitation variability. The driest winters were identified in the beginning of the 18th century, whereas the latter part of the 20th century was suggested to be the wettest in a 400-year context.

All the tree-ring derived hydroclimatic reconstructions provided for Fennoscandia have hitherto focused on exploring the temporal aspects of past moisture variability. Yet, hydroclimatic variability is a complex spatiotemporal process. Hence, in order to be able to assess the nature and cause of past moisture variability firm knowledge of its spatial characteristics is needed.

2. Aim and objectives

The overall aim of this thesis is to provide the first spatiotemporal hydroclimatic reconstruction for Fennoscandia using a dendroclimatological approach, and to use it to explore the length, frequency and severity of historical dry and wet periods in the region and their spatial extent.

The specific objectives are to:

- Examine the character, strength, spatial coverage and stability of climate signal in $\delta^{13}C$ and $\delta^{18}O$ in tree-ring cellulose of Scots pine from a tree-line site in central Sweden for potential as hydroclimatic predictors (paper I),

- Increase the network of xeric site tree-ring width chronologies throughout southern and central Sweden, and, focusing on southeastern Sweden, evaluate its potential in a regional reconstruction of past summer moisture availability (paper II),

- Apply a multi-proxy approach to dendroclimatology in order to infer and verify information of 20th-century temporal and spatial moisture variability in tree-rings (paper III).

- Provide an annually resolved "atlas" of past warm-season moisture variability over Fennoscandia for the last millennium (paper IV).

The first objective is dealt with in in paper I. The paper is examining and discussing the potential of tree-ring stable carbon and oxygen isotopes of Scots pine from the central Scandinavian Mountains as a climate proxy. As far as I know, this is the first published study of isotope dendroclimatology conducted in Sweden.

Paper II provides a regional reconstruction of past moisture variability for southeastern Sweden, as expressed by the SPI, spanning back to the mid-17th-century. The reconstruction, based on ring-width data from Scots pine growing mostly in drought-prone areas, lack any spatial component, but is regional in the sense that it provides information of the average moisture condition for the target area.

In papers III and IV, the objectives related to spatiotemporal reconstructions of past hydroclimate over Fennoscandia are addressed. Paper III focus on the instrumental era only, and explores the potential of using Fennoscandian tree-ring data, including ring-width, maximum latewood density, and stable isotopes parameters, in a field reconstruction for the region. The reconstruction methodology applied is the point-by-point regression approach. Paper III lays the groundwork for paper IV, providing the methodology and dataset used to produce the millennium long spatiotemporal hydroclimatic reconstruction that is presented therein. The field reconstruction is used to assess spatial and temporal aspects of the past ten centuries. Finally, major hydrocliamatic patterns are identified in the instrumental era, and the robustness of these patterns over time using the field reconstruction is evaluated.

3. Theory and methods

3.1 Climatic setting of the Fennoscandia

The thesis work includes local (paper I), sub-regional (paper II) and finally regional scale analyses (i.e. referring to the entire Fennoscandia; papers III-IV). Hence, the spatial area, geographical location, climatological and topographical settings of the study domains of the work presented in papers I-IV varies considerably, but reflects a logical progression in describing more and more complex systems and processes. The descriptions of these specific settings are given in papers I-IV, whilst a broad overview of the geographical and climatological characteristics of the full study domain is given in the current section.

This work is focused on Fennoscandia, defined here as Norway, Sweden and Finland. The climate in the region is greatly influenced by the adjacent North Atlantic Ocean and by the topography of the region. The Scandinavian Mountain range crosses Norway and the central and northern parts of Sweden in a SW-NE direction (fig. 2A), and divides Fennoscandia into two climatically different zones: a more oceanic in the west and a more continental in the east of the mountain divide. 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]. The highest annual rainfall amounts, mostly of orographic origin, occur along the west coast and in the Scandinavian mountain range, where locally, annual precipitation may reach 2500mm (fig. 2B). The continentality generally increases towards the east, although slightly moderated around the Baltic Sea and towards the Arctic Ocean in the north (fig. 2C).

The climate variability over the region has been tightly linked to the North Atlantic Oscillation (NAO), a mode commonly defined as the difference in normalized sea level pressure (SLP) between the Icelandic low and the Azores high [Hurrell, 1995]. In a general sense, the NAO is a measure of strength of the westerly winds blowing across the North Atlantic Ocean in the 40°-60°N latitude belt. When the NAO index is high (i.e. an accentuated pressure difference between the two action centers), the westerly winds are stronger than normal, on which the dampening effect of the North Atlantic Ocean will lead to warmer and wetter than normal weather conditions over Fennoscandia and the rest of the Eurasian sector. When the NAO index is low the westerly winds are relatively weak and the influence of cold continental air masses increases in Fennoscandia. Although NAO is an important feature of atmospheric variability throughout the whole year, it is less dominant during the warmer seasons [Wanner et al., 2001]. Applying an eigenvector analysis to the fields of North Atlantic-European high summer (July-August) mean SLP Folland et al. [2009] identified a structure similar to that of winter NAO. The summer pattern, denoted as the SNAO, has a smaller spatial extent than its winter counterpart, and has its southern action lobe located over northwestern Europe, rather than over the Azores, and a smaller-scale northern through positioned over Greenland. The SNAO exerts a strong influence on the northern European weather through changes in the position of the North Atlantic storm tracks. Positive SNAO phases, with northward shifted storm tracks, favors warm, dry and relatively cloud-free conditions over Northern Europe, especially over the British Isles and much of Scandinavia. Conversely, cold, wet and cloudy summers prevails during negative SNAO phases.

3.2 Fieldwork

All new data presented in papers II-IV were collected during multiple fieldwork campaigns between 2008 and 2011. The strategy of these campaigns was to increase the number of existing moisture sensitive tree-ring chronologies throughout southern and central Sweden, as an expanded network of moisture-sensitive chronologies may provide critical information about the spatial extent and patterns of past moisture variability in the region and give key insight into their underlying controls. The site selection is of crucial importance when seeking hydroclimatic information from Fennoscandian tree-rings, since, as previously mentioned, the moisture influence on the tree growth in the region is usually weaker than that of temperature. The sites targeted for sampling were therefore almost exclusively drought-prone environments. These could for example be slopes, characterized by thin soil layers and a high runoff, or permeable sandy glaciofluvial deposits (fig. 3). As in many other parts of the world, the overall dynamics and structure of the forest ecosystems in the Nordic countries have fundamentally been altered by humans over the course of the past centuries. Selective logging was introduced in mid-19th century, aiming at the largest (and often the oldest) trees in the forest. Logging on the larger scale took place throughout Sweden in the late 19th century, whereupon much of the forested areas were cleaned of dead trees [Holmgren, 1959]. Hence, a major obstacle for dendroclimatic studies in the region is to find old enough trees that could bring the resulting climate reconstruction beyond the instrumental era and as far back in time as possible. One solution to this problem is to extend the tree-ring chronologies with material from dead and subfossil trees. However, unlike in the northernmost parts of Scandinavia, the moist and temperate climate of southern Sweden does not provide favorable conditions for preservation of organic material, and it is therefore extremely hard to find dead tree material that have been preserved for more than a century or so. The field campaigns within the frames of this thesis work were focused on sampling living trees only, growing in the few old-growth forests that still remain in southern and central Sweden. These forests are often either protected or growing in more or less remote and not easily accessible areas. During the sampling procedure two cores were extracted from each tree using an increment borer. The number of trees sampled varied between 20 and 50 at each site, in most cases covering all available age classes. The sampling campaign resulted in two updated ITRDB chronologies, and twenty-seven chronologies from previously unsampled sites (fig. 2A).

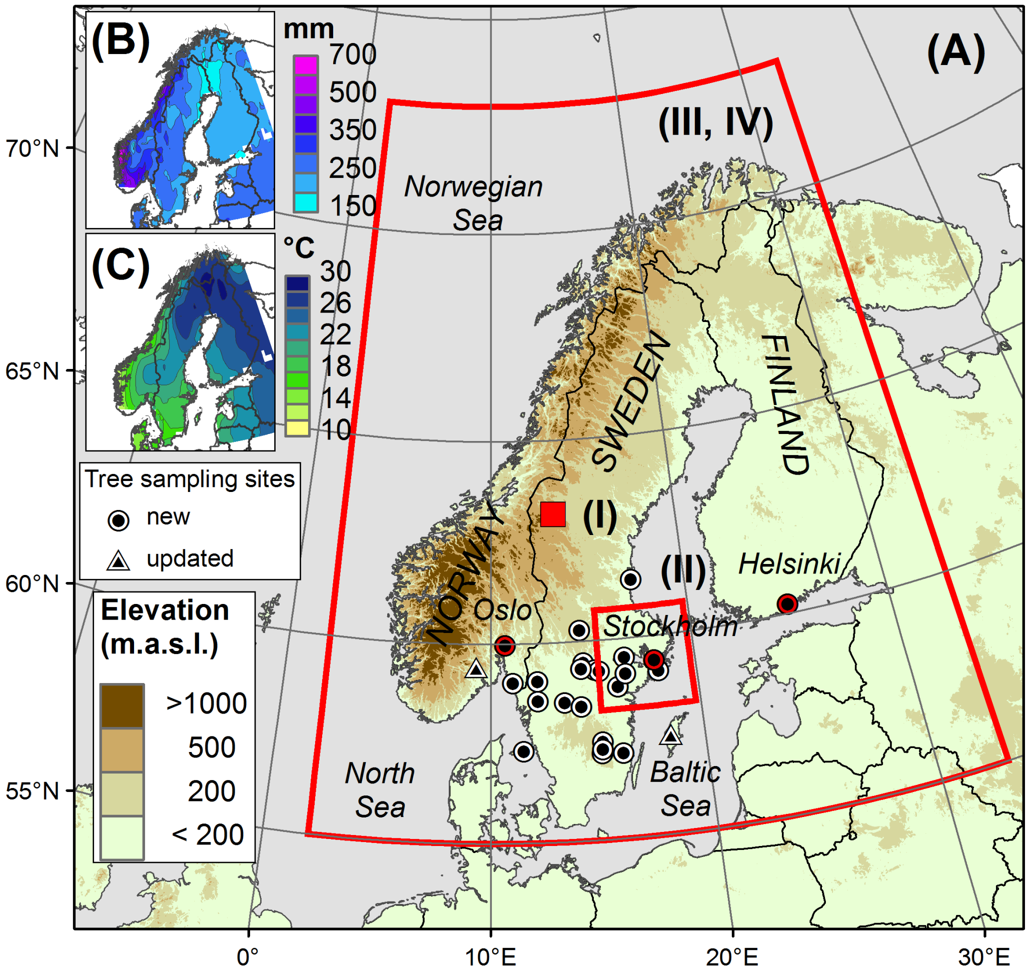

Figure 2. A: Topographical map of the study region, with the specific study domains of papers I-IV marked out in red. B: warm season (May-August) precipitation distribution, and C: continentally (defined as the difference between July and January temperatures) over the region. Plots B and C are based on gridded CRU TS3.0 dataset over the twentieth century [Harris et al., 2013].

3.3 Development of TRW chronologies

Back in the laboratory, 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 0.001 mm using a stereomicroscope connected to a Lintab measurement table and the Time Series Analysis Program (TSAP) software [Rinn, 1996]. To exclude possible measurement biases and to correctly ascertain the year in which each tree ring was formed, the samples were cross-dated through the matching of ring-width patterns of cores from each tree and among different trees from the same site. This procedure was performed visually and verified statistically using the COFECHA software [Holmes 1999].

All the tree-ring data sampled within the frames of this thesis work, except from one site in the southernmost of Norway, were clustered in the southern and central parts of Sweden (fig. 2A). However, since the goal of this thesis was to provide moisture reconstruction for the full Fennoscandian domain it was not possible to restrict the predictor network to just the newly sampled chronologies. Additional tree-ring data were thus downloaded from the International Tree-Ring Data Bank [ITRDB; www.ncdc.noaa.gov/paleo/treering.html; Grissino-Mayer and Fritts, 1997]. These data included annual ring-width (TRW; data used in papers II-IV), and maximum latewood density (MXD; papers III-IV) chronologies of Scots pine and Norway spruce (*Picea abies* L.) sampled throughout Norway, Finland and (mostly in northernmost parts of) Sweden. Also, annually resolved tree-ring $\delta^{13}C$ and $\delta^{18}O$ chronologies of Scots pine and Pedunculate oak was kindly contributed by colleagues to the network utilized in paper III.

The radial growth of trees is commonly affected by their age, manifested generally as a monotonically declining growth rate with tree maturation [Fritts, 2001]. It is often desirable to remove this non-climatic trend, as well as trends related to e.g. the height within the stem and geometry [Cook and Kairiukstis, 1990], prior to use of the tree-ring data in paloclimate studies. The procedure of trend removal, commonly referred to as standardization or detrending, rescale the data from each tree converting it to dimensionless indices. Many of the tree-ring sites included in the current work were characterized by closed-canopy conditions. The tree-growth at these sites was thus more or less affected by competition and disturbance histories. In order to make sure that the long-term variations present in the radial increment was climate-related, and not caused by tree-competition and tree ageing, a rather flexible curve fitting standardization was applied to the data. The functions used included a negative exponential curve, a regression line, or a straight line (paper II), a 35-year cubic smoothing spline with a 50% frequency response cutoff (paper III), and a Friedman Super Smoother with a smoothing parameter of 7 (paper IV). The standardization procedures outlined in papers II and IV were performed in the computer program ARSTAN [Cook and Krusic, 2005] where also variance stabilization was applied to the detrended series in order to remove variance fluctuations caused by changing sample size [Osborn et al., 1997]. Because of the huge amount of data in paper III it was not feasible to use ARSTAN. Hence, the standardization was performed in Matlab environment. Each tree-ring series were divided (or subtracted in case of MXD) by the value of the fitted curve. The dimensionless series from each site were then averaged together to produce site chronologies. The Expressed Population Signal statistic [EPS; Wigley et al., 1984], a measure of chronology quality, was used to determine the usable length of the chronologies retained for reconstructions outlined in papers II and III, whereas in paper IV chronologies were simply cut where the number of series comprising each chronology dropped below ten.

Figure 3. Photos from the fieldwork, showing the diverse characteristics of the sampling sites. *Upper left*: core extraction from 200-year Scots pine growing Tresticklan National Park; *upper right*: the mountainous area of southern Norway, *middle right*: 500-year old Scots pine growing on the rocky slopes of Salboknös nature reserve. *Bottom*: the island of Gotland, eastern Swedish archipelago- one of the most drought prone sampling sites. The trees here are growing on extremely thin soils, overlaying plateaus of sedimentary rock.

3.4 Development of the tree-ring $\delta^{13}C$ and $\delta^{18}O$ chronologies

Stable isotopes of the main constituents of tree-rings, elements of carbon (C) and oxygen (O), have previously been shown to provide paleoclimatic and environmental reconstructions with a perfect annual resolution [McCarroll and Loader, 2004]. This section summarizes the theory of isotope fractionation in tree-rings, and describes the analytical work behind isotope chronology construction.

3.4.1 Theory

During photosynthesis trees and C3-plants discriminate between the lighter isotope of carbon (^{12}C) and the heavy stable isotope of carbon (^{13}C). This fractionation primarily takes place during the diffusion of CO_2 from the free atmosphere into the intercellular leaf spaces and during carbon fixation catalyzed by the carboxylating enzyme ribulose bisphosphate carboxylase (RuBisCO). The mechanisms behind the incorporation of carbon isotopes in C3-plants can be explained by the model developed by Farquhar et al. [1982] and described for trees by Francey and Farquhar [1982]:

$$\delta^{13}C_{plant}(‰) = \delta^{13}C_{atm.} - a - (b - a)\left(\frac{c_i}{c_a}\right) \quad (1)$$

where: $\delta^{13}C_{plant}$ and $\delta^{13}C_{atm}$ are the stable isotope ratios of photosynthetically fixed carbon and atmospheric CO_2, respectively. Fractionation which occurs due to diffusion (≈ 4.4‰) is denoted as a, while b refers to the fractionation associated with carboxylation (≈ 27 to 28‰). The factors c_i and c_a are the CO_2 concentrations at the reaction sites (internal) and in the environment (plant atmosphere), respectively. The c_i/c_a ratio is directly related to the CO_2 assimilation rate (A) and stomatal conductance (g_s), i.e. the rate of CO_2-transfer from the surrounding air into the stomata cells [Francey and Farquhar, 1982; fig. 4]:

$$c_i = c_a - \frac{A}{g_s} \quad (2)$$

Both A and g_s are dependent on several environmental factors; while the rate of photosynthesis is mainly controlled by photon flux and temperature, the rate at which CO_2 diffuses through the openings of the stomata is closely linked to the soil moisture status and air relative humidity [McCarroll and Loader, 2004]. In a dry and warm environment, where soil moisture is the major limiting factor for tree growth, stomatal apertures are reduced in area to conserve the plant's water. Stomatal conductance declines accordingly, thereby leading to lower c_i-values. In these cases, the amount of photosynthetically assimilated ^{13}C will increase, i.e. the $\delta^{13}C_{plant}$ will increase [Winter, 1981]. If, on the other hand, moisture is not a limiting factor, the stomata will open up to optimize the CO_2 assimilation, and the photosynthetic rate will dominate the fractionation. In such situation the $\delta^{13}C$-composition of the plant will be positively correlated to high summer temperatures and/or many sunshine hours during the season of growth [Lipp et al., 1991; McCarroll and Pawellek, 2001].

The $\delta^{18}O$ variability in tree ring cellulose is a result of (1) the $\delta^{18}O$-composition of the source water taken up by the plant, which can be ground water and/or precipitation, (2) the fractionation that may occur during transpiration, leading to enrichment of $\delta^{18}O$-values of the leaf water, (3) and the fractionation occurring during cellulose synthesis (fig. 4). Groundwater is relatively stable in its $\delta^{18}O$-composition, but is directly dependent on that of precipitation. The $\delta^{18}O$ in the precipitation ($\delta^{18}O_p$) changes with condensation temperature, origin and transport of the air mass, amount of rain [e.g. Dansgaard, 1964]. Warm conditions result in enriched $\delta^{18}O_p$ while cold conditions give depleted $\delta^{18}O_p$. The water uptake through the roots and the subsequent transport of water via xylem to the leaves/needles does not involve any fractionation of the oxygen isotopes [Ehleringer and Dawson, 1992]. However, an isotopic enrichment of the heavier $H_2{}^{18}O$ can takes place in the leaf water relative to the source water at the sites of evaporation ($\Delta^{18}O_e$). The following model describes this effect [Craig and Gordon 1965; Dongmann et al. 1974]:

$$\Delta^{18}O_e = \varepsilon^* + \varepsilon_k + (\Delta^{18}O_v - \varepsilon_k)\frac{e_a}{e_i} \qquad (3)$$

where $\varepsilon^*$is the fractionation associated with the proportional depression of water vapour by the heavier $H_2{}^{18}O$, and ε_k is the fractionation due to the diffusion of water vapor through the stomata and the leaf boundary layer. $\Delta^{18}O_v$ denotes the $^{18}O/^{16}O$ ratio of the water vapor in the atmosphere, and e refers to the partial pressure of water vapor in the ambient air (e_a) and in the leaf intercellular spaces (e_i). Thus, where source water and the water vapor of the bulk air have the same isotopic composition the $\Delta^{18}O_e$ is linearly dependent on 1 - e_a/e_i [Barbour et al., 2001]. Trees growing in conditions with high relative humidity (i.e. high e_a) will experience a lower enrichment due to transpiration compared to trees growing in drier environments [Yakir and Sternberg, 2000]. The Craig and Gordon model may however overestimate the leaf water enrichment [e.g. Flanagan et al., 1991], especially during conditions when transpiration rate is high [Barbour et al., 2004]. This phenomenon, the so-called Péclet effect, has been ascribed to an exponential gradient of isotopes within a leaf, which arises when enriched water is hindered to diffuse away from the evaporation sites of the leaf by the convection of unenriched source water to the sites where evaporation take place [Farquhar and Lloyd, 1993]. Due to this effect the $\delta^{18}O$ variations of tree cellulose will tend to be damped compared to the variations in the leaf water.

3.4.2 Stable isotope analysis

Tree-ring cores for stable isotope analysis were provided by H. Linderholm. These were sampled using an increment corer from living and dead Scots pine trees at a tree-line site in the central Scandinavian mountains (fig. 2a). Annual tree-ring increments, including both earlywood and latewood and dated to their precise year of formation, were separated under magnification using a scalpel. The rings from different cores that were formed during the same calendar year were then pooled, and processed to isolate α-cellulose by successive elimination of non-cellulose components from the wood [Loader et al., 1997]. The resulting purified α-cellulose samples were homogenized in deionized water using a Hielscher ultrasonic probe in order to ensure complete homogeneity within each sample pool, and then freeze-dried for 48 h prior to the mass spectrometry.

For carbon isotope analysis, 0.30-0.35 mg samples were loaded into tin foil cups, and combusted (1000 °C) over Cr_2O_3 and CuO. For oxygen isotope analysis, 0.30-0.35 mg dry α-cellulose samples were weighted into silver foil cups and pyrolised (1090 °C) over glassy carbon. The isotopic compositions were expressed as conventional $\delta^{13}C$ and $\delta^{18}O$ values, measured as deviation in parts per thousand (‰) from VPDB and VSMOW standards.

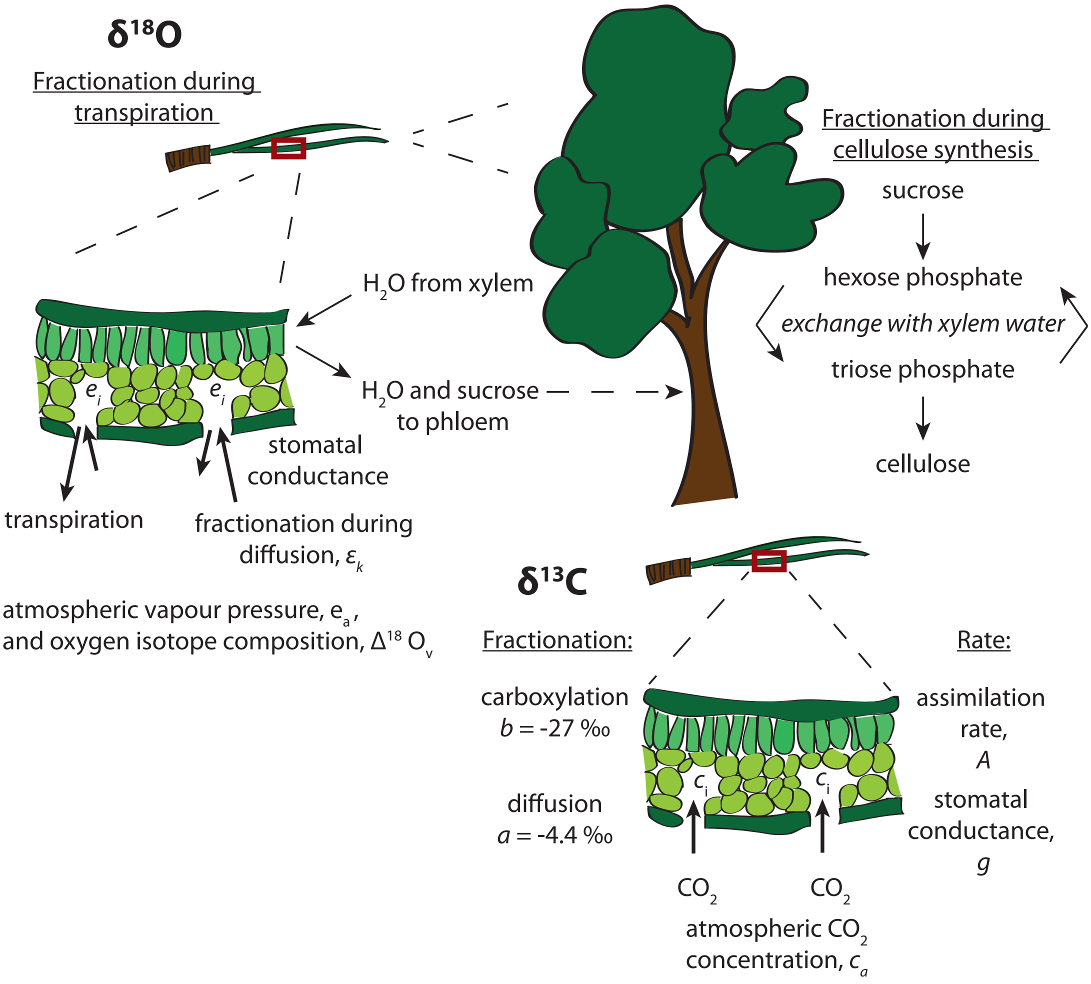

Figure 4. A simplified schematic picture of (*top*) oxygen and (*bottom*) carbon fractionation in trees (see text for explanation and equations). The figure is adapted from McCarroll and Loader [2004].

3.5 Modeling past hydroclimatic variability

3.5.1 Measures of regional moisture availability

Many quantitative measures have been developed to capture the aridity or moisture of a given area. In this thesis work, two different indices were selected: the Standardized Precipitation Index (SPI) and the Standardized Precipitation-Evapotranspiration Index (SPEI). The former is easily computed and can be derived over multiple time scales, and was therefore chosen as the target climate data in the reconstruction provided in paper II. However, temperature may have a profound effect on the availability of water, by influencing the evapotranspiration rates. Indices that include temperature in their formulation have therefore been shown to be preferable. Hence, the relatively recently developed SPEI was used as the target climate field in papers III-IV.

Table I. Classification of dry and wet events defined by the SPI.

SPI value	Category
>= 2.00	Extremely wet
1.50 – 1.99	Severely wet
1.00 – 1.49	Moderately wet
0 – 0.99	Mildly wet
0 – -0.99	Mild drought
-1.00 – -1.49	Moderate drought
-1.50 – -1.99	Severe drought
<= -2.00	Extreme drought

SPI, provided by McKee et al. [1993], is simply the number of standard deviations that observed cumulative precipitation deviates from the climatological mean. Computation of SPI is basically a transformation of precipitation time series into a standardized normal distribution (z-scores). It involves fitting a gamma probability density function to the frequency distribution of precipitation totals summed over the time scale of interest, and then transforming it into a standardized normal frequency distribution. This is performed separately for each month (or whatever temporal scale of the raw precipitation time series) and for each location in space (station or a grid point in case of gridded climatology). The classifications of wet and dry SPI events are given in table I. The SPI dataset used in paper II was generated from the CRU TS 3.10 0.5° x 0.5° gridded precipitation data, using the program provided by The National Drought Migration Center[1] to compute the index. The target climate data for the reconstruction was an average of 46 grid points located over the southeast of Sweden (fig. 2A, II).

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[1] http://drought.unl.edu/MonitoringTools/DownloadableSPIProgram.aspx

Table II. Climate datasets, observed and reconstructed, used in papers I to IV. P refers to precipitation, and T to temperature.

	Paper I	Paper II	Paper III	Paper IV
Station data [a]	Bredkälen ($\delta^{18}O_{prec.}$), Duved (monthly T, P), Frösön (sunshine, hourly), Storlien-Visjövalen (station-level pressure), Trondheim-Vaernes (monthly T)	Stockholm (monthly P)		
Gridded data	CRU TS 3.00 [b] (T)	CRU TS 2.10[c] (P)	SPEIbase v1.0[d], CRU TS 3.00 (P, T)	SPEIbase v1.0, CRU TS 3.20 (P, T), Trenberth and Paolino, 1980 (SLP)
Monthly reanalysis fields	NCEP/NCAR Reanalysis (1000 hPa geopotential height)	NCEP/NCAR Reanalysis (500 hPa geopotential height)		NCEP/NCAR Reanalysis (500 hPa geopotential height)
Monthly climate indices				SNAO (UCAR, Folland et al., 2009), NAO (Jones et al., 1997)
Historical reconstructions		Jönsson and Nilsson (P), Helama et al., 2009 (P), Luterbacher et al., 2002 (500hp geopotential height)		Luterbacher et al., 2002 (500hp geopotential height),

[a] Data provided by the Swedish Hydrological and Meteorological Institute (SMHI).
[b] [Harris et al., 2013]
[c] [Mitchell and Jones, 2005]
[d] [Vicente-Serrano et al., 2010]

SPEI, the second type of index used in the thesis work (papers III and IV; fig. 5), came from relatively new global gridded dataset developed by Vicente-Serrano et al. [2010; available for download at http://sac.csic.es/spei/index.html; SPEIbase v1.0]. SPEI is based on the climatic water balance, which is simply the difference between precipitation (*P*) and potential evapotranspiration (*PET*) for month *i*:

$$D_i = P_i - PET_i \tag{4}$$

Thus, D_i provides a simple measure of the water surplus (deficit) for the month of interest. Estimation of *PET* (mm month^{-1}) is made according to the Thornthwaite water balance model [Thornthwaite, 1948], which only requires data on mean monthly air temperature and the geographical location of the site of interest:

$$PET = 16\left(\frac{10T}{I}\right)^{a} \tag{5}$$

Where T is the monthly mean air temperature (°C), $a = 0.49 + 0.0179I - 0.0000771I^2 + 0.000000675I^3$, and I is the annual thermal index. The latter is the sum of monthly indices i:

$$I = \sum_{i=1}^{12}\left(\frac{T}{5}\right)^{1.514} \tag{6}$$

The computation of SPEI is based on a similar approach used to derive SPI. However, instead of gamma probability density function, a log-logistic probability distribution function is fitted to the series of D_i. The resulting SPEI commonly range between -2.5 and 2.5 (corresponding to exceedance probabilities of 0.006 and 0.994, respectively), where, similar to SPI, negative values corresponds to dry conditions, and positive to wet.

3.5.2 Proxy-climate relationship

Table II provides the instrumental and reconstructed datasets used in the analyses outlined in papers I to IV. The associations between the tree-ring proxy data and the climate variables were estimated mainly by Pearson product-moment correlation coefficient, and the significance of the sample correlation was established with a t-test [Snedecor and Cochran, 1989]. The persistence in the tree-ring and climate data was accounted for by computing the effective sample size [Dawdy and Matalas, 1964; paper I], or reduced by converting the time-series into first-differences, filtering with a high-pass filter, or prewhitining (see next section). In addition simple correlation, response function analysis was applied in paper II to test for climate association. The technique is a variant of principal component regression (see section 3.5.4), which is designed to overcome the problem of collinearity in the climate predictors. The analysis was performed in software DENDROCLIM2002 [Biondi and Waikul, 2004].

A strong association exists between temperature and precipitation over the study region. Hence, in order to get the “real” correlation between the tree-ring parameters and temperature and precipitation, respectively, partial correlations were computed in paper III, where the influence of the climate variables on one another was removed prior to correlation.

3.5.3 Prewhitening

The persistence from the time-series of tree-ring data (and climate data, paper III) was removed using a low-order autoregressive (AR) model (papers II-IV):

$$x_t = \sum_{i=1}^{p} \phi_i x_{t-i} + e_t \tag{7}$$

Where x_t is the is the climate or the tree-ring series, p is the order of the model, ϕ_i is the AR parameter at lag i years, e_t is the resulting series of "white noise". The order p was selected by the Akaike Information Criteria [Akaike, 1974]. The prewhiting was performed to (1) remove biologically-related persistence from the tree-ring data, and thereby amplify the contemptuous climate signal in the data, (2) correct for the difference in the short-lag autocorrelation between climate and tree-rings, and (3) give the data serially random properties in order to simplify the test of association between tree-ring data and climate (see section 3.5.2).

3.5.4 Principal Component Analysis

Principle Component Analysis (PCA) is a data reduction technique that transforms the original variables (e.g. tree-ring chronologies or climate data) into a smaller set of uncorrelated variables (principle components). The first few components encompass the bulk of the variability in the original variables. Hence, the method can be used to identify principle modes of variance within a dataset. Two different modes of decomposition were used in the PCA within this work: S-mode (papers III and IV) and T-mode decompositions (paper IV). The former one is the most commonly applied within dendroclimatology, and is used to find persistent patterns in the data over time, while the latter one is used to find recurrent patterns in space [Machado-Machado et al., 2011]. Both approaches were based on correlation matrices, describing the relationship between the input variables. In the S-mode PCA, which is one of the main building blocks of the point-by-point nested regression approach (method used for climate field reconstruction, see next section), the correlations were computed between normalized tree-ring chronologies over their common interval. The purpose of the procedure was to reduce the number of chronologies into just a few variables explaining the bulk of the variance (the presumable climate signal) in the tree-ring data. In the T-mode PCA correlation was computed between the annual fields of gridded SPEI data. The purpose of the procedure was to identify the major patterns of droughts and pluvials through space.

3.5.5 Reconstruction techniques

Multiple linear regression is the most widely used method in dendroclimatology for developing models to reconstruct climate variables from tree-ring series. In paper II, a stepwise regression was applied to establish the relationship between June-July SPI and a regional ring-width chronology, averaged from a total number of seven site chronologies from southeastern Sweden, and to generate estimates of SPI beyond the instrumental period.

There are different methods that can be used to produce spatially resolved reconstructions of climate fields (e.g. canonical correlation analysis, point-by-point regression, and regularized expectation maximization). The method to spatial reconstruction outlined in papers III and IV is the point-by-point regression approach (herein, abbreviated as PPR). The method is essentially a variant of the principal component regression, which in PPR is used to reconstruct a single predictand (the climate time series at a given grid point) from multiple predictors (tree-ring chronology time series) [Cook et al., 1999].

PPR is build 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. Two different methods have been used to define "proximal" (paper III), a search radius (SR) method and a correlation contour (CC) method. In the SR approach a circle, with a defined radius, is centered over the grid point that is reconstructed. All tree-ring data from sites that falls within the circle are retained as candidate predictors for the hydroclimatic reconstruction. The CC approach is a little bit more sophisticated than the former one, and may be a more appropriate method in environments characterized by a high spatial heterogeneity in climate. Figure 5 illustrates the difference between the SR and CC methods. Spatial CCs are computed between the climate data of the target grid point, and the surrounding gridded climate field. The CCs will indicate the similarity in climate between the target point and the surrounding areas. Trees growing at sites with similar climate to the target grid point are assumed to be the best predictors for the reconstruction, since they are most likely capturing the climate signal that is reconstructed (i.e. they are significantly correlated with the predictand). Hence, all tree-ring data that was located within a defined CC were retained as candidate predictors. In order to establish the "right" values for the CC and SR multiple PPR runs were conducted, where the CC and SR varied over a wide range of values (paper III). The spatial and temporal properties of each resulting climate field reconstruction were assessed. The CC and SR values that produced reconstructions that most closely mimicked the spatiotemporal properties of the instrumental climate field were retained for the final reconstruction. This testing indicated that a SR of 210 km and a CC of $r = 0.76$ are optimum for deriving a field reconstruction of hydroclimate over Fennoscandia, using the tree-ring network that is available within this thesis work.

After the candidate chronologies have been located around the grid point for which the climate reconstruction is to be obtained, the reconstruction is derived through the following subsequent PPR steps:

1. There is no guarantee that the located tree-ring chronologies will have a significant relationship with SPEI at the specific grid point. In order to exclude data that are poorly correlated with SPEI from the candidate pool, all tree-ring chronology time-series are subjected to a statistical screening prior to use in regression analysis. This is accomplished by means of Pearson correlation analysis between the climate variable that is reconstructed and the tree-ring chronologies. The correlation is performed over the calibration period interval, using a two-tailed screening probability of $\alpha = 0.05$.

2. Next, all tree-ring chronology time-series that have passed the screening are transformed, by performing a PCA (see previous section), into their principal components. The components are uncorrelated, which helps to overcome the problem of multicollinearity in a multiple regression.

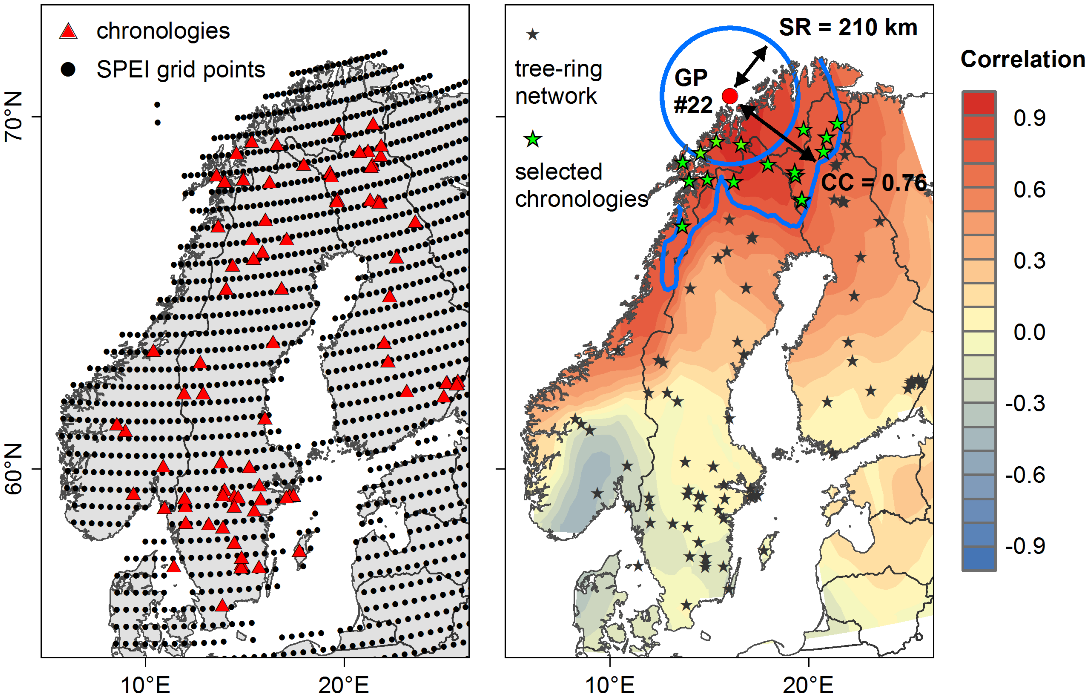

Figure 5. *Left*: the SPEI grid net and tree-ring network used to produce the hydroclimatic atlas in paper IV. *Right*: example of computation of SR and CC of 210 km and r = 0.76, respectively, for the SPEI grid point number 22 (centered over 20.0 E and 70.5 N), superimposed on its spatial decorrelaiton pattern (i.e. the correlation between grid point number 22 and all the other grid point in the field). While only three chronologies falls within the defined SR, the CC is able to locate a total number of 16 chronologies.

3. It is assumed that the variance associated with the high-order tree-ring components is insignificant and is associated with background noise. Hence, only the low-order PCs (those for which the eigenvalue > 1; Kaiser-Guttman criterion), representing the bulk of the common tree-ring variance, are retained as candidates for the stepwise multiple linear regression. The entry into the model is based on the R^2 statistic.

4. The time span covered by the predictor tree-ring series changes through time; some chronologies only spans back to the mid-19th century, while other chronologies cover the full length of the last millennium. In paper IV, where PPR was used to construct a 1000-year long field reconstruction, *nested* reconstructions were produced for each grid point in order to account for the change in the sample depth through time. In this procedure, steps 2 and 3 are first performed for the period covered by all chronologies that have passed the screening (step 1). Steps 2 and 3 are then repeated for progressively longer

periods back in time, corresponding to the change in the availability of the tree-ring chronologies. Each nest is scaled to have the mean and standard deviation of the calibration period instrumental data. All the nests are then joined into the final long reconstruction, so that each period is represented by the nest increment produced from the highest number of available tree-ring predictors during that interval. This procedure is performed for every grid point in the reconstructed field.

All above outlined PPR steps were executed in the Matlab environment.

3.5.6 Validating the prediction skill

The skills of the hydroclimatic reconstructions presented papers II-IV were assessed by means of mean squared error, averaged squared Pearson correlation, reduction of error [RE; eqn. 8], coefficient of efficiency [CE; eqn. 9], and the sign test statistics [Fritts, 2001; National Research Council, 2006].

Average RE and CE over the verification period are given by:

$$RE = 1 - \left[\frac{\sum(x_i - \hat{x}_i)^2}{\sum(x_i - \bar{x}_c)^2}\right] \qquad (8)$$

and

$$CE = 1 - \left[\frac{\sum(x_i - \hat{x}_i)^2}{\sum(x_i - \bar{x}_v)^2}\right] \qquad (9)$$

Where x_i and $\hat{x}_i$ are the actual and reconstructed data in year i of the verification period, and $\bar{x}_c$ and $\bar{x}_v$ are the mean of the actual data in the calibration and verification periods, respectively. Both RE and CE can range between a maximum value of +1, indicating perfect prediction for the validation period, to -∞. The CE statistic is more rigorous than RE, since, unlike the latter one, it depends on the validation data that is withheld from the calibration procedure. As a rule of thumb, CE and RE statistics close to zero or negative suggests that the reconstruction has no predictive value.

The Sign test is a non-parametric approach, which for each year counts the departure of actual and estimated time-series from its mean (the direction of change is recorded, while the magnitude of the departure is not quantified). The departures of both series are compared, and the numbers of times they agree or disagree are quantified. The significance of the sign test is obtained from cumulative distribution tables for the normal distribution.

A split-sample strategy was used to calibrate and validate the reconstruction models. The full-length instrumental climate data (predictand) was split into segments of roughly equal length (usually the early and latter half of the 20th century). 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.

Additional validation of the reconstructions was made by comparison with independent climate reconstructions (see table II, historical reconstructions).

3.5.7 Identifying the extremes

The identification of severe episodes of droughts and pluvials in the reconstructions was made according to the method proposed by Biondi et al. [2002]. The duration, i.e. the number of consecutive years, the reconstruction remains continuously above (below) the reconstruction period mean is first quantified. The magnitude of each (single- or multi-year) anomaly is then computed, by summing the departures of the reconstruction from the mean over the given duration. Finally, the intensity, defined as the ratio between the magnitude and the duration, is computed (fig. 6). The magnitude and intensity are then ranked, separately for wet and dry anomalies. The sum of these ranks assigned to an event provides a score, which is used to quantify the severity of each episode.

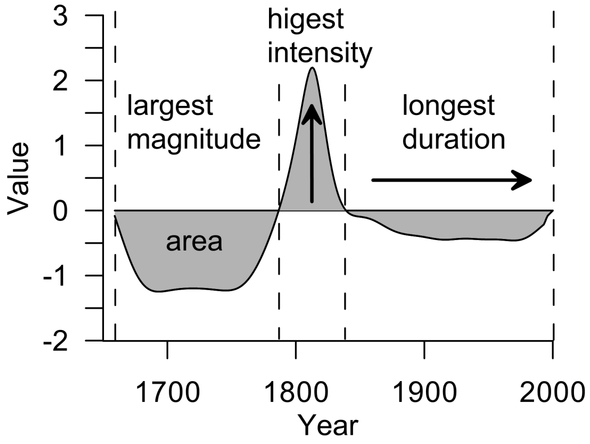

Figure 6. Example of a time-series plot illustrating three multi-annual events, characterized by the largest magnitude (equivalent to the area under the curve), the highest intensity and the most prolonged duration [Biondi et al., 2002].

4. Main results and discussion

4.1 Fennoscandian tree-ring data as a proxy for past hydroclimate

4.1.1 Tree-ring $\delta^{13}C$ and $\delta^{18}O$ from the central Scandinavian mountains

The analyses presented in this dissertation (paper I) show that both $\delta^{13}C$ and $\delta^{18}O$ from tree-ring cellulose of Scots pine growing proximal to the tree line in the Central Scandinavian Mountains (fig. 2A, I) record the local moisture signal, as described by warm season precipitation averages, strongly enough to be used as a proxy of past hydroclimatic conditions. However, moisture variability does not seem to be the main driving force of isotope fractionation, at least not for carbon. The climate analysis conducted in paper I reveals an exceptionally strong positive association between $\delta^{13}C$ values and temperature/sunshine, suggesting that although both assimilation rate and stomatal conductance are influential on the cellulose $\delta^{13}C$ variability, the former one exerts the dominant control. These results are not surprising. Trees in which $\delta^{13}C$ values correlate positively with temperature are usually found in cool and moist environments typically at high altitudes or latitudes [Sidorova 2008; Tardif et al., 2008], whereas trees with $\delta^{13}C$ signal sensitive to the amount of precipitation are predominantly found in dry environments and on well drained soils [Saurer et al. 1997; Warren et al., 2001; Kagawa et al. 2003; Gagen et al., 2004]. The results from paper I thus indicate that although maritime high-altitude Scandinavia tree-ring carbon data is able to reflect a regional moisture signal, the origin of the carbon isotope signal is in the assimilation rate; hence, the $\delta^{13}C$ composition should rather primarily be used as a proxy for parameters associated with temperature.

The climate signal extracted from the $\delta^{18}O$ series is more ambiguous, capturing a mixed temperature and precipitation signal. The tree-ring $\delta^{18}O$ variability is most likely reflecting a combined effect of source water, which itself is related to the isotope value of meteoric water supply, residence time in the soil, evaporation effects and leaf water enrichment due to transpiration at the stomata (fig. 4). Hence, although oxygen is generally less responsive to the regional climate than carbon, $\delta^{18}O$ may have the potential to be used to infer past moisture variability, and possibly even be used to get information of the origin of the precipitation. Increasing understanding of environmental controls and physiological mechanisms affecting tree ring $\delta^{18}O$ composition will make possible more accurate climatic interpretation of the isotope data.

4.1.2 Climate signals within the Fennoscandian tree-ring network

As discussed in the previous paragraph, a moisture signal can be extracted from the tree-ring $\delta^{13}C$ and $\delta^{18}O$ values of Scots pine growing in the central Scandinavian mountains. The next key question is, what is the potential of the other proxy measures extracted from Fennoscandian trees? And more importantly, may they be used in a hydroclimatic reconstruction?

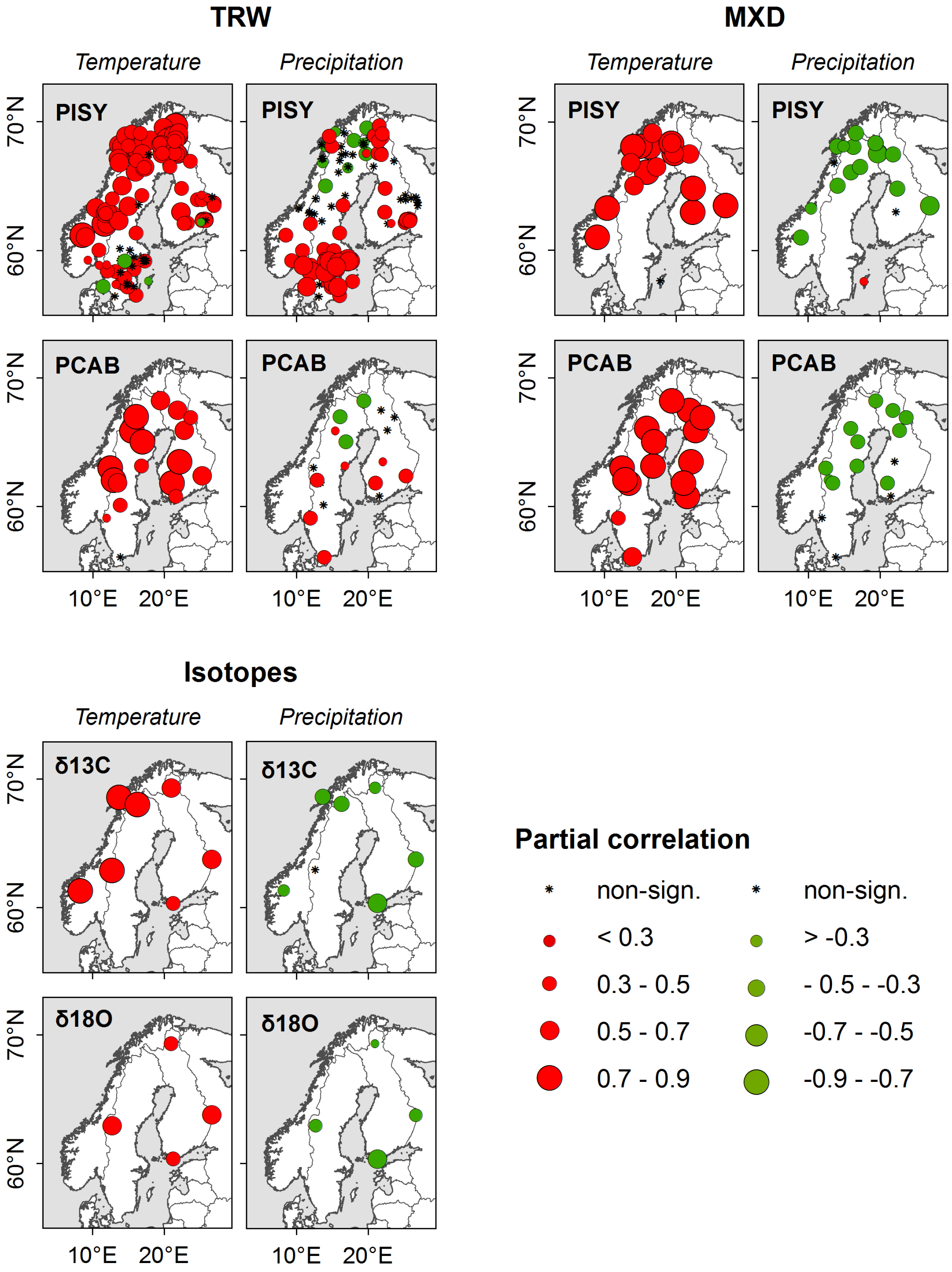

Figure 7. The relationship between various tree-ring proxies and best-fit seasonal combination of precipitation and temperature within the April to September window of the current year. PISY and PCAB refer to Scots pine and Norway spruce, respectively.

The sub-regional scale assessment (fig. 2A) presented in paper II revealed that an early summer (May-June) precipitation signal could be extracted from the TRW data of Scots pine growing in the area of Stockholm. The tree growth was also shown to be sensitive to June-August SPI. Building on the assessment of climate signal preserved in trees growing in the Stockholm region, the analysis was expanded to examine the tree-ring record of hydroclimate over the entire Fennsocandia (paper III). The results indicates that the temperature signal captured by the tree-ring network (including TRW, MXD data from Scots pine and Norway spruce, and carbon and isotope data from Scots pine and Pedunculate oak) is, in general, stronger than that of precipitation (fig. 7), which is not surprising given the high latitude of the target region. The influence of climate on the radial growth of both pine and spruce has a clear latitudinal component. The response to temperature is shifting from being strong and positive in the north to being weaker, and for some sites even negative (usually for the most xeric sites), towards the south. Furthermore, the results show that there is also a significant warm season precipitation signal in many of the TRW, MXD and isotope chronologies, showing a distinct opposite geographical pattern to the one obtained for temperature. While the growth is responding positively to increased moisture availability in the south, the importance of summer precipitation is less dominant, even sometimes negligible, for many high-latitude sites.

Furthermore, the analysis conducted in this dissertation work showed that much of the Fennoscandian tree-ring data, including TRW, MXD and the isotope chronologies, might serve as an effective proxy of summer season SPEI (papers III and IV). The strongest association is generally found with SPEI aggregated over a 3-month time scale (i.e. meteorological drought), indicating that the response of the trees to precipitation deficit/surplus is occurring over a rather short time interval. The thin soil layers, characterizing many of the sampling sites, and the shallow root system of pine (the most frequently used species in this thesis work) might be factors contributing to the rather quick response of the tree-ring proxy data to droughts/pluvials.

Temperature, wind and relative humidity are all important factors in affecting the hydroclimate. Yet, drought has been showed to be a natural hazard that primarily results from lower levels of precipitation than what is considered normal [Heim 2002]. For this reasons, only tree-ring chronologies that captures a significant amount of warm season precipitation have been selected as predictors for the hydroclimatic reconstruction in this thesis work. Furthermore, although several isotope chronologies showed significant association with precipitation, these were not included in the final reconstruction presented in paper IV. The reasons behind this were the somewhat ambiguous trends present in some of the isotope chronologies in the low frequency domain.

4.2 Reconstruction skill

This section describes the quality of the reconstruction models developed in papers II-IV. In paper II, the first attempt to extend the hydroclimatic record beyond the observational period was made. The resulting reconstruction covered the 1650-2002 interval, and accounted for 42% of the total variability in the 20th century instrumental SPI data. Validation against the closest independently developed proxy reconstructions of past moisture variability showed a general agreement between dry and pluvial phases, suggesting that the reconstruction had captured the moisture variability over a broader geographical area. The reconstruction showed an overall better performance than many of the previous attempts to use tree-ring data from the region to infer past moisture variability, implying that better reconstructions might be obtained if a network of moisture sensitive chronologies is used, and if the model is calibrated against meteorological data that are averaged for the whole region instead of using a single grid point or a single weather station data.

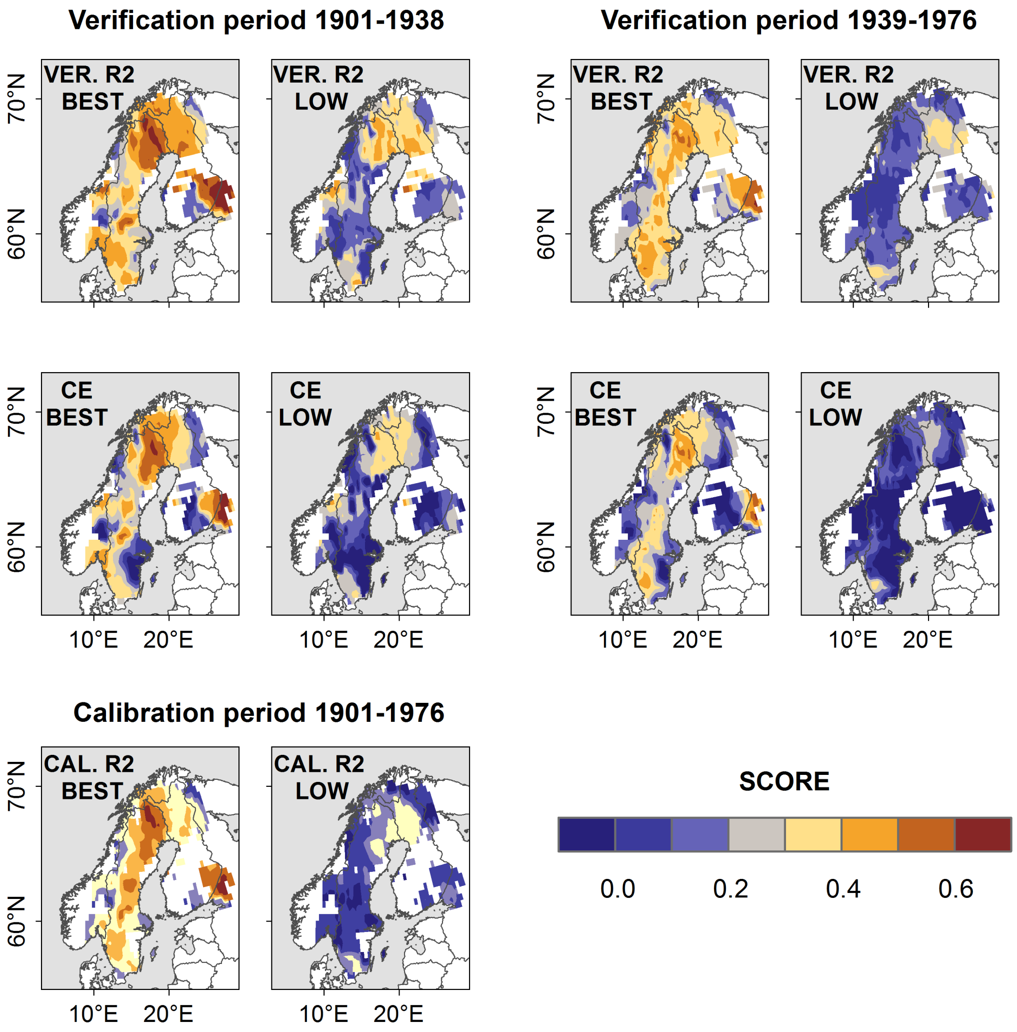

Figure 8. Maps of verification R^2 and CE statistics of the early (1901-1938) and late (1939-1976) verification periods (*upper plot*), generated in paper IV by the split-sample calibration and verification approach. Reconstruction skills are shown for the ‘best’ nests, which almost always correspond to the nests with highest number available tree-ring predictors. ‘Low’ denotes the nests with the least skill at each grid point, usually corresponding to the least replicated nest (see section 3.5.5 for explanation). The lower plot shows the R^2-values of the calibration models constructed using the full 1901-1976 calibration period.

The results from papers III and IV confirms that by using a multi-proxy approach, i.e. combining moisture sensitive TRW and MXD chronologies (as well as isotope data in paper III) to reconstruct past SPEI variability, extremely accurate reconstructions in a temporal sense may be provided for a rather large portion of the Fennoscandian domain (see calibration and verification statistics in fig. 8). The quality of some grid point reconstructions (e.g. northern part of Fennoscandia, southeast Finland, and southern Sweden) is even comparable to some previous tree-ring derived moisture reconstructions from region characterized by much drier climate conditions [e.g. Cook et al., 1999; Touchan et al., 2011]. As discussed in paper III, the remarkably high temporal performance of the reconstructions can most likely be attributed to the nature of the target climate field, i.e. the SPEI itself. As described in section 3.5.1 SPEI is basically a combination of precipitation and temperature data (the latter is used to derive potential evapotranspiration), and, as noted in section 4.1, much of the tree-ring data from Fennoscandia show a mixed influence of both temperature and precipitation (c.f. fig. 7). It should therefore come as no surprise that reconstructions of a drought index, which combines both variables, yields overall much better results than estimations of precipitation and temperatures separately, or estimations of a precipitation based drought index such as SPI.

The results from papers II-IV thus demonstrates that Swedish tree-ring data can provide useful information of past *temporal* variations in hydroclimate. But can the *spatial* patterns of historical moisture variability be reconstructed by applying the PPR method to Fennoscandian tree-ring data? Results from papers III and IV indicate that the spatial performance of the reconstructed SPEI field is generally quite decent, capturing many of the regional-wide anomalies and the finer-scale climatology in the instrumental data. However, the results also show that the models fail to replicate some of the annual patterns over certain years, especially the smaller-scale anomalies. It is certainly not easy to pinpoint the reasons behind the poorly modeled years, and at this stage one can only speculate over the causes. The fact that the reconstructed field showed geographically varying spatial performances (best skills were obtained for the central and southern parts of Fennoscandia, and the poorest for the northern part) may imply that the spatial qualities of the reconstructed field has to do with the spatial properties of the tree-ring predictor network. Maybe the tree-ring network is not dense enough in certain parts of the domain to be able to capture the full range of all the small-scale hydroclimatic patterns? Or maybe it is a result of the geographically varying climate response of the tree-ring data used for the reconstruction, e.g. the fact that the climate signal captured by the tree-ring proxies is biased towards temperature at higher latitudes, and towards precipitation in the south? The consequence is likely that tree-rings from the northern region performs well in reconstructing temperature induced drought stress, but on the other hand may be insufficient in reconstructing smaller-scale drought patterns caused by a precipitation shortage.

In addition to exploring the potential of Fennsocandian tree-ring data in hydroclimatic field reconstructions, paper III also tested the difference in applying the

SR and CC methods, respectively, to locate the tree-ring chronologies in the PPR procedure (see section 3.5.5 for definition of SR and CC). Although the results pointed towards some regional differences in the reconstructions produced by the SR and CC methods, the overall results generated by both methods were rather similar. This is maybe not surprising since the threshold values of both the SR and CC were "tweaked" to capture the essence of the spatial and temporal properties of the instrumental data. Hence, applying the principle of parsimony, the SR method was chosen for the reconstruction in paper IV, because it required much less computational work than the CC method, and was not shown to be inferior.

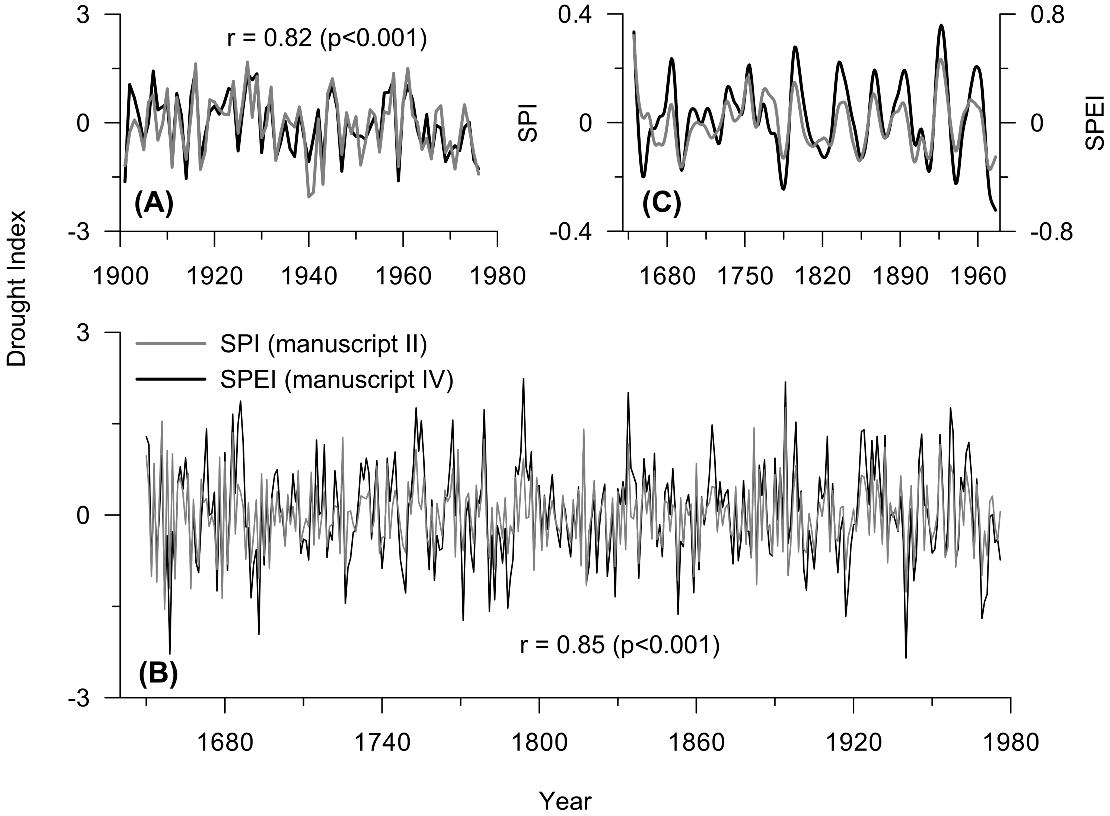

Figure 9. Comparison of the SPI and SPEI datasets used in manuscript II and IV, respectively. A: gridded instrumental data averaged over the 58.25-60.75 N and 15.25-19.75 E region. B-C: reconstructed drought indices over the 1650-1976 common period, smoothed with a 20-year cubic smoothing spline with a 50 % frequency cutoff (C).

4.3 Temporal and spatial characteristics of past moisture variability in Fennoscandia

The regional hydroclimatic history, as defined by the SPI, developed for the southeast of Sweden (paper II) indicates decadal to multi-decadal scale variability in wet and dry phases over the last 350 years. None of these phases show any clear indications to have been more intense and more long lasting than those observed in the instrumental record. A longer consecutive period of below average moisture conditions was reconstructed between 1660s and 1720s, co-occurring with Late Maunder Minimum, a period characterized by cold and dry springs and summers in northwestern Europe [Luterbacher et al., 2001; Bauer et al., 2002]. Overall wet conditions prevailed over the latter half of the 18th century, but shifted towards a drier regime in the early 19th century. Evidence for regional drought during this time can also be found in historical documentary sources from the region [Linderholm and Molin, 2005]. The SPI reconstruction developed in paper II show a strong agreement with the SPEI reconstruction developed over the same region in paper IV (fig. 9B,C). The number of predictor tree-ring chronologies used to develop the grid point reconstructions over the area in paper IV ranged between 3 and 19, with an average number of 11 chronologies (c.f. seven chronologies in paper II). A strong agreements is also seen between the instrumental SPI and SPEI data over the area, highlighting the dominant role of precipitation as the main driving agent of droughts and pluvials in the region (fig. 9A).

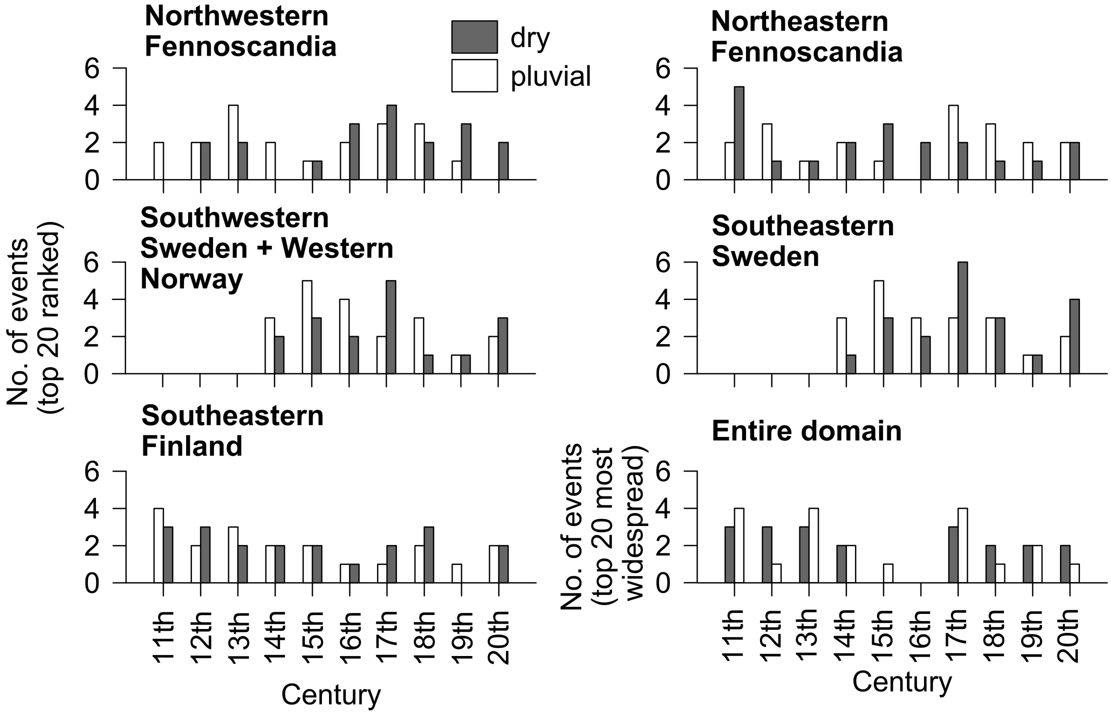

Figure 10. The distribution of the top 20 most severe multi-year (i.e. five or more years) droughts and pluvials over the last ten centuries, throughout five sub-regions comprising the full reconstructed domain. *Bottom right*: the temporal distribution of the five most widespread dry and wet extremes throughout Fennoscandia.

Paper IV provides the first field reconstruction of hydroclimate, as defined by SPEI, spanning back to 1000 CE and covering predominantly Sweden, eastern Norway, and northern and southern Finland. There is a gap in the reconstruction over central Finland, due to scarcity in the tree-ring data over the area. Hence, the resulting spatial estimates of SPEI are not continuous in space. Comparing the reconstructed SPEI, averaged over the entire reconstructed domain, with instrumental data over the same region reveals an exceptionally strong agreement (r = 0.84 over 1901-1976 period), underscoring the robustness of the reconstruction, and proving the paper IV reconstruction to be the most robust tree-ring derived hydroclimatic estimation so far available for Fennoscandia. One of the most eye-catching features of the reconstruction is the large number of extensive and severe dry and pluvial spells characterizing the 17th century, the latter phase of the Little Ice Age (fig. 10). The 15th 16th centuries are on the other hand strikingly free of any widespread anomalies, although some severe but local events seem to have occurred throughout the domain during this time.

Furthermore, the analysis outlined in paper IV revealed that the moisture distribution throughout Fennoscandia could be characterized by two major modes, together explaining approx. 70% of the total variance. Hence, the moisture pattern for any given year might be a mixture of the two PC patterns, in addition to other factors. The two patterns are remarkably robust over time, equally evident in both instrumental and reconstructed SPEI data, for the instrumental period as well as for the past seven centuries. Composite maps of years that best represents the two patterns, shows that the first major mode is characterized by a “monopole” moisture distribution throughout the Fennoscandian region, whilst the second mode is described by a north-south “dipole” structure (fig. 11). The 500-mb circulation patterns associated with the two hydroclimatic patterns shares some main features with the summer North Atlantic Oscillation, suggesting an important role of the circulation on the moisture distribution in the region.

4.4 Remaining challenges and future outlook

This study is the first attempt to derive fields of drought and pluvials for Fennoscandia using tree-ring data, and as such contributes with unique long-term climatological context for the recent hydroclimate in the region. Although it is clear that annually resolved tree-ring proxies hold a great potential for learning about historical moisture variability at annual to decadal time scales, it is also evident that some more work remains to be done in order to improve the reconstruction over Fennoscandia.

As shown, the Scandinavian tree-ring network is dominated by a temperature signal in the north and a precipitation signal in the south. Limited attention has been paid to this issue within this thesis work; all the data that had a significant precipitation signal (either positive or negative) has simply been combined into a predictor network of hydroclimate for the region. Theoretically this should produce a reconstructed field that is biased towards temperatures in the north and towards precipitation in the south, meaning that the reconstruction will fail to capture the smaller-scale precipitation induced anomalies in the north and perform well in capturing the broad-scale temperature caused moisture shortages. The opposite, although presumably less pronounced, is likely to occur in the southern region. Most of the longer tree-ring chronologies used in this work originate from the north, and are predominantly temperature sensitive. This could potentially cause a problem in the

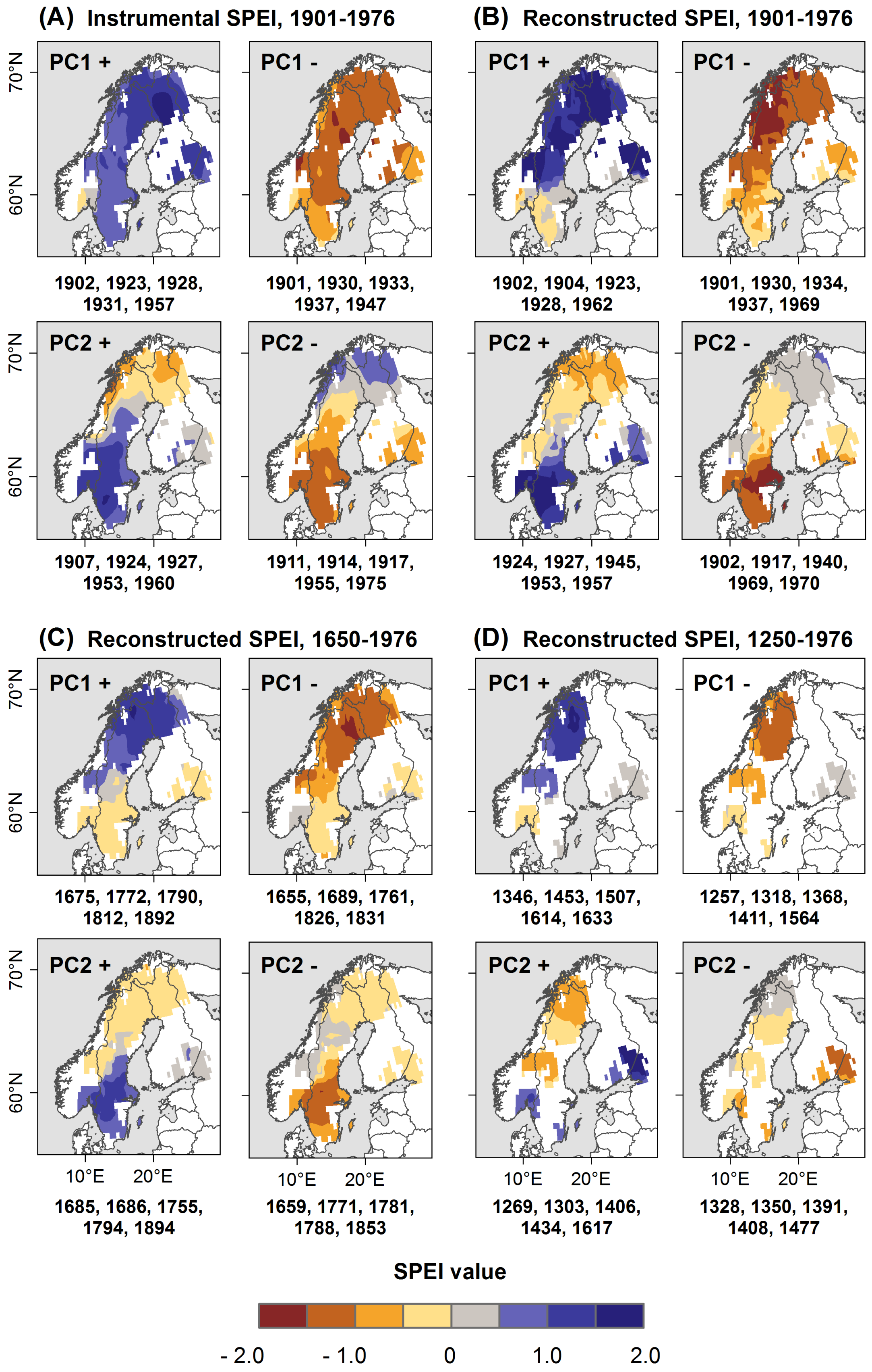

Figure 11. Composite maps of annual SPEI fields for five years that best represent the PC1 and PC2 of the SPEI dataset, identified in paper IV. PC+ PC- refers to the years with the highest positive and negative loadings, respectively.

estimated data, when the shorter, precipitation sensitive, predictor tree-ring series progressively fall out from the reconstruction over time. This would essentially mean that the properties of the regional average reconstruction provided in paper IV is changing through time, from reflecting a mixed temperature and precipitation signal in the most recent nests to becoming more temperature sensitive in the early parts of the reconstruction. These issues, possibly causing serious biases in the reconstructed data, remain to be investigated.

Another potentially complicating factor is the multi-proxy approach used for reconstructions in papers III and IV. Although much better reconstruction skills are obtained when combining different parameters as compared to using TRW data alone, different tree-ring proxies may differ in their spectral properties. The deviations in the lower-frequency domain are not an issue within this thesis work, since trends are removed through the standardization procedure of the tree-ring data. However, there are clear differences in the short-lag autocorrelation amongst the various proxy data, which are also manifested in the reconstructed time series. For example, estimations that are predominantly derived from MXD data will exhibit a lesser degree of autocorrelation than the ones derived from TRW data (believed to be due to physiological and stand dynamics effects) (c.f. the regional reconstructions in paper IV; especially reconstruction I, II and III, IV, where the former are derived mainly from MXD data and the latter from TRW). Hence, it is a complex matter to compare the reconstructions against one another, since they might provide different information when it comes to, for example, the average length of past multi-annual moisture anomalies.

The curve-fitting standardization methods applied to detrend the tree-ring data in papers II-IV limit the preservation of long-term variance in the tree-ring chronologies produced from them. Hence, the resulting reconstructed climate time-series, derived from detrended tree-ring data, will provide information on annual to decadal scales, but not over longer time intervals. The rather flexible curve-fitting method applied herein is a necessity, given the high impact of stand dynamics on the annual tree-growth in many of the sampled tree-ring sites. However, the amount of medium-frequency signal offered by the reconstruction could potentially be increased in the future by applying the quite recently developed “signal-free” standardization approach to the tree-ring data [Melvin and Briffa, 2008]. The method is used to remove the common signal amongst the tree-ring series (which is presumably related to climate) from the curves that are used to detrend the tree-ring data, ensuring that the trend that is removed is related to the tree ageing and not to climate. The signal-free approach can be applied to the curve-fitting standardization used herein, but must be cautioned when working with thinned or managed sites where common signals may include just this.

One obvious future directions for Fennoscandian tree-ring based hydroclimate field reconstructions is an extension of the spatial and temporal coverage of the moisture sensitive tree-ring network, especially over Norway, central parts of Finland, and other areas that are weakly modeled herein. The temporal extension of the newly sampled tree-ring network outlined in this thesis work with in situ dry-dead (i.e., preserved on the forest floor) wood material would practically be very hard to accomplish simply because of the rapid decomposition of organic material in the climate offered by the region. Helama et al. [2003 and 2009] demonstrated the potential of using subfossil wood material from lakes in southeastern Finland to push the reconstruction beyond the period covered by the living trees. Scouting nature reserves and National Parks in southern Sweden showed that there are indeed lakes in the region that could potentially offer preserved dead wood material. However, results have showed that riparian tree-growth around some of these lakes (not published) offer a complex mixture of environmental and climatic signals that needs to be disentangled before the use in hydroclimatic reconstructions.

The work outlined in this thesis work is the first step towards an improved understanding of drought variability in the Fennoscandia, especially on the decadal to interdecadal timescale, which is very difficult to investigate with instrumental climate data alone. More and more methods are now being developed to understand past climate change. For example, a new statistical tool called data assimilation has been implemented in paleoclimatology over the last decade [e.g. Mairesse and Goosse, 2013], allowing to build reconstructions of past climate change which are both consistent with the climate computed by a model and that inferred from the proxy data. An application of the data assimilation technique on the reconstructions provided by this thesis work could be a potential future outlook for Fennoscandian hydroclimatic studies, that could further contribute to an increased knowledge of past moisture regimes in the region.

5. Major conclusions

From the results in papers I-IV and the discussion presented in this summary, it is possible to draw the following broad conclusions:

i. The Fennoscandian tree-ring network provide information mainly of past temperature changes. This is because temperature is the most severe limiting factor for tree-growth in the cool and moist climate characterizing the region. However, this thesis work demonstrates that a network of tree-ring data from carefully selected sampling sites, typified by well-drained and drought-prone environments, is able to provide a good proxy of moisture variability and can successfully be used to infer past broad scale changes in Fennoscandian hydroclimate.

ii. Stable isotopes of carbon and oxygen in tree-rings of Scots pine may give information of past climate variability, and could potentially be used as proxies of hydroclimate. However, in the moist high-latitude Scandinavia carbon is shown to be a superior proxy for parameters associated with temperature rather than moisture, suggesting a stronger role of assimilation rate rather than stomatal conductance on the carbon fractionation in the trees. Stable isotopes of oxygen show a weaker response to climate than the carbon isotope composition, and are presumably reflecting a combined effect of source water, residence time in the soil, evaporation effects and leaf water enrichment due to transpiration at the stomata.

iii. Applying a point-by-point regression approach to the Fennsocandian tree-ring data to reconstruct past hydroclimatic variability, as expressed by the SPEI, produces grid point estimates that are remarkably robust in the temporal sense, and that are overall faithfully recording the general spatial features of droughts/pluvials in the region. The successful application of tree-ring data from temperate and subarctic Fennoscandia in a hydroclimatic reconstruction is likely a product of the nature of SPEI, which combines both temperature and precipitation data in its computation, thereby capturing the mixed climate signal of the Fennoscandian tree-ring network.

iv. A millennium long field reconstruction of summer season hydroclimatic changes has been developed for Fennoscandia. The history reveals that the region has experienced both more and less frequent intense and widespread summer droughts and pluvials over preceding centuries than those observed in the instrumental era. Two major hydroclimatic patterns across Fennoscandia, together accounting for approx. 70% of the total variance, are identified. These two patterns are rather robust over time, equally evident in the observed and reconstructed data, for the instrumental period as well as for the seven preceding centuries, implying a common casual mechanism. The 500mb circulation patterns associated with these two modes suggests summer North Atlantic Oscillation being an important driver of Fennoscnadian moisture distribution over the last centuries.

v. This thesis work is the first attempt to develop high-resolution fields of drought and pluvials for Fennoscandia, and as such contributes with unique long-term climatological context for the recent hydroclimate in the region. Future analysis of these reconstructions will hopefully lead to an increased understanding of moisture variability in the region. Moreover, the reconstructions are expected to be improved in the future by increasing the tree-ring network over areas that are now weakly modeled. Emphasizes should also be made on extending the existing tree-ring network back in time, to enable assessments of hydroclimate over longer time-scales.

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