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MILLENNIA-LONG TREE-RING CHRONOLOGIES AS RECORDS OF CLIMATE VARIABILITY IN FINLAND

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UNIVERSITY OF HELSINKI
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Millennia-long tree-ring chronologies as records of climate variability in Finland

by

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Abstract

There have been great advances in the field of dendroclimatological research during the past decades. Tree-ring data have been used to derive various climate variables for certain localities and for larger regions. Characteristics of tree-rings provide measurements which can be used as records of climate variability prior to any instrumental weather observations. This is how dendroclimatology contributes to the urgent need for greater understanding of the nature of the fluctuations in climate that have occurred in the past and that are occurring in the present. Present study focus on the long tree-ring material collected from Finland and adjacent areas.

Four regional datasets of tree-rings were used here to study their climate-dependent variability and feasibility for palaeoclimate research. Datasets of carefully cross-dated ring-widths provided the annual increments of Scots pine (*Pinus sylvestris* L.) at the northern forest-limit, northern, middle and southern boreal forest zones in Finland. Ring-widths from northern forest-limit were used in the comparison of tree-ring standardization methods. Ring-width chronologies from forest-limit and south-east Finland were used to reconstruct past variations in climate, in temperature and precipitation, respectively.

Characteristics of tree-rings from north to south exhibited a clear environmental and climatological gradient. Three northernmost regional chronologies showed significant and positive dependence on mid-summer temperatures (July). All four chronologies correlated significantly and positively with May precipitation. The latter relationship was greatest in the southernmost region where also June precipitation had similar influence on tree-rings. Three out of four regional chronologies correlated significantly with winter-time North Atlantic Oscillation.

Comparison of standardization methods included two types of splines, negative exponential function with regression line as well as regional curve standardization (RCS). In addition, indices were computed by division and subtraction, as well as subtraction after power transformation. This part of the study focused on the preservation of the growth variability at long time scales. Yet, the behaviour of typical forest-limit ring-widths in the standardization process was thoroughly studied. It was shown that although RCS bears potentiality for preservation of great amount of low-frequency variability in the resulting chronology, it is also the most sensitive method for temporal irregularities in the data. This fact points to the uncertainties in the behaviour of tree-ring indices at time scales longer than the mean segment length, to the issue which is still not completely understood.

Tree-ring chronology from northern forest-limit was used in the reconstruction of mid-summer temperatures for past seven and half millennia. Due to wide inter-tree spacing, original tree-ring material was expected to contain non-climatic bias of tree ageing only, and ring-widths for this work were standardized using RCS method. Reconstruction explained 37 percent of the observed variability and was successfully verified using several statistical tests.

Tree-ring chronology from south-east Finland was used in the reconstruction of early-summer (May-June) precipitation for past eleven centuries. Due to clear closed-canopy signature of tree-rings, standardization in this work was made using 67 %n splines in order to remove non-climatic growth disturbances prior to any palaeoclimatic interpretation. Reconstruction explained 31 percent of the observed rainfall variability; it was verified and correlated successfully with independent climatic series.

Both of the tree-ring based palaeoclimate reconstructions provided evidence for greatly fluctuating Holocene climate. Anomalous changes in the reconstructed temperature occurred from annual to multicentennial time scales. Negative temperature anomalies of single years were shown to be associated with volcanic forcing. Due to methodological restrictions, the reconstructed precipitation was limited to exhibit fluctuations at interannual to multidecadal time scales. Uncertainties in both of the reconstructions were further discussed in the context of literature review.

Key words: tree-ring, dendrochronology, dendroclimatology, standardization, Finland, Scots pine, megafossils, palaeoclimatology

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Tiivistelmä

Dendroklimatologia, tieteenala joka tarkastelee puiden vuosilustojen ja ilmaston välistä suhdetta, on viime vuosikymmenten aikana kehittynyt yhdeksi kaikkein tärkeimmistä ilmastotutkimuksen menetelmistä. Puiden vuosilustoja on tänä aikana käytetty yhä enenevässä määrin yhdessä meteorologisten havaintosarjojen kanssa johtamaan ilmaston vaihtelevuutta kuvaavia aikasarjoja. Dendroklimatologisten havaintosarjojen suurin etu meteorologisiin lähteisiin nähden on puulustosarjojen pituus; ne voivat ylettyä vuosisatoja ja jopa vuosituhansia ajassa taaksepäin. Tämä tutkimus keskittyy tarkastelemaan Suomesta sekä aivan maamme lähialueilta kerättyjä pitkiä puulustosarjoja joiden materiaalina on elävien puiden vuosilustojen lisäksi käytetty vuosilustosarjoja keloista, vanhoista puurakennuksista sekä eritoten järvien pohjasedimentistä kerätyistä subfossiilisista puunäytteistä.

Tutkimuksen käytettävissä oli ristiinajoitettuja männyn (*Pinus sylvestris* L.) vuosilustosarjoja neljältä erilliseltä alueelta, pohjoiselta metsänrajalta, pohjois-, keski- sekä eteläiseltä boreaaliselta metsävyöhykkeeltä. Tarkastelun kohteena oli ensin kunkin alueen vuosilustojen ja kyseisen alueen ilmaston välinen suhde, lisäksi tarkoituksena oli havainnollistaa alueiden vuosilustosarjojen käyttökelpoisuus paleoklimatologisessa tutkimuksessa. Pohjoisen metsärajavyöhykkeen vuosilustoja käytettiin rekonstruoimaan alueen lämpötilavaihteluita sekä tutkittaessa erilaisia vuosilustojen standardointimenetelmiä. Kaakkois-Suomen vuosilustoja käytettiin rekonstruoimaan sademäärien vaihteluita alueella.

Puiden vuosilustoista lasketut niiden ominaisuuksia ilmaisevat matemaattiset tunnusluvut osoittivat vuosilustojen käyttäytymisen vaihettuvan pohjoiselta metsänrajaseudulta Etelä-Suomeen alueiden välistä ilmasto- ja ympäristögradienttia kutakuinkin vastaten. Puulustojen kasvu kolmella pohjoisimmilla alueella oli riippuvainen keskikesän (heinäkuun) keskilämpötilasta. Tämä riippuvuussuhde oli kaikkein voimakkain eteläisimmällä alueella, missä myöskin kesäkuun sademäärällä oli samankaltainen vaikutus vuosilustojen kasvuun. Tämän lisäksi korreloi puiden vuosilustojen kasvu kolmella neljästä tutkitusta alueesta merkittävästi talviajan NAO-indeksin kanssa. Viimeksi mainittu kuvastaa Pohjois-Atlantin alueellisia ilmanpaine-eroja.

Puiden vuosilustojen standardointimenetelmien ja niiden tuottamien lustoindeksien vertailussa tarkasteltiin kullekin yksittäiselle vuosilustosarjalle laskettavien spline-tyyppisten funktioiden ja negatiivisen eksponentiaalifunktion tuottamia keskinäisiä eroavaisuuksia sekä niiden eroja standardointitapaan jossa yhtä ainoaa kaikkien vuosilustosarjojen välinen keskiarvofunktiota sovellettiin kaikkiin käytettävissä oleviin vuosilustosarjoihin. Havaittiin, että vaikka viimeksimainittu menetelmä onkin kaikkein suosiollisin pitkän aikajänteen vuosilustoindeksien vaihteluiden selvittämiseen, on se myöskin kaikkein virheherkin menetelmä useille vuosilustoaineistossa havaituille poikkeavuuksille kuten esimerkiksi vuosilustokronologian ikäjakauman muutoksille.

Puiden vuosilustoja pohjoiselta metsänrajalta käytettiin rekonstruoimaan kesälämpötiloja alueella 7.5 tuhatta vuotta ajassa taaksepäin. Kaakkois-Suomen vuosilustoja käytettiin rekonstruoitaessa alkukesän (touko-kesäkuun) sademääriä alueella noin 1100 vuotta ajassa taaksepäin. Lämpötilarekonstruktio selitti 37 % ja sademäärärekonstruktio 31 % havaitusta ilmastovaihtelusta tarkasteltuina ajanjaksoina. Johtuen alueiden puunkasvun häiriötekijöiden eroavaisuuksista, myös materiaalin käsittelymenetelmät poikkesivat toisistaan. Johtuen nimenomaan menetelmien eroavaisuuksista voitiin pohjoisen metsänrajaseudun puulustokronologiaan pohjautuvassa lämpötilarekonstruktiossa havaita enemmän pitkän aikajänteen vaihteluita. Molemmat ilmastorekonstruktiot osoittivat viimeisten tuhansien vuosien ilmaston alueella olleen luonnollisilta ominaisuuksiltaan hyvin vaihteleva. Useiden yksittäisten erittäin kylmien kesien katsottiin olevan seurausta samanaikaisten tai kylmää kesää edeltäneenä vuonna tapahtuneen tulivuorenpurkauksen ilmastovaikutuksista. Ilmastorekonstruktioiden mahdollisia epävarmuustekijöitä pohdittiin erikseen olemassaolevan alan kirjallisuuden pohjalta.

Avainsanoja: vuosilusto, dendrokronologia, dendroklimatologia, standardointi, mänty, megafossiili, palaeoklimatologia

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Contents

List of original publications

This is an article dissertation, based on the material and results presented originally in the following papers referred to in the text with Roman numerals. The author is responsible for all the data analysis and interpretation of the results. Co-authors provided the original data and reviewed papers. In addition, Papers III and IV include original ring-width material collected and measured by author.

I **Helama S.**, Lindholm M., Timonen M., Meriläinen J. & Eronen M. 2002: The supra-long Scots pine tree-ring record for Finnish Lapland: Part 2, interannual to centennial variability in summer temperatures for 7500 years. The Holocene 12 (6): 681-687.

II **Helama S.** & Lindholm M. 2003: Droughts and rainfall in south-eastern Finland since AD 874, inferred from Scots pine ring-widths. Boreal Environmental Research 8 (2): 171-183.

III **Helama S.**, Lindholm M., Timonen M. & Eronen M. 2004: Detection of climate signal in dendrochronological data analysis: a comparison of tree-ring standardization methods. Theoretical and Applied Climatology (accepted).

IV **Helama S.**, Lindholm M., Meriläinen J., Timonen M. & Eronen M. 2004: Multicentennial ring-width chronologies of Scots pine along north-south gradient across Finland. Tree-Ring Research (submitted).

Paper I was reproduced here by permission of the Arnold Publisher. Paper II was reproduced by permission of the Boreal Environmental Research Publishing Board. Papers III and IV are unpublished manuscripts.

1. Introduction

1.1. Concept of dendrochronology

Radial growth of trees is composed of annual increments of xylem and phloem in the stem. In temperate zone tree growth recurs after dormancy and cell divisions begin to yield xylem and phloem which causes the stem to increase in thickness. In xylem, cells formed early in the growing season are larger and less dense than those formed later in the season. This difference between the different parts of the annual increments of xylem, earlywood and latewood, will create the annual rings of trees (Kozlowski 1971). Tree-rings, often visually observable in the cross-sections of tree stems, are thus reflecting the annual growth cycle of the trees which in turn is largely governed by the circumstances of the growth during the year. Careful examination of tree-ring characteristics may thus unveil some of those circumstances occurred in the past living environment of a tree.

The discipline of dendrochronology seeks to examine variations in tree-rings and their characteristics. The common practise of dendrochronology is the synchronization of this variance among the samples from one tree, among several trees of one stand, or among regional dataset of samples. Systematic use of this synchronization, called as tree-ring cross-dating, is most appropriately characterizing the discipline of dendrochronology (Fritts 1976; Fritts & Swetnam 1989). In cross-dating the exact year during which each ring was formed can be absolutely determined in relation to all other cross-dated samples. Most often examined characteristic of tree-rings is the total ring-width, being a sum of both earlywood and latewood widths. In addition to total ring-width, referred hereafter as ring-width, variations in the width of earlywood or latewood, wood density or isotopic composition of tree-rings can be measured and cross-dated. Cross-dated ring-widths can be further averaged into a mean value chronology, which therefore represents the variations in radial growth of trees as a function of time on absolute annual basis.

In a usual case, tree-ring chronology consists of at least tens of tree-ring series, examined and measured from samples of living trees, and the correct calendar years of forming of tree-rings closest to the bark are easily resolved. In this case, the length of the tree-ring chronology is restricted by the length of the life span of oldest living trees and for this reason most of the existing tree-ring chronologies do not elongate more than several hundreds of years back in time. In some circumstances, it is however possible to find wood material older than the oldest existing living trees. Application of cross-dating then enables the synchronization of rings of that old sample to a mean chronology if the time of overlap between the series is adequate in length. Time span of a mean chronology can be therefore elongated to the past depending on the availability and the age of the ancient tree-ring material. Possible sources of dead wood are buildings constructed by timber and natural archives. In favourable conditions dead wood can be preserved as a dry standing or fallen dead logs, as snags. Dead wood can be also found in the sediment if the conditions were favourable for preservation, preferably oxygen-free (Eronen 1979; Leuschner 1992). These tree findings are often called as megafossils due to great size of many well-preserved logs, or as subfossils due to their taphonomic history. Some tree species have longevity of several thousands of years, and tree-ring chronologies constructed from those trees are correspondingly as long. These species are for example Great Basin bristlecone pines (*Pinus longaeva*) (Schulman & Ferguson 1956; Schulman 1958) and Rocky Mountain bristlecone pines (*Pinus aristata*) (Brunstein & Yamaguchi 1992) in United States, and alerce trees (*Fitzroya cupressoides*) in southern Chile (Lara & Villalba 1993). Scots pine is known to live in optimal conditions 700-800 years (Sirén 1961; Lindholm 1996; Kirchhefer 2001) in northern Fennoscandia. Longest continuous tree-ring chronologies, which are composed of trees with relatively short segment length, span over the entire Holocene. Oak (*Quercus petraea* and *Quercus robur*) chronologies from German, Netherlands and Ireland (Pilcher et al. 1984; Kelly et al. 2002; Leuschner et al. 2002) as well as chronologies combining subfossil oak and Scots pine mainly from Germany, but also from other parts of Central Europe and Italy (Friedrich et al. 1999, 2001; Spurk et al. 2002) span over the past twelve centuries. Finnish Lapland Scots pine ring-width chronology is longer than seven and half thousand of years (Eronen et al. 2002; I) being the third longest continuous tree-ring chronology at the moment of writing. Yet, Boninsegna et al. (2001) were able to recover large number of samples of *Fitzroya cupressoides*. This one thousand and two hundred year long floating chronology was dated by radiocarbon method to the time of last interstadial, around 50.000 BP.

Motivation of the construction of many of these tree-ring chronologies is in their applicability in radiocarbon C-14 calibration (e.g. Becker 1993), tree-ring dating, or in reconstructions of past climate variables.

1.2. Dendroclimatology and extraction of climate signal in tree-rings

Dendroclimatology is a subfield of dendrochronology. Dendroclimatological work examines the relationships between the variations of tree-rings characteristics and climate. This is can be done statistically by comparing modern meteorological records with overlapping records of tree-rings. Dendroclimatological examination is therefore an empirical test for detecting what are the climate variables bearing significant impact for tree-ring variability. The strength and the sign of the variables can be ideally determined. If a strong covariation between climate and tree-rings is evident and relatively unchangeable as a function of time, statistical equation for the relationship can be successfully established and verified. If the length of tree-ring record exceeds that of the meteorological record, it may be possible to estimate the variations of the past climate using the annual values of tree-rings. However, climate is not the only factor bearing impact on the tree-ring growth, in many cases it is not even the most significant factor, but its signal can be strengthened in the processes of tree-ring data analysis. The most important such a method is the procedure of tree-ring standardization (Fritts 1976; Cook 1985; Cook et al. 1990).

In theory, the total variation in tree-rings can divided into the components of variation due to tree ageing, climate, and pulses of local endogenous and stand-wide exogenous growth disturbance. In practise, tree-ring series often contain also variance not explained by any of the main components of tree-ring variance mentioned above. Including the latter into the model, the total observed tree-ring variance may be expressed linearly as a sum of all above mentioned five factors (Cook 1985). That is also to suggest that if the variation in tree-rings due to all other factors but climate (i.e. noise) can be determined, captured and removed, then the remaining variance will be composed of indications of pure climate signal. As the variation due to climate is common to all of the tree-ring series of a homogenous sample, this removal process will increase the variance common to all trees (signal) in the chronology and reduce the proportion of noise. That is to say that tree-ring series are converted into the series of climatic variance. This is the rather simplified view of the aims of tree-ring standardization, but the base of the theory is applied in all dendroclimatological works concerning on the climate signal in tree-ring chronologies. It is notable that other applications of tree-ring analysis may define signal and noise differently.

The methods of standardization are very essential part of any dendrochronological or dendroclimatological study and they had significant role in the course of the present research, too. As will be shown (III), the selected methods will bear considerable impact on the obtained results. Papers of this volume are predominantly dendrochronological (III) and dendroclimatological (I, II, IV) but all of them have significance also for palaeoclimatology (I, II, IV).

1.3. Applications of palaeoclimatology

Couple of last decades or so have experienced greatly increased awareness of the significance of climate fluctuations, either natural or anthropogenic, to the many fields of life (e.g. Lamb 1972). In the same time, previous interpretation of relatively stable Holocene climate (in relation to glacial times), has changed into the picture of distinct variability at the millennial, centennial and shorter time scales. This picture has been drawn from several palaeoclimatic time series providing information of past temperature and relative humidity. One of the variations in climate is the 20th century trend, often described in the literature.

According to instrumental observations of climate, global and hemispheric temperatures have been risen during the last 140 years. The change in annual temperature has been estimated to be 0.055°C per decade in Northern hemisphere but 0.098°C per decade and thus more pronounced in Arctic (60°-90°N) (Jones & Moberg 2003). According to instrumental weather data of Klingbjer & Moberg (2003), temperatures have risen also in northern Fennoscandia at an average rate of 0.099°C per decade during the last 200 years, 1.97°C in total. Instrumental weather observations are the most accurate measures of climatic fluctuations, but their length is usually no more than slightly over one hundred years. Instrumental observations are therefore commonly inadequate to resolve the full spectrum of the climate variability and in particular the amplitude of the recent warmth in relation to past warm periods. Centennial and even millennial records of past climate can be derived from several sources of palaeoclimate proxies. These records bear indications of past climate of different seasons at the resolution depending on the proxy and methodology.

Tree-rings has provided information of past temperature and precipitation, but past climate has been similarly investigated also from ice-cores, lacustrine and marine sediments, speleothems, boreholes, corals, advances and retreats of vegetation boundaries and mountain glaciers, among others. Yet, records of past climate can be derived from historical weather and farmers' diaries. The list of potential sources of palaeoclimate information is in deed increasing in line with the concern of the recent climatic fluctuations on the society and could be extended. The records most comparable to tree-rings are those being constructed of annual information, increments or layers, i.e. annually resolvable. Such records include historical or 'early' weather data (Vesajoki & Tornberg 1994; Holopainen & Vesajoki 2001), annually laminated ice-cores (Stuiver et al. 1995; Alley et al. 1997; White et al. 1997), lake sediments (Goslar 1998; Ojala 2001) and corals (Cook 1995) as well as speleothems (Betancourt et al. 2002). It is also notable that different natural proxies or identical proxies in different environments provide information of palaeoclimate at different seasons. None of the proxies can therefore hardly named superior but being more or less complementary to each others.

The use of regionally large-scale reconstructions of palaeoclimate masks the details concerning the spatial patterns and seasonal timing of climate changes (e.g. Jones & Kelly 1983), and therefore the local reconstructions of temperature and precipitation of different seasons are important to be used also as separate records.

1.4. Dendroclimatology in the field of palaeoclimatology

Dendroclimatology is an efficient tool of palaeoclimatology, being one of the few procedures resolving the past variability of climate on both short (annual) and long (centennial) time-scales with absolute dating accuracy. The advantage of tree-rings as palaeoclimate information in relation to many other proxies is that tree-rings can be statistically calibrated against the instrumental weather records and further transferred into the estimates of the climatic variable. Ring-widths of Scots pine have been used to reconstruct summer temperatures in Fennoscandia and Kola Peninsula (Lindholm 1996; Lindholm et al. 1995, 1996a, b; Lindholm & Eronen 2000; Kirchhefer 2000, 2001; Gervais & MacDonald 2000; Grudd et al. 2002; I), early-summer rainfall in Tyrol, Austria (Oberhuber & Kofler 2002; II), annual and late-summer rainfall in Mongolia (Jacoby et al. 1999) and winter rainfall in Siberia (Thomsen 2001) as well as North Atlantic Oscillation (NAO) (Lindholm et al. 2000). In addition, Scots pine tree-ring widths have also been used in combination with early and late wood widths (Kalela-Brundin 1999), and maximum densities of tree-rings in combination with ring-widths (Briffa et al. 1988, 1990, 1992) in summer temperature reconstructions in Fennoscandia. Yet, ring-widths and maximum densities of Scots pine tree-rings have been used in several regional or hemispheric temperature reconstructions (e.g. Briffa et al. 2001, 2002a, 2002b), as well as complements to North Atlantic dataset of tree-rings to reconstruct NAO (Cook et al. 1998).

In several other papers, tree-ring chronologies of Scots pine have been used as proxies for indications of past climate variations, without any attempt to transfer tree-ring record into reconstruction. Such a diversity in Scots pine sensitivity to different climatic variables indicates great flexibility of the species adjusting for different environmental conditions and climate regimes, as well as to habit over wide ecogeographical gradients, which in turn makes it excellent species for the work of palaeoclimatology.

1.5. Dendroclimatology in Finland prior to present work

Dendroclimatology has long tradition in Finland; the progress of the science with Scots pine tree-rings could be reviewed by following examples. Laitakari (1920) studied the relationship between Scots pine ring-widths and climate in southern Finland. As some other contemporaries, he applied early dendrochronological works of Huntington (1914) and Douglass (1914) as a guideline for his own study. Boman (1927) examined the periodicities in Scots pine ring-width chronologies in Finland and he reported several cycles between 7 and 70 years. Hustich & Elfving (1944) and Hustich (1945, 1948) have studied the ring-width variations in northern Finland and its correlation with fluctuations in climate.

Mikola (1950) studied the climate and age dependent ring-width variations of Scots pine and Norway spruce in Finland. Material of his study contained over 6500 trees (of which ca. 4500 pines) from north to south parts of the country. Mikola (1952) further focused on the relationship between the tree-rings and climate at the forest-limit region. Sirén (1961) constructed Scots pine ring-width chronology for northern Finland, studied climate-growth relationships and examined periodicities in the tree-ring growth. Kärenlampi (1972) studied the importance of temperature and precipitation on ring-widths in the northeastern Finnish Lapland. Sirén and Hari (1971) compared the periodicities between tree-rings and laminated sediments. Hari and Sirén (1972) described the pine radial growth at the forest-limit using a model including temperature, day light and the seasonal stage of development of trees. This model was later used by Nöjd and Hari (2001) in comparison of models describing the climate-growth relationship. Pohtila (1980) examined the dependency of ring-widths on temperature, precipitation, atmospheric patterns and sunspots in Lapland. Henttonen (1984) determined the relationship between Scots pine and Norway spruce ring-widths mainly in southern Finland. Lindholm (1996) studied in details the network of Scots pine ring-width chronologies at the northern forest-limit in Finnish Lapland, statistical properties of ring-width variability and their dependency on climate. Berninger et al. (2004) investigated pine growth at the forest-limit using a combination of dendroecological and process-based models. Lindholm et al. (1997) studied the relationship between climate and ring-widths around Saimaa Lake in south-east Finland and Lindholm et al. (2000) using tree-rings from north and south Finland. Miina (2000) studied the climate-growth relationships using early and late wood widths as well as total ring-widths in North Karelia. Mielikäinen et al. (1996) concentrated on the recent radial growth variations of both pine and spruce in Finland, and compared them with earlier growth and prevailed climate conditions. Mäkinen and Vanninen (1999) examined the particular influence of the sample selection on the reduction of noise in resulting ring-width chronologies in southern Finland.

Already Sirèn (1961) used tree-rings of living trees in combination with cross-dated samples from dead wood, but it was decades later when the construction of long (millennial) chronologies was intensified in Finland. Eronen & Hyvärinen (1982) and Eronen et al. (1991) had discussed the opportunities for such a work in Finland, and the construction of tree-ring chronologies and the palaeoclimatic imprints in them was reported by Eronen et al. (1994a, b, 1999a, b), Zetterberg et al. (1994, 1996) and Eronen & Zetterberg (1996a, b). Continuous millennial ring-width chronologies were recently presented by Eronen et al. (2002) for the northernmost Finland as well as by Lindholm et al. (1998-1999) for south-east Finland.

Actual tree-ring based reconstructions of past climate have been made during the last twenty years. Several examples of them were already mentioned in previous section (1.4.). In addition, Ogurtsov et al. (2001, 2002, 2003) have used these temperature reconstructions in order to detect potential natural climatic forcings for temperature climate in northern Finland during the last 2000 years.

1.6. The aims and purpose of the study

In the present study, tree-ring chronologies of Scots pine are used as indicators of past climate variability in the region (I, II). Different climate variables are extracted and reconstructed from ring-widths, and obtained reconstructions are compared with other existing palaeoclimate proxies in order to strengthen the understanding of the past climate variability (I, II). Tree-ring chronology from northern Finnish Lapland is used as a proxy for mid-summer temperatures (I) and chronology from south-east Finland is shown to useful record as proxy for early-summer precipitation (II). Four regional tree-ring chronologies, of which three possess millennia-long records, are compared in terms of dendrochronology and dendroclimatology (IV). Comparison is made between regional datasets of tree-rings, as well as between the tree-ring records and climatic time series. As always in tree-ring related studies, the methods of utilized tree-ring standardization bear significant impact on the obtained results. In all three above works tree-ring series were chosen to be standardized by different methodology. This was partly due to different ecogeographical source region of tree-ring data, but also due to predetermined signal processing desires. Methods of tree-ring standardization are compared in details using tree-ring material from northern coniferous forest-limit zone of Finnish Lapland (III). This comparison is done focusing into the features of forest-limit tree-ring material, and its behaviour in the process of standardization. The extraction of low-frequency climate signal in tree-rings due to standardization is emphasized in the comparison (III). In relation to previous dendroclimatological works in Finland (see section 1.5.), research in hand systematically seeks to examine the full feasibility of the long tree-ring records from north to south Finland in the field of palaeoclimatology.

As a whole, present study (I, II, III, IV) can be seen as an attempt recording and understanding spatiotemporal variations in Finnish Scots pine ring-width chronologies, in the timeframe of mid and late Holocene. The present study is not by any means the final stage of such a study in Finland but a part of extensive research on tree-ring records in Finland, hopefully even contributing stimulations for future studies.

2. Material and methods

2.1. Present Scots pine tree-ring records

The present dataset includes Scots pine (*Pinus sylvestris* L.) tree-ring series from ca. 2100 trees in all. Dataset forms four regional chronologies of ring-widths, each of them being distinctly different from each other (IV). Each of the regional chronology is a composite ring-width chronology of living tree, construction timber and dead wood samples. The latter source comes from the logs lying on the ground as snags, and from the lake sediments where they have been preserved over the years.

Four regional chronologies originate from northern coniferous forest-limit in northernmost Finland (I, III, IV), northern (IV), middle (IV) and southern boreal forest zones (II, IV). Ring-width material from northern forest-limit and its vicinity (I, IV), where it was collected by teams of University of Helsinki (Department of Geology), Finnish Forest Research Institute (Rovaniemi Research Station) and SAIMA Centre for Environmental Sciences (Savonlinna), was previously published by Lindholm (1996) and Eronen et al. (1999, 2002). Ring-width material from south-east Finland (II, IV), where it was collected by team of SAIMA Centre, was previously published by Lindholm et al. (1998-1999). In addition, present work includes ring-width material previously unpublished, partly collected and measured by author at the forest-limit region of northernmost Finland (III, IV).

Differences in the nature of regional chronologies by means of tree-ring statistics and response functions created possibilities for different kind of and type of palaeoclimate estimates to be extracted from each regional ring-width datasets. In relation to previous tree-ring works in Finland (see sections 1.4. & 1.5.), research in hand presents, examines and discusses considerably elongated tree-ring chronologies.

2.2. Dendrochronological data analysis

Methods used in each paper of this volume are explained in details in the individual papers (I, II, III, IV). In the following sections (2.3. & 2.4.), dendrochronological and dendroclimatological data analyses are reviewed in the context of requirements of the aims of the research on present datasets of non-homogenous ecogeographical origin. More detailed discussion on the methodology and its validity in each case of the research are further provided in the section below (4.1.). Data analysis was greatly benefited by the software from International Tree-Ring Data Base Program Library (Holmes et al. 1986), as well as tree-ring data processing and control software of Timonen (2002).

2.3. Ring-widths and time series analysis

2.3.1. Cross-dating of ring-widths

Dendrochronological cross-dating examines the variations in ring-widths. Visual and statistical comparison of the patterns of narrow and wide rings is used to determine the synchronism of all available sequences of tree-rings from a given species and region. Covariation among tree-ring series ensures the dating of each ring by the accuracy of one year. It is usually the high-frequency variation (year-to-year) which is to be used in the comparison between series, but also variations at longer terms ought to show covariation in visual examination, especially at the forest-limit conditions. This is a synchronization of tree-ring series called cross-dating and it provides the annual dating control of examined characteristics (e.g. Fritts 1976). Statistical comparison can be simply and reliably exercised for example by interseries correlations (Holmes 1983). Correlations between trees are lower in the forest interior (and in general towards the south in Finland) compared to forest-limit trees (IV), and therefore dating by tree-rings is, at least in theory, more difficult there.

2.3.2. Removal of the growth trend in ring-width series

Time series of tree-rings are measures of tree radial growth from pith to bark, from the first to the last measurable ring, at annual resolution. These series of tree-ring widths are generally known to bear trend, usually associated with age-size dependency in tree radial growth. This trend, commonly referred as growth trend, is a non-stationary process owing to a geometric constraint of adding an annual volume of biomass to a stem of a tree with increasing radius (Cook, 1985, 1990). In addition to ageing of the tree, the growth trend reflects the growing conditions of a tree, such as soil composition, external disturbance and competition and thus also the density of the forest (Mikola, 1950; Cook, 1985, 1987; Fritts & Swetnam, 1987; IV).

Growth trend in ring-width series commonly exhibits an abrupt and short lived increase in annual growth from the pith to a juvenile growth maximum. Thereafter, exponential decrease in the growth occurs as a function of cambial age until the outermost observed ring (Matalas, 1962; Fritts, 1976). This is also known to be case of average Scots pine growth trends in natural grown sites in Fennoscandia (Erlandsson, 1936; Mikola, 1950; Briffa et al., 1992; Cook et al., 1995; Grudd et al., 2002; I; III; IV). Since the growth trend in assumed to be largely non-climatic, arising from the increasing age of the tree, it is, in any dendroclimatological research, to be captured and removed before the computation of the mean chronology.

Great variety of techniques has been used to define the growth trend (e.g. Huntington 1914; Kuusela & Kilkki 1963; Fritts et al. 1969; Fritts 1976; Warren 1980; Cook & Peters 1981; Briffa et al. 1983; Holmes et al. 1986). In practise, growth trend can be in most of the cases determined as being the low-frequency component of the observed radial growth.

It can be as simple as regressed straight line, which is often used as an alternative for negative exponential function, or greatly more flexible frequency-dependent filter. It serves the expected value of the growth for each year of tree-life, assumed to arise from factors other than climate. However, the differentiation between the low-frequency variability due to climate, tree ageing and growth disturbances is by no means an unambiguous task. In fact, the preservation of low-frequency climate related variability is even largely depending on the type of growth trend models utilized in standardization. Due to great disparity of the methods, the choice of the technique bear significant influence on obtained indices and it ought to be done with greatest care. The choice of the technique used to model the growth trend should be based on the knowledge on the general behaviour of tree-rings due to tree-ring source environment as well as on the signal property desires, where the former defines the realms of the latter. Methods to estimate the growth trends in ring-width series in the studies of the volume in hand were so-called Regional Curve Standardization (RCS) (I, III), 67 %n spline function (II, III), douple-detrending with negative exponential curve or regression line in combination with 67 %n splines (III, IV) and yet flexible 32-year cubic spline with 50% cutoff (III).

Once the growth trend is to be captured, it is further removed by extracting the dimensionless tree-ring indices from the curve. This is usually done by division to simultaneously stabilize the heteroscedastic variance in original ring-widths. Alternatively, logarithmic or power transformation (Cook et al. 1992; Cook & Peters 1997) could be used prior to growth trend modelling to stabilize the variance after which the indices could be properly extracted from the curve by subtraction (III). In power transformation, which was used also in the present work (III), the power applied to series is the slope of a linear regression in logarithmic space between the local spread (standard deviation) and local level (ring-width mean) (Cook & Peters 1997). In order to ensure the unbiased and correct values of tree-ring growth, the methods of growth trend modelling and index extraction by division and subtraction were tested during the course of the present work (III). Dendroclimatological works (I, II, IV) of the present volume were done using the traditional ratio based indices.

2.3.3. Models for physiological preconditioning

Each measured ring-width represents tree growth during the specific calendar/cambial year. Tree-ring growth occurs during the growing season of the year (t), but the growth in year (t) also reflects the growing conditions during the preceding dormancy as well as during the previous years (t-n, n = 1 … x). This means that although the growth starts and ceases during the beginning and the end of the growing season of year (t), respectively, and therefore distinctly represents the growth of year (t), it also depending on the growth of years (t-x). Statistically speaking, serial correlation can be found not only between the annual increments of previous (t-n) and concurrent years (t), but between the past, present and forthcoming years (t-n, t, t+n). The influence of climatic factors in previous years therefore modifies the capacity of the tree to respond in later years to climate. This is the phenomenon called physiological preconditioning (Fritts 1976), which can be expressed mathematically by autoregressive-moving average models (ARMA) of Box & Jenkins (1970) in tree-ring analyses (Cook 1985; Guiot 1986). Tree-ring indices can be modelled and prewhitened as AR or ARMA processes of data-adaptively determined order prior to estimation of mean chronology. Resulting series are referred as white noise, containing no persistence but amplified signal (Cook 1985). Prewhitened series were used in the present work (IV) in order to minimize the influence of non-climatic growth disturbance in the comparison between the chronologies from forest-limit and forest interior, and further to focus on the comparison of solely climate related variation in tree-ring datasets of different origin.

2.3.4. Computing the mean chronology

Once the transformation of absolute ring-widths to tree-ring indices is completed, mean chronology is estimated. The average growth for each year can be calculated by arithmetic mean. In this process, all variations not common to the majority of the trees are expected to be reduced, and the climatic signal within the chronology is strengthened. If, however, sampled trees originate from closed canopies of forest interior, then it is suggested that the biweighted robust mean is to be used (Cook 1985). Unlike arithmetic mean, biweight robust mean reduce the influence of outliers due to growth disturbances in the computation of mean growth estimate. Both arithmetic (I, III) and biweight robust mean (II, IV) were used in the present study. The former was used at the northern coniferous forest-limit conditions where such disturbances were expected to be minimal in relation to more closed canopy conditions. Therefore, biweight robust mean was used when calculating the mean chronology for southern boreal forest (II), as well as when comparison between chronologies along the north-south gradient was performed (IV).

It has been shown that fluctuations in the chronology sample size as a function of time can cause artificial change in the variance in the mean chronology (e.g. Osborn et al. 1997). In order to adjust the variance to sample size, greater variance of smaller sample and reduced variance of greater sample, the procedure presented by Osborn et al. (1997) was used in the present work (II, III, IV). In addition, computation of mean chronology using serially correlated time series (e.g. tree-ring indices without prewhitening) may cause changes in the ARMA process of the chronology due to temporally varying sample size (see Granger & Morris 1976). If great temporal variations in sample size cannot be avoided, described bias could be minimized by averaging prewhitened series rather than serially correlated indices (Cook 1985).

2.4. Dendroclimatological data analysis

In order to determine the relationship between tree-rings and climate is processed through the response (Fritts 1962; Fritts et al. 1971; Fritts & Wu 1986) and transfer (Lofgren & Hunt 1982; Guiot 1985, 1991; Osborn & Briffa 2000) functions. Response functions analyse the influence of climate on the tree-ring growth. Fritts & Shashkin (1995) classified three basic types of possibilities to model this relationship in dendrochronology as conceptual, empirical and mechanistic models. Conceptual models translate the verbal models into diagrams designed to clarify specific relationships, empirical models include statistical analysis establishing probable associations within tree-ring series and their relationships to climate, whereas mechanistic models attempt to portray the relationship with mathematical equations as simplifications of the processes that link the causal factors to tree-rings. Response functions of the present work are empirical modelling (I, II, IV) by simple correlations (e.g. Briffa et al. 1990, 1995). They have been applied here to tree-ring data from northernmost to south-east Finland mainly by means of palaeoclimatology, that is, mainly in order to seek the possibilities to reconstruct different variables of weather over the different regions. In contrast to purely dendroecological studies, the emphasis here is therefore more on the amplitudes of the most significant coefficients of response functions rather than detailed interpretation of the interactions between climate and cambial activity. Compared to response functions by orthogonalized climatic variables (e.g. Fritts et al. 1971; Fritts 1976), the output of response functions by simple correlations are more robust to researcher's more or less subjective *a priori* decisions about the input data (Blasing et al 1984).

Transfer functions are statistical equations relating tree-ring chronologies and climate series over the calibration period. Transfer functions are used in tree-ring based reconstructions of past climate, where tree-ring chronologies serve as the predictor (independent) variables and the climatic series serve as the predictand (dependent) variable. In contrast to many palaeontological reconstructions where calibration is derived using a spatial array of palaeontological indicators with a spatial array of climate means, dendroclimatological transfer functions are calibrated using time series. Due to physiological preconditioning (see section 2.3.3.), tree-ring growth during the year (t) reflects the climatic conditions during the previous years (t-n). That is, in turn, to say that the climatic conditions during the year (t) are further reflected to the growth of the forthcoming years (t+n). Therefore the records of tree-rings can be transferred to the variations of climate using the growth estimates of over several years (t-n, t, t+n). In the present work (I, II), transfer functions were derived from single regional tree-ring chronologies by multiple regressions (Fritts 1962, 1976). After the calibration on dependent data of tree-rings and climate series, the equation is applied to the predictors for extended period, which was withheld from the calibration. The obtained retrodiction is further verified to ensure the applicability of the equation on independent data. Verification is processed by visual and statistical means including several tests of association (Fritts 1976; Gordon et al. 1982; Briffa et al. 1988).

According to dendroclimatological implication of the uniformitarianism principle, the relationship that govern the environmental and tree growth conditions must have been the same in the past as in the present (Fritts & Swetnam 1989). If this principle does not hold, conclusions concerning the past cannot be made. Successful verification supports the validity of unifomitarianism principle and therefore the validity of the reconstruction (Fritts 1976).

3. Results

Obtained main results and conclusions drawn in separate papers of this volume are presented in the sections below (3.1.-3.4.). These results are further discussed and summarized in the context of previous dendrochronological and palaeoclimatological literature in the subsequent section (4.).

3.1. Temperature variations during the past seven and half millennia

July temperatures, which prominently control the tree-ring variability at forest-limit of northern Finland, were reconstructed using the ring-width chronology of Scots pine since ca. 5500 BC (I). Calibration and verification procedures exhibited reasonable skill of reconstruction for examined test periods (1879-1992). This study applied Regional Curve Standardization (RCS) in growth trend removal process. RCS was shown to reveal greater centennial-scale variability in resulting tree-ring chronology, compared to the earlier works using the similar tree-ring material but different tree-ring standardization. Variations at lower frequencies should not however be interpreted without great caution. Interestingly, the 20th century AD was shown to be one of the warmest spells during the past millennium, and amongst the warmest centennial period during the entire reconstruction. On the other hand, coldness during the preceding century, 19th AD, was shown to be contrastingly amongst the severest periods during the past millennium.

3.2. Precipitation variations during the past eleven centuries

Precipitation during the concurrent May and June was shown to govern Scots pine ring-width variability in south-eastern Finland (II). This was done by comprehensive calibration-verification practise that was processed in order to determine the most suitable season for reconstruction. Early-summer precipitation reconstruction based on tree-rings was derived using the millennia-long chronology from the region since AD 874. Verification practise showed reasonable skill of reconstruction, but less compared to temperature reconstruction at the northern forest-limit. However, the reconstruction correlated significantly with early meteorological observations from Turku (1750-1794) and St. Petersburg (1758-1767), showing that also the earlier part of the reconstruction is reliable measure of rainfall in the region. The reconstruction was also shown to be applicable several hundreds of kilometres to the west and the south. Strongest feature in the reconstruction was the component of the interdecadal rainfall variation that was present trough the reconstruction, observed visually and by frequency-analysis.

3.3. Comparison between tree-ring standardization methods

The test, including four methods of growth trend modelling, ratio and residual based indices and power transformation (PT) (Cook & Peters 1997), was performed using Scots pine ring-widths from northern forest-limit in Finland (III). PT stabilized the heteroscedastic variation in original tree-ring widths series more diligently than other standardization methods with potentiality to low-frequency growth variability preservation. RCS showed to bear great potentiality preserving great amount of variation in tree-ring series at longest time-scales. On the other hand, it was shown that great variability in the mean sample cambial age (natural feature in forest-limit tree-ring chronologies) might in some cases produce sporadically inflated chronology values when RCS is used in growth trend removal process, especially when the mean sample cambial age is very low (i.e. young). High (i.e. old) mean sample cambial age did not seem to produce fallaciously too high chronology values during the past 150 years of the chronology (AD 1850-2000). This indicates that climatic interpretation of summer temperatures using the same set of data (I) was correspondingly correct.

3.4. Climate related variation in regional millennia-long tree-ring chronologies

Comparison between four regional ring-width chronologies of Scots pine, along the north-south gradient through Finland, was derived using previously accepted techniques (e.g. Fritts et al. 1965; Fritts 1976) (IV). It was shown that common growth signal, sensitivity and strength of climate signal all increased from south to north, whereas the growth trend concavity decreased towards the same direction. Precipitation during the concurrent May had significant correlation with all regional chronologies and temperature during the concurrent July with three northernmost chronologies from northern forest-limit, northern boreal forest zone and middle boreal forest zone. Similarly, three northernmost chronologies showed response to volcanic forcing of climate during the past five centuries, whereas the southernmost chronology did not show such a temperature related response. Three out of four regional chronologies showed significant correlation to winter-time North Atlantic Oscillation (NAO) by response functions. Running correlation between the chronologies fluctuated roughly in line with changes in the intensity of NAO at decadal time-scale. This indicates that NAO drives the common growth signal among the chronologies.

4. Discussion

4.1. Tree-ring chronologies and their standardization

Time series of different regional ring-width datasets were shown to contain different characteristics of tree-ring statistics (IV). North-south –gradient from northern forest-limit to south-east Finland occurred by means of common growth signal, mean sensitivity and growth trend concavity (IV), implying significantly different growth environment from region to region as experienced by pines, i.e. increasing growth disturbance/competition and decreased climate dependency from north to south (IV). All of these features are present in the resulting mean chronology but they also indicate different demands and possibilities of tree-ring data-analysis in each case of different regional datasets. Most importantly, the nature of source environment bears impact on the selection of the tree-ring standardization methods. The latter in turn largely determine the frequency-dependent characteristics of the resulting chronology (see Cook & Briffa 1990; Murphy & Palmer 1992).

In dendroclimatic studies, the desired growth signal in resulting chronology is climatic, and the variation of any other kind is considered as noise. As the non-climatic noise increases in the study region from north to south (IV), the demands of the standardization process increase in accordance. As stated out by Briffa et al. (1986), no one method of standardization works ideally in all situations. In fact, due to different requirements in different parts of the present study, different methods of standardization were used in all four individual papers (I, II, III, IV) of this volume.

4.1.1. Regional Curve Standardization

It has been suggested that at the forest-limit region, where wide inter-tree spacing decreases the amount of growth disturbance, the standardization method could be targeted to remove only the growth trend arising from the factors intrinsic to tree-growth (e.g. Briffa et al. 1992, 1996; Cook et al. 1995). If this growth trend due to tree ageing and sizing is supposed to remain same over the long intervals of time, one could further estimate it by averaging all the available ring-width time series, after realigning them by their cambial ages (e.g. Briffa et al. 1992). This procedure could create a single average growth trend, from which the climatic influence would be largely ruled out due to law of averages. This growth trend could be then used as an expected growth from which the tree-ring indices could be extracted for example as ratios.

This relatively simple method for growth trend estimation was already used by Huntington (1914) in his dendroclimatological investigations and it is thus amongst the first procedures of growth trend estimation in tree-ring literature. However, it was Briffa et al. (1992) who used RCS in order to preserve great amount of low-frequency (multi-centennial) growth variability in standardized tree-ring series (III). During the recent years, RCS has been used in dendroclimatological studies to remove the growth trend from series of ring-widths and maximum densities in several papers in which the low-frequency growth and/or climatic variation has been emphasized (Hari et al. 1984; Becker 1989; Briffa et al. 1992, 1995, 1996; Nicolussi et al. 1995; Arseneault & Payette 1997; Cook et al. 2000; 2002, 2003; Naurzbaev & Vaganov 2000; Grudd et al. 2002; Gunnarson & Linderholm 2002; Naurzbaev et al. 2002; St. George & Nielsen 2002; Esper et al. 2002, 2003).

In the present study, RCS was used in two independent studies (I, III). It was included in the comparison of methods of tree-ring standardization where its use was shown to produce more low-frequency growth variation into the chronology than any other tested method (III). RCS was also applied in tree-ring based temperature reconstruction at the northern forest-limit (I). Due to its potentiality to retain great amount of growth variations in the chronology at all time-scales from years to centuries, the use of RCS could be recommended in wide range of tree-ring studies aiming to reconstruct past climate, assuming that the material originates from the forest-limit region where the influence of stand dynamics on tree-rings can be assumed to be (close to) absent. However, its use requires more consideration about the population dynamics of the tree growth than the methods of standardization where the expected growth trend is fitted individually to all series of original tree-rings. For example, RCS has been shown to be sensitive to temporal variations in the mean cambial age (see Briffa et al. 1996; III). That is, the danger of biased chronology values may occur in the periods of extremely low or high mean cambial age (Briffa et al. 1992, 1996; III).

It was demonstrated by Cook & Peters (1997) that in the case of slowly growing trees, such as forest-limit pines, there is a danger that the ratio based indices are to be inflated due to standardization curves approaching zero (division by 0.5 or smaller values is actually multiplication by 2 or higher values). The bias may occur with any type of relatively stiff growth trend models, such as negative regression lines, negative exponential curves or with RCS. The zone of danger occurs where chronology is constructed by old trees of low radial growth increment, i.e. commonly (but not only) during the last 150 years of the chronology (e.g. AD 1850 onwards). In order to avoid this problem, Cook & Peters (1997) applied the power transformation to series of original ring-widths prior to growth trend removal and to then extract the indices by subtraction instead of division. Power transformation of Cook & Peters (1997) was applied also to ring-widths in hand (III). However, in the case of northern forest-limit tree-rings, similar distortion towards biasely high chronology values over the past 150 years was not detected (III). This further implied that the overall level of the 20th century temperatures was not overestimated in tree-ring based temperature reconstruction (I), as partially same data of tree-ring measurement series was used in these two studies (I, III).

The use of RCS assumes that one single growth trend, smoothed average of all growth series, is applicable over the centuries or even millennia as a model for tree ageing (Briffa et al. 1992). However, that might not always be a case. Actually, it has been found in several studies that the growth trend of living and subfossil trees is not exactly the same (Briffa et al. 1996; St. George & Nielsen 2002; I). Possible reasons for the change in growth trend has been suggested to be attributable to the altitude of the growing site (Briffa et al. 1996), to properties of growing site soil (Briffa 1993) or to intensification of anthropogenic influence (St. George & Nielsen 2002). According to present study (IV), also changes in the tree density (competition) of the growing site influence the average concavity of the growth trends, in line with similar results of Mikola (1950). Therefore, if the changes in the tree density at the forest-limit region through the Holocene have been sufficient (see e.g. Eronen et al. 1999a, b), it could be that the assumption of a single standardization curve for the entire time period is not properly held.

Despite of some of its weaknesses, which predominantly arise due to non-homogeneity of the original data (III), RCS is the key to overcome the ‘segment length curse’ in tree-ring chronologies, described by Cook et al. (1995). This curse means, that when the expected growth trend (i.e. standardization curve) is fitted individually to all series of tree-rings and the indices are extracted from the curve, the maximum wavelength of recoverable information by a resulting chronology is related to the mean sample length (Cook et al. 1995). That is to say that the longevity of the trees included into the chronology determines the maximum low-frequency loading of a tree-ring based climate reconstruction if original ring-width series were individually standardized. Similarly, it was also shown by Sheppard et al. (1997) that when the tree-ring series were broken into fragments due to e.g. missing part of a sample, inserting values (which were later omitted before chronology calculation) to connect fragments of measurements considerably increased the low-frequency growth variation in resulting chronology. As it was shown in the present work (III), it can be very useful and informative to plot differentially standardized tree-ring chronologies (originating from same original data set) for a comparison between the amplitudes of the fluctuations in different chronologies. Such a comparison, used also for example by Esper et al. (2003), could help experienced researcher to reveal the potential biases in each chronology, particularly in their low-frequency domains (see Esper et al. 2003; III).

4.1.2. Standardization by fitting curve individually to ring-width series

In the forest-interior, tree-rings are not only influenced by factors intrinsic to trees but also largely by extrinsic factors such as competition and other stand dynamics –related agents (e.g. Fritts 1976; Cook 1985, 1987; Fritts & Swetnam 1989). If a standardization curve is fitted individually to series of ring-widths as a model of expected growth trend, then it is supposed that this curve captures not only the trend due to tree ageing but also the impact of some of the extrinsic agents. Various methods for this kind of curve fitting have been introduced to the tree-ring standardization in the literature, from a simple regression line to more ‘flexible’ functions for example by low-pass filters (Kuusela & Kilkki 1963; Fritts et al. 1969; Fritts 1976; Warren 1980; Cook & Peters 1981; Briffa et al. 1983; Holmes et al. 1986).

In general, the more flexible the standardization curve gets, the more closely it follows the growth perturbations observed in tree-ring characteristics, and the greater amount of growth variations at corresponding time scales are lost in the standardization (III). If, however, standardization curve is too stiff it is apparently not able to capture non-climatic noise present in ring-width series in the forest-interior. In this context, Cook (1985) combined smoothing splines (Cook & Peters 1981) and the 'trend in mean' concept of Granger (1966). The latter refers to variance with wavelengths longer than the series length (n). Furthermore, the lowest resolvable frequency that can be theoretically differentiated from the pure trend is equal to 1/n, i.e. the standardization should not remove variance resolvable from the trend (Cook 1985). Due to shape of the spline frequency response functions (see Cook & Peters 1981), criterion of the concept is approached by cubic-splines (with 50 % frequency response cut-off) using percentages between 67 %n and 75 %n (Cook 1985). The use of these percentages ensures that low-frequency variation will be greatly preserved in the resulting indices (Cook 1985). Tree-ring material from south-east Finland, which was used to reconstruct variations of past precipitation, came from sites of interiors of the forests and this data was standardized using 67 %n splines (II). This method was chosen to be used (along with biweight robust mean) in particular to capture potential pulses of non-climatic growth disturbance, prior to climatic calibration of the reconstruction.

In order to remove the non-climatic variation equitably from tree-rings of different source environments the standardization method of double-detrending (Holmes et al. 1986) was used here (IV) as a combination of modified negative exponential curve (Fritts et al. 1969) and 67 %n splines (Cook 1985). As an alternative, negative regression line or line through the series mean were in some cases used instead of modified negative exponential curve. The use of double-detrending was justified as follows: the concavity of modelled growth trends were shown to change in line with environmental gradient and this trend was equitably removed by negative exponential curves. Non-climatic growth disturbances were further aimed to be removed by stiff splines (and by biweight robust mean) in order to preserve considerable amount of variations in the resulting indices at multi-decadal and longer time scales (IV).

4.2. Climate-related variation in tree-rings

4.2.1. Impact of temperature and rainfall on ring-widths

In this section, the relationship between climate and ring-width series is being discussed. In this study, this relationship was studied separately in the northern forest-limit, in the region of Pääjärvi, North Karelia and south-east Finland, referred as regions A, B, C and D (IV). The species under discussion is hereafter Scots pine if not otherwise mentioned.

Mid-summer temperatures, July concurrent to growth, bore greatest influence on ring-width variability amongst the three northernmost regions, from northern forest-limit to North Karelia, somewhat 70°N to 63°N (I, IV). This spatial homogeneity of climate-related growth is well parallel to study of Mikola (1950). In the northern forest-limit of Fennoscandia and Kola Peninsula, the prominent dependency of radial growth to summer temperatures is known from wide range of studies (Erlandsson 1936; Hustich & Elfvig 1944; Mikola 1950; Sirén 1961; Briffa et al. 1988; Lindholm 1996; Kirchhefer 2000, 2001; Gervais & MacDonald 2000; Grudd et al. 2002).

In south-east Finland early-summer precipitation, May-June concurrent to growth, became to strongly control the ring-width growth (II, IV). This is in line with results of Henttonen (1984) who found the precipitation sum of May-July to be the most important climatic factor governing the radial growth on the network of ring-widths chronologies in southern Finland. Precipitation of May controlled the growth significantly not only in the south but consistently along the north-south gradient across Finland, from northern forest-limit to southern Finland (IV). At least within the northern regions, the occurrence of rain in May can intensify the snowmelt and frost and thus make the growing season to begin earlier. Effect of snow-melt timing has been discussed also by Lindholm (1996: p. 138), Thomsen (2001) and Vaganov et al. (1999). Spring rain can also serve as complement to water deficit after conceivable winter-desiccation which has also been described from northern Finland (Holtmeier 1971).

Interestingly according to Miina (2000), who studied the climate-growth relationships on intra-annual time-scale in North Karelia, it is particularly the earlywood growth that can be explained by precipitation of concurrent May. In the same region, concurrent late-summer temperatures explained the variation in latewood growth more clearly than in the total ring-widths (Miina 2000). Although this founding cannot be extended over larger areas prior to research, it is however possible that precipitation in May bears impact particularly on earlywood growth instead of total ring-width also elsewhere.

The climate signal in the northern forest-limit tree-rings is prominently caused by mid-summer temperatures and in the southernmost Finland by spring-summer precipitation, whereas the climate signal in tree-rings between these two regions is assumingly driven by several climatic factors, none of them prominently crucial for radial growth. This could be noted from the amplitudes of the coefficients of the response functions as well as from the low percentage of explained climatic variance in the regional tree-ring chronologies from Pääjärvi and North Karelia (IV) which are situated somewhat on the borders of north and middle, and middle and south boreal forest zones, respectively. In south-east Finland, ring-width variability was explained by higher percentage than in the regions of Pääjärvi and North Karelia (IV). In southern Finland, the ring-width variability was found to be stronger in south-east than in south-west Finland by Thammincha (1981), indicating stronger climatic dependence in the former than in the latter region, and similar conclusion could be also drawn from the results of Lindholm et al. (2000). These suggestions are in line with high percentage of explained climatic variance in south-east ring-widths in the present study (IV).

4.2.2. Transfer functions in north and south Finland and their interpretation

Present work used ring-width chronologies to reconstruct past July temperatures at the northern forest-limit (I) and May-June precipitation in south-east Finland (II). Temperature reconstruction in the north shows higher coefficient of determination (R^2) in relation to precipitation reconstruction in the south (I, II). This is apparently due to higher climatic dependence of growth at the distributional limits of the species in the north, due to climatic severity there (IV). In addition, the presence of growth disturbance in the closed canopy type forests in the south increases the influence of stand dynamics in tree-rings and correspondingly decreases the level of dependency of the growth due to climate, in relation to wide inter-tree conditions at the forest-limit (IV). Yet, the precipitation reconstruction was based on the ring-widths of concurrent year of growth only, in relation to northern temperature reconstruction which was determined by ring-widths of concurrent (t) and forthcoming (t+1) year of growth (I, II). The climate-growth model in south-east Finland did not show significant improvement after inclusion of leading or lagging growth estimates (t-n, t+n) (I, II). This was due to lower serial dependence of ring-widths in the south in relation to north, owing to physiological (e.g. long needle retention in the north) or methodological factors. It can be that more flexible standardization curves used in the growth trend removal process of south-east Finnish ring-widths lowered the level of serial dependency of annual ring-widths in the resulting chronology in relation to stiff standardization curves in the case of northern ring-width series (see paper III). The use of lagging and/or leading estimates of annual ring-widths is preferable as the response function of model (t-n, t, t+1) modifies the autocorrelation of the resulting chronology to the serial behaviour of climate series. The use of transfer function model (t) may thus partially explain the lower R^2 in the case of south-east tree-rings in relation to the model (t, t+1) of which use was possible in the north.

Any reconstruction of past climate is optimally built using the principal components of a pool of predicter variables. This would, however, require the use of relatively large data sets of tree-ring site chronologies (or some other proxy series). In order to lengthen the reconstruction, a single average chronology can be used if the temporal coverage of sample size (replication) is large enough.

In the context of palaeoclimatology, no one proxy alone is adequate for reconstructing the full spectrum of seasonal climate variability or large-scale patterns of past climate (e.g. Mann 2002). That is to say that the reconstructions of mid-summer temperatures (I) and early-summer precipitation (II) should not be extended to represent variations of the past climate on any other season or beyond the reasonable geographical limits of the study region. According to Briffa & Jones (1993), temperature fluctuations in the regions bordering the northern North Atlantic were not well representative of hemispheric mean data. This was particularly true for summer season and for Fennoscandia, Greenland and Siberia (Briffa & Jones 1993).

In general, temperature series bear greater correlations over distances than series of precipitation, and this is also known to be the case in Finland (Heino 1994). Present precipitation reconstruction was applicable over several hundreds of kilometres from the actual site under study (II).

4.2.3. Time-dependency of climate sensitivity in tree-rings

Briffa et al. (1998b) reported reduced sensitivity in high-latitude tree-rings of several species to growing season temperatures roughly during the past 50 years. Similar loss in the sensitivity of tree-ring characters to temperatures was noted already by Briffa et al. (1992) in northernmost Sweden, with their climate calibration using maximum densities and ring-widths of Scots pine tree-rings. This change in the sensitivity of tree-rings to growing season temperatures occurs mostly with maximum (latewood) densities, particularly in its low-frequency component, but in addition, although much less clearly, in ring-widths (see Briffa et al. 1998b: Table 1 and Fig. 2). The change occurs differently in different regions of northern hemisphere (Briffa et al. 1998b). According to Briffa et al (1992, 1998a, b, 2004), tree-rings have exhibited lower growth values than could be expected by the level of temperatures during the late half of the 20th century. For tree-ring based climate reconstructions using regression-based transfer functions, this non-temperature-related bias could cause too warm estimates of palaeoclimate. Possible contributors to the dissociation could be increasing influence of later snow cover delaying the onset of season tree-growth (Vaganov et al. 1999), or, enhanced ultra violet radiation on the photosynthetic process, a possible consequence of falling concentrations of ozone in the stratosphere (Briffa et al. 1999a, b, 2004).

At the forest-limit, it was shown that ring-widths were slightly more strongly correlated with July temperatures over the early interval 1879 to 1935 than over the late interval 1936 to 1992 of response functions (I). On the other hand, the influence of August temperatures increased from early to late growth interval and therefore somewhat balanced the decreased July-growth correlation. Yet, calibration and verification statistics indicated real skill of reconstruction over both the early and late intervals (I). Parallel results of slightly but by no means significantly decreased intercorrelation of summer temperatures and ring-widths have been obtained for example by Lindholm et al. (1995) and Lindholm (1996b) in northernmost Finland, and by Kirchhefer (2000) in the vicinity of the present study region (I) in northernmost Norway. Therefore the tree-ring based estimates of palaeoclimate in the present study (I) could be concluded not being biased due to dissociation described by Briffa et al. (1998b).

Interestingly, the response of ring-widths to May-June precipitation in south-east Finland was shown to decrease as a function of time during the 20th century (II). During the same period, there occurred no significant increase in any other climatic factor to be more strongly correlated with ring-widths. As these trees were expected being natural-grown individuals without no clear human impact (e.g. logging) (Lindholm et al. 1997: p. 154), the actual reason for the decline remains unknown. On the other hand, trees growing in the interior of the forest, such as these trees in the southern part of the boreal forest belt, are however expected to contain considerably more sporadic non-climatic disturbance in the radial growth than trees at their distributional limits, and therefore it could be unwise to straightforwardly associate this decline with the reduced temperature sensitivity described by Briffa et al. (1998b). It was further shown that the reconstruction correlated significantly with couple of early instrumental meteorological observations from 18th century: this provided further complements to the questions of the reliability of the model of transfer function (II).

4.2.4. Inter-regional growth signal

The amplitude of the common growth signal in tree-rings between northern and southern Finland fluctuated as a function of time (IV). That is, the periods of associated growth were driven by same climatic factors whereas during the periods of weak correlation no common climatic factor over the regions occurred. It was shown by response functions that the radial growth from northern forest-limit to south-east Finland was linked also to North Atlantic Oscillation (NAO) (van Loon & Rogers 1978; Hurrell 1995). It was further suggested that the intensity fluctuations of NAO at decadal time-scales could have driven some of the common variation during the past five centuries (IV). Behaviour of NAO is known to influence the climate over large areas of North Atlantic, and especially in Fennoscandia: positive phases of NAO are associated with increased precipitation (Hurrell 1995; Uvo & Berndtsson 2002).

4.3. Tree-ring based reconstructions of past climate

Characteristics of palaeoclimate reconstructions shown here are based on the corresponding properties of their counterparts, tree-ring chronologies, and transfer functions. Whereas transfer functions have affect greatly on high-frequency (year-to-year) variation of the reconstruction, chosen methods of tree-ring standardization (see section 4.1.) bear great influence mainly on the lower-frequency variation of the obtained reconstruction (III). All reconstructions of past climate are forcefully based on the uniformitarianism principle. Dendroclimatological implication of the principle is that the relationships that govern the environmental and tree growth conditions must have been all the same in the past as in the present (Fritts & Swetnam 1989). Yet, each of the estimates of annually resolvable palaeoclimate record is either interpolation or extrapolation. According to Weisberg (1984), interpolation (extrapolation) occurs when the predictors are within (outside) the range used to build the transfer function. Interpolations are thus safer to interpret than extrapolations which should be taken with greater caution.

4.3.1. Summer temperatures during the past millennium

Last decades have experienced intensive discussion on the temperature changes of the past millennium. Major part of this debate has concerned the amplitude of the warmth of the twentieth century. Recent temperatures have been studied in the perspective of past centuries in order to detect other periods of similar climate, that is, in order to accept or reject the theory of the unprecedentness of the twentieth century climate (e.g. Briffa et al. 1995; Mann et al. 1995, 1999; Esper et al. 2002). Fluctuations of hemispheric climate have been studied to determine the importance of natural (e.g. solar and volcanic activity) and anthropogenic (greenhouse gases) factors forcing climate variability (Crowley 2000; Mann et al. 1998).

Using the records produced in the course of this study, the question of the 20th century climate could be studied by two records (I, III) from northernmost Finland. It was shown, that the 20th century has experienced relatively warm summer-time climate in the context of the past one thousand years (Table 5 in Paper I). Especially warm were the summers of the 1930s (in line with the observational series). It was also shown, that the coldness during the 19th century was perhaps severest of centennial periods during the past millennium. Therefore, if one would rely only on instrumental observations, the 20th century climate (relative warmness) could stand out as an eye-catching warm period due to shortness of instrumental temperature series. The warmness of the summer-time climate during the 1930s in northern Finland was challenged by the temperatures during the 16th century (I). Most of the 16th century experienced mild weather in northern Finland, like in most of Europe north of the Alps until the 1570s after which relatively abrupt coldness began (Briffa et al. 1999; I). In northern Finland, this relatively mild century period seemed to be warmer than the 20th century (I). It was however also shown, that due to low mean sample cambial age in tree-ring chronologies during the 16th century (III) the estimated growth level during the same spell (from which the reconstruction is derived) could have potentially been slightly inflated (III). However, in the present case (III) the low mean sample cambial age was an implication of the high rate of pine regeneration (III) which, in turns, could be also interpreted as a sign of summer-time temperatures well above the long-term averages (see Henttonen et al. 1986). Based on the present results (I, III) it could be concluded that the warmness around the 1930s were amongst the highest during the past millennium but because of cold periods after that as well as in the beginning of the 20th century the century as a whole was not that warm. Towards the end of the past century (reconstruction in Paper I ends in the beginning of the 1990s) summer-time temperatures do not seem to be rising (as with the observational records from the study region) unlike some of the hemispheric average series (Mann et al. 1998; Jones & Moberg 2003), implying the presence of spatial non-homogeneities in temperature climate.

Apart from decadal and centennial changes in tree radial growth, the abrupt year-to-year changes are well imprinted in the ring-width variations. It was shown that in the extreme conditions of forest-limit, negatively extreme growth years in tree-ring chronologies (or reconstructed low summer-time temperatures derived from them) correlate well with the occurred volcanic events bearing hemispheric influence on climate (I, III). Gervais & MacDonald (2001) showed that in addition to extreme index years, the measure of sensitivity (see Gervais & MacDonald 2001) of Scots pine ring-widths correlated well with the volcanic signature years in Kola Peninsula. In Finland, pines from the northern forest-limit region to North Karelia were able to record the volcanic events, whereas the pines south of that did not. This result was in line with the results from the response functions (IV).

4.3.2. Interpretation of the mid and late Holocene temperatures

The long ring-width chronology from Finnish Lapland spans over large part of the Holocene. RCS method was used in standardizing the original tree-ring series and therefore it is possible, at least theoretically, to overcome the 'segment length curse', as it was described by Cook et al. (1995) and discussed above (section 4.1.). The behaviour of the tree-ring variability at time scales longer than the segment length, is not, however, as well known as the variability at shorter time scales (see Cook et al. 1995; Briffa et al. 1996; Esper et al. 2003; III). As stated out by Jones et al. (1998: p. 457), in practise this means that one can be more confident in comparing the centennial average of twentieth and nineteenth or the twelfth and thirteenth than the twentieth and twelfth centuries, for example. In this sense, the examination of the extreme climatic periods in consecutive millennia during the reconstructed period (Table 5 in Paper I) is perhaps more reliable than examination of climatic periods during the entire reconstructed period (Table 4 in Paper I).

There are some factors which may have caused non-climatic bias for the reconstruction at time scales longer than the mean segment length. Agents for bias include soil development and changes in the ecogeographical conditions, for example due to altitudinal and latitudinal fluctuations in the forest-limit (Eronen 1979; Eronen et al. 1999a, b). Also the continentality of the climate in the region has increased through the Holocene (Eronen 1979). Yet, the atmospheric CO_2 content, which has been related to increased radial growth of many tree species during the past decades (LaMarche et al. 1984; Hari & Arovaara 1988; Nicolussi et al. 1995), has risen with undulation during the Holocene (White et al. 1994; Indermühle et al. 1999). Yet, the humidity of the climate in the region has fluctuated at millennial time scales throughout the Holocene (Hyvärinen & Alhonen 1994; Eronen et al. 1999a; Seppä & Birks 2002; Jones et al. 2004); this may have caused, judging from the response functions (I, IV), fluctuations in the radial growth at the same time scales which are not related to temperature only.

Despite of the uncertainties which were associated here mainly with the very low-frequency growth (reconstructed temperature) variability, the mid-summer record presented (I) is, at the moment of writing, one of the only annually resolved, statistically calibrated and verified, climate reconstruction spanning over the mid and late Holocene times.

As mentioned in the previous section, one of the major tasks of the recent palaeoclimatology has been the placement of the 20th century climate in the context of past centuries and millennia. Furthermore, recent years have experienced increased discussion on the complexity of the Holocene climate on centennial to millennial time scales (Denton & Karlén 1973; Briffa et al. 1990; Eronen et al. 1999b; O'Brien et al.

1995; Keigwin & Boyle 2000; McDermott et al. 2001). Strong centennial variability is present also through the mid-summer temperature reconstruction (Fig. 1 in Paper 1) pointing to the presence of great climatic variability and perturbations. Detailed frequency analyses in the future will reveal if any of these fluctuations are concentrated on some specific time scales and if there are statistically significant cycles of temperature. Such an analysis can also reveal occurrence of pervasive, or sporadic, climate forcing mechanisms. In agreement with present indication of insignificant number of cold centennial temperature means roughly between 2000 B.C. and 500 B.C. (bottom plot of Fig. 1 in Paper I), there is also some independent multi-disciplinary evidence of increased temperatures in northern Fennoscandia around that time. This evidence originates from chironomid-based reconstruction of Seppä et al. (2002) in northeast Finnish Lapland (maximum at ca. 4200 cal. BP), tree-ring isotopes of Boettger et al. (2003) in northeast Kola Peninsula (ca. 4000-3500 cal. BP), and speleothem isotopes of Lauritzen and Lundberg (1999) in northern Norway (ca. 4000 cal. BP). Due to uncertainties in the low-frequency component of the reconstruction (I), the exact relationship between the amplitudes of these mild temperatures and the 20th century temperatures remains a challenge for improved model.

4.3.3. Rainfall during the past eleven centuries

Studies of proxy-based as well as instrumentally detected climate variability are in majority concentrated on the history of the thermal climate. However, not only the thermal but also the hydrological climate contains great variability of which nature is not completely understood (e.g. Karl et al. 1996; Ohmura & Wild 2002). Reconstructions of past precipitation over different regions can serve valuable contributions to the questions on the past and present changes of hydrological climate.

In Finland, changes in the humidity have been previously detected mainly at centennial-to-millennial time scale by studying lake-level changes using the diatom and cladoceran evidence in the analyses of sediment records (e.g. Hyvärinen & Alhonen 1994; Sarmaja-Korjonen 2001). Therefore the benefit of using tree-rings as proxy for precipitation is in particular in their contribution to the high-frequency (from year-to-year to multi-decadal) domain of estimated rainfall variance.

In Finland, the most severe drought of the 20th century was experienced during the four years between (and including) the years 1939 and 1942 (Hydrografinen toimisto 1944, 1948; Heino 1994: Table 5.2). Accordingly, this was also the driest four-year period during the calibration period in the early-summer precipitation reconstruction (II), suggesting further reliability of ring-width based rainfall reconstructions in the region. More precisely, observed May-June rainfall during these years in Punkaharju weather station (using for calibration) was 56 mm, whereas the reconstructed rainfall was 62 mm. Moreover, the individual years of 1940 and 1942 were listed amongst the driest of the entire record (Table 3 in Paper II).

Marked feature in the reconstruction was the component of the interdecadal rainfall variation, present trough the record: the most prolonged wet and dry periods occurred during the intervals 1081 to 1095 and 1173 to 1191, respectively. Interestingly, both of these intervals could enter the period of Medieval Warmth, or the ending spell of it (Lamb 1965).

4.4. Prospects for future studies

In the present study, response functions have been drawn over one or two periods (I, II, IV). Response functions could be however computed additionally using running time windows by means of evolutionary or moving response functions (Biondi 1997) in order to reveal the temporal changes in the relationship between climate and growth.

Precipitation reconstruction for south-east Finland presented here (II) was based on index series being standardized using 67 %n spline functions as growth trend models. This method is ideal to reduce non-climatic noise in the resulting series with simultaneous ability to retain considerable amount of low-frequency variation (Cook 1985; III). However, the proportion of the preserved growth variation at long time scales could be improved by including only the trees of very long life span (Cook et al. 1995). In addition, growth trend models such as negative exponential curves or linear regression lines, albeit not as optimal for reduction of non-climatic noise, could improve the proportion of the low-frequency in the chronology and in the reconstruction (e.g. Lindholm 1996; Esper et al. 2003; III). Recent years have experienced relatively dry climate in Finland (Rönkä 2003); this further emphasizes the need for improved rainfall reconstructions in the region, in order to determine the natural spectrum of rainfall variability as well as its forcing factors.

At forest-limit, RCS method was applied to remove the growth trend from original ring-width series, applying a single standardization curve for all series. However, as it was discussed in above section (4.1.1.), the assumption of a time-invariant standardization curve might not be proper if any non-climatic factor bearing influence on growth trends are changing though the time. Detailed investigation of even slight changes in the spatiotemporal nature of different components (e.g. concavity, juvenile maximum) of growth trends could potentially improve the understanding on the needs of the standardization procedure with desire to preserve low-frequency growth variability.

Densitometric measurements of tree-rings yield time series which are known to correlate with climate better than ring-widths (e.g. Briffa et al. 1988, 1990, 1992). Inferred from response functions, long tree-ring chronologies from northern forest-limit and North Karelia could serve material for millennial temperature reconstructions with higher degree of explained variance in relation to ring-width chronologies. Similarly, densitometric measurements using south-east tree-rings could produce improved precipitation reconstruction.

Multi-centennial and even millennial tree-ring chronologies of Scots pine are available at present in Sweden (Grudd et al. 2002; Gunnarson & Linderholm 2002) and Estonia (Läänelaid 2001).Work with network of long chronologies instead of single chronologies could be done in order to reconstruct large-scale climate fluctuations. Similarly, comparison between forest-limit ring-width chronology and records of annually laminated lakes from southern and central Finland (e.g. Ojala 2001) will produce information about the spatiotemporal climate variability in Finland.

5. Conclusions

Several concluding remarks were drawn based on the results and their interpretation. These can be listed as follows:

1) North-south –gradient from northern forest-limit to south-east Finland occurred by means of common growth signal, mean sensitivity and growth trend concavity, indicating different demands and possibilities of tree-ring data-analysis in each case of different regional datasets. The nature of source environment thus had an impact on the selection of the tree-ring standardization methods.

2) The use of RCS requires more consideration about the population dynamics of the tree growth than the methods of standardization where the expected growth trend is fitted individually to all series of original tree-rings. That is, RCS was sensitive to temporal variations in the mean cambial age.

3) Bias towards high chronology values over the past 150 years, due to division based standardization methods in index extraction, was not detected in the case of the northern forest-limit tree-rings. This further implied that the overall level of the 20^{th} century radial growth (reconstructed temperatures) was not overestimated.

4) Changes in the tree density of the growing site influenced the average concavity of the growth trends; if the changes in the tree density at the forest-limit region through the Holocene have been sufficient it could be that the assumption of a single standardization curve for the entire time period is not properly held

5) Common interregional growth signal was driven by July temperatures and May precipitation. Tree-ring chronologies from different regions responded similarly also to NAO and volcanic forcing.

6) Due to higher climatic dependence of growth at the distributional limits of the species in the north, temperature reconstruction in the north showed higher coefficient of determination (R^2) in relation to precipitation reconstruction in the south. Higher R^2 in the temperature reconstruction was also partly due to higher autocorrelation in the northern tree-rings allowing the use of tree-ring index of lagging or leading years (t-n, t+n) in the transfer functions there.

7) Both of tree-ring based palaeoclimate reconstructions provided evidence for greatly fluctuating Holocene climate. Apart from volcanic impact, potential climatic forcings, driving the temperature or precipitation variability, were not examined here but this part of the research remained to be tested later. This can be done using for example frequency, correlation and regression analyses.

8) Whereas the 20^{th} century experienced relatively warm summer-time climates in the context of the past one thousand years, the coldness during the 19^{th} century was

perhaps the severest of centennial periods during the past millennium. On the other hand, there were indications that the 16th century was in overall warmer than the 20th century. Towards the end of the past century summer temperatures did not seem to be rising.

9) Along with some independent multi-disciplinary evidence of increased temperatures in northern Fennoscandia, low number of cold centennial temperature means occurred roughly between 2000 B.C. and 500 B.C. Due to uncertainties in the reconstruction variability at the millennial time scales the exact comparison between the means of these mild temperatures and the 20th century temperatures remains a challenge for improved model. Understanding of the tree-ring growth variations at the time scales longer than the segment length is a prerequisite of such a model.

10) The drought in Finland between the years 1939 and 1942 was also the driest four-year period in the tree-ring based rainfall reconstruction during the calibration period but there were also indications of drier individual year conditions prior to the 20th century. The former implied reliability of the model, the latter that there might have occurred even more severe droughts in the past.

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