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Dendroclimatology in Fennoscandia – from past accomplishments to future potential

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Abstract. Fennoscandia has a strong tradition in dendrochronology, and its large tracts of boreal forest make the region well suited for the development of tree-ring chronologies that extend back several thousands of years. Two of the world's longest continuous (most tree-ring chronologies are annually resolved) tree-ring width chronologies are found in northern Fennoscandia, with records from Torneträsk and Finnish Lapland covering the last ca. 7500 yr. In addition, several chronologies between coastal Norway and the interior of Finland extend back several centuries. Tree-ring data from Fennoscandia have provided important information on regional climate variability during the mid to late Holocene and have played major roles in the reconstruction of hemispheric and global temperatures. Tree-ring data from the region have also been used to reconstruct large-scale atmospheric circulation patterns, regional precipitation and drought. Such information is imperative when trying to reach better understanding of natural climate change and variability and its forcing mechanisms, and placing recent climate change within a long-term context.

1 Introduction

Analyses of past climate from proxy data provide knowledge of the climate system and its natural variability. This knowledge is needed in order to make predictions of the future climate evolution (Bradley, 1985). Analyses of long proxy records can emphasize distinctions between natural long-term modes and anthropogenic induced climate variability. Presently, a large number of hemispheric and global temperature reconstructions are available (see, Jansen et al., 2007). Key features may be masked by hemispheric or global reconstructions of climate and consequently studies of regional climate variability are of importance (Luterbacher et al., 2004), especially when impacts of climate change on the environment are evaluated (e.g., Shindell et al., 1999).

Reconstructions of Holocene climate variability in Fennoscandia have mainly been based on relatively low-resolution climate proxies such as fluctuations of glaciers (e.g., Karlén, 1976), tree-limit variations (Karlén, 1976; Kullman, 1995), pollen/macrofossil analysis (Barnekow, 2000; Korhola et al., 2000; Seppä and Birks, 2001), speleothems (Lauritzen and Lundberg, 1999), peat humification (Nilssen and Vorren, 1991), and lake sediments (Yu and Harrison, 1995; Shemesh et al., 2001; Bjune et al., 2005). However, dendroclimatology is currently the only viable method to provide annually-resolved, calendrically dated, well-replicated proxy climate records in Fennoscandia going back more than five centuries. But still, few multi-millennial tree-ring records have been constructed and most tree-ring records span only a few centuries to up to one and a half millennium (Gouirand et al., 2008).

In this paper, we present a review of dendroclimatology, the study of climate and tree-growth parameters, and their use in the reconstruction of past climates across Fennoscandia. Studies of the climate/tree-growth relationships have a strong and long tradition in this region where the forests

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plays a significant part of the economies. After a short description of the geographical and climatological features of Fennoscandia (Sect. 2), we give a brief history of early dendroclimatological research (Sect. 3). Then we present reconstructions of a range of climate parameters, including multi-millennial temperature reconstructions from the northernmost part of Fennoscandia (Sect. 4). An outline of the status of isotope dendroclimatology is given in Sect. 5. Finally, in Sect. 6 we present our outlook for the future prospects for dendroclimatology in Fennoscandia.

2 Fennoscandia

2.1 Geography and climate

Fennoscandia is a geographic term used to denote the Scandinavian Peninsula, Finland and the Kola Peninsula and Karelia, both in Russia. Because most dendroclimatological studies in Russia have been conducted farther east, here we focus on tree-ring research in Norway, Sweden and Finland. The climate in the region is greatly influenced by the adjacent North Atlantic Ocean. The Scandinavian Mountain range, which runs in SW-NE direction through Norway and the central and northern parts of western Sweden, forces orographic precipitation to occur along its western margins. This process results in an oceanic climate to the west of the mountains where locally annual precipitation may reach 2500 mm or more. The continentality generally increases to towards the east, enhanced by the Scandinavian mountains where local montane climate can be found (Barry, 1992) although it decreases around the Baltic Sea and towards the Arctic Ocean in the north. Climate variability over the North Atlantic region has been closely associated with the North Atlantic Oscillation (NAO) (Visbeck et al., 2001), a mode described as a measure of the strength of westerly winds blowing across the North Atlantic Ocean (e.g., Hurrell, 1995; Slonosky et al., 2000). The NAO, which can be defined as a see-saw of atmospheric mass between the Icelandic low and the Azores high, is most dominant during winter due to the large north-south temperature, and hence pressure, gradients (Hurrell, 1995). During high NAO-index winters, westerly winds are stronger than normal, causing climate conditions over Fennoscandia to be warmer and wetter. During low index winters the westerlies are relatively weak and the influence of cold continental air masses increases in Fennoscandia. Although this relationship is most pronounced in winter and early spring (Rogers, 1990), leading atmospheric circulation patterns similar to that of winter NAO are also found in summertime (Hurrell et al., 2003). However, the summer pattern has a smaller spatial extent than in winter, and is located further north, with the southern node over North West Europe and a northern node over Greenland. It has been shown that the NAO has a significant impact on Fennoscandian climate also in summer (Folland et al., 2009). Instrumental records of North Atlantic sea surface temperatures (SSTs) show significant multidecadal variability over the last 150 years (Sutton and Hodson, 2005), and this has been related to the strength of the thermohaline circulation (THC) (Knight et al., 2005). The leading mode of low-frequency, North Atlantic (0–70°) SST variability has been termed the Atlantic Multidecadal Oscillation (AMO) (Kerr, 2000). The NAO seems to be linked to the AMO (Rodwell et al., 1999; Folland et al., 2009), but also temperature and precipitation variability in the North Atlantic region, including Fennoscandia (Knight et al., 2005; Sutton and Hodson, 2005). Thus, on multidecadal timescales, it is likely that the variability in SSTs in the North Atlantic Ocean plays an important role in driving climate variability in Fennoscandia.

2.2 Tree growth in relation to climate

The N-S and W-E climate gradients in Fennoscandia yield differences in seasonal climate such as the length of the growing season, and this is of importance for the association between climate and tree growth in the region. The strongest dependence on a climate parameter is most likely to be found where trees are growing at their limit of their distributions (Fritts, 1976; Travis et al., 1990). Trees growing in the vicinity of latitudinal or altitudinal tree lines are mainly sensitive to growing season temperatures (Mäkinen, 2002; Helama et al., 2005; Andreassen et al., 2006). In general, the temperature dependence decreases to the south and east in Fennoscandia, while the influence of precipitation increases. But since there are few truly arid areas in Fennoscandia, it is not expected that trees in the region can provide precipitation information of the same strength as temperature. In general, associations with spring or early summer precipitation can be found, especially in the central and southern parts of Fennoscandia, in addition to temperature responses (Linderholm et al., 2003; Macias et al., 2004; Helama et al., 2005). This growth dependence on both precipitation and temperature, where the dependence on one or the other factor may vary through time, makes these trees unsuitable as temperature or precipitation proxies. Still, locally in more continental areas, such as parts of eastern Fennoscandia, tree growth may be more influenced by precipitation than by temperature (Helama et al., 2009a). This general dependence of trees on both precipitation and temperature across large parts of Fennoscandia, suggests that the spatial and temporal variability of large-scale circulation patterns in the atmosphere, such as the NAO, may be of importance for the growth on different timescales. Indeed, Schove (1954), related tree-growth in northern Scandinavia to the northerly "monsoon" (the pressure difference of Haparanda minus the mean of Stykkisholmur on Iceland and Bruxelles), and several studies have shown links between annual growth and NAO (Lindholm et al., 2001; Solberg et al., 2002; Linderholm et al., 2003; Macias et al., 2004).

3 Early studies of dendroclimatology in Fennoscandia

The link between climate and the annual growth of trees in Fennoscandia has been the subject of scientific study for over 300 years. Already in the 18th century, Carl Fredric Broocman (1709–1761) related the annual growth of trees, in the eastern part of southern Sweden, to favorable summer conditions (Broocman, 1760) and Carl von Linné (1707–1778) viewed ring-width patterns from an oak in southern Sweden as a record of winter severity (Linné, 1745). Ulric Rudenschöld (1704–1765) compared pine trees in northern and southern Finland finding both differences and similarities, which he attributed to regional climate and soil conditions (Rudenschöld, 1899). Although dendroclimatology has strong traditions in the Nordic countries, it was the American astronomer Andrew Ellicott Douglass (1867–1962), who in the beginning of the 20th century established a statistically valid relationship between climate and tree-ring widths (Douglass, 1909, 1919). He set out to investigate the influence of sunspots on precipitation in America and chose tree-rings as a suitable drought indicator. During his studies he noted that trees growing in similar environments showed homogenous growth patterns, even for sites far apart. During the 1920s to 1930s Douglass made occasional research trips to Europe, and in Stockholm he met Professor Gerhard de Geer, who worked with the Swedish clay varve chronology. Gerhard de Geer had an idea that external, cosmic, forcings, such as solar variability, influenced the thickness of the clay varves and thus ought to be teleconnected to the North American tree rings. His wife, Ebba Hult de Geer, attempted to prove this and collected a number of tree-ring material from Scandinavia which she compared to the Douglass American *Sequoiadendron giganteum* (Gigant Sequoia) tree-ring curve. Her claim that she could date clay varves and tree-ring series from Sweden with the Sequoia curve (Hult de Geer, 1937) was, however, later refuted by one of the pioneers in European dendrochronology, Professor Bruno Huber who noted that the similarities in ring-with patterns among sites decrease with distance Huber (1948), which would be a proof against the proposed teleconnections.

Most of the features of modern Fennoscandian dendroclimatology were outlined in some key investigations during the early decades of the 20th century. One of the reasons for the interest in the factors – climatic and others – affecting tree growth was the important role of the forests for the economies in Fennoscandia. Thus, early in the twentieth century, a number of studies sought to find the relationship between tree growth and parameters such as weather, soil conditions, insect attacks and forest fires. Laitakari (1920) studied more than 300 Scots pine (*Pinus Sylvestris* L.) trees from southern Finland and found that the radial growth was dependent on spring temperatures of the growth year. In northern Norway (Eide, 1926) and the North-West of Sweden (Erlandsson, 1936), a dependence of summer temperatures on Scots pine growth was established. Using hundreds of Scots pine and Norway spruce (*Picea Abies* (L.) *Karst*) samples collected in national forest surveys in Finland, it was established that i) the diameter growth of pine was correlated to July temperature, ii) spruce was more dependent on June temperatures and that iii) no correlation was found between tree growth and precipitation, although it was noted that very dry summers had been unfavourable to trees at dry sites (Mikola, 1956). This confirmed the earlier results from Sweden (Erlandsson, 1936) and Norway (Ording, 1941). Based on results from dendrochronological studies of timber-line regions, Hustisch (1949) stressed that variations in ring width are largest where growth is mainly determined by one factor, such as temperature at the northern timberline, or moisture in the transitional zones between forest and steppe. This observation was in agreement with the statement from Eklund (1954), analysing pine and spruce from northern Sweden, that the harsher the climate conditions under which the tree rings are formed, the stronger the accentuation of ring widths of the extreme years. Moreover, Mikola (1952) argued that climatic variations in pine growth at the northern timberline are often accentuated by extensive frost injuries, and that one single year of heavy frosts may result in a prolonged growth depression. Related to such differences in regional climate, Eidem (1953) found that the chronologies from sites in the interior of Norway as well as from the coastline showed considerable differences, and that Norway spruce correlated better with June but Scots pines with July temperatures. In Norway, Slåstad (1957) noted marked growth differences between trees growing in dry valley bottoms and those growing at higher elevation, close to the tree line.

Several authors commented on the difference in temporal autocorrelation between spruce and pine, where pine in general show a strong dependence on previous year's growth, which seems to be absent in spruce (Ording, 1941; Hustisch and Elfving, 1944; Eklund, 1954; Jonsson, 1969). This difference was thought to depend on the different development and assimilation-rates in the needles of pine and spruce (Ording, 1941), and Eklund (1954) noted that the autocorrelation increased with latitude for pine, a feature also seen in spruce, but to a much lesser degree.

Based on the results from dendrochronological investigations in Fennoscandia, Schove (1954) provided some guidelines for dendrochronology or dating by tree-ring analyses: (1) data from individual tree species should be considered separately; (2) the trees should be growing within a small, climatically-uniform region; and (3) the growth measurements for each year should be corrected for age and standardized by a single objective method. The selection of trees (2) was especially important in Scandinavia, due to the spatial differences in temperature and precipitation across the region. The last point (3), concerns one of the more important features in dendroclimatology. Standardization is a process where non-climatic long-term variations or trends, due to normal physiological ageing processes and changes in the surrounding forest community, are removed from a tree-ring time series (Fritts, 1976). Standardization is accomplished by dividing (or subtracting) the actual measurements by a fitted mathematical function, such as a negative exponential curve or a spline, which describes the growth of the tree associated with the ageing of the tree. Depending on the method used, part of the variability in the tree-growth that is related to climate may also be removed. The process of retaining as much as possible of the climate signal, especially on long timescales, in the tree-ring data while removing the unwanted "noise" is under constant research and development, but will not be dealt with in detail here.

4 Reconstructing past climates

The strong forestry traditions in Fennoscandia have resulted in large-scale, long-term, national forest inventories in Norway, Sweden and Finland over the last hundred years. Hence there exists an enormous amount of tree-ring data from these inventories held at Metla in Finland (http://www.metla.fi), Skog og Landskap in Norway (http://www.skogoglandskap.no) and Riksskogstaxeringen (http://www-nfi.slu.se/) in Sweden. However, these surveys have in general been made to investigate growth trends (i.e. production) of forests in a systematic way for large regions, such as by sampling predefined sampling plots. Thus, sites were seldom selected from a climatological viewpoint, although some effort was made to select stands without thinning (e.g., Eklund, 1954). But, as the reputation of the science of dendroclimatology grew and the methodology was clearly defined (see, Fritts, 1976), the interest in utilizing tree-rings as climate indicators increased. In northern Fennoscandia, old dead wood from the ground and from lakes were collected to be used in comparison with other climate proxies, such as lake sediments and pollen records (Eronen and Hyvärinen, 1982) or to be used to infer past tree-limit variations (Karlén, 1976; Aas and Faarlund, 1988). Moreover, as a part of creating a European network of tree-ring width and density chronologies, conifers sites selected for climatological purposes were sampled by Fritz Schweingruber and colleagues in the late 1970s and early 1980s. These efforts may be considered the starting point for the modern dendroclimatology in Fennoscandia. Below we present an overview of those reconstructions of climate that have emerged in the last 25 years. For locations and information of the chronologies and reconstructions mentioned in Sect. 4, we refer to Fig. 1, as well as Tables 1 through 3.

4.1 Temperature

Sirén (1961) argued that tree-ring chronologies could be interpreted directly as records of summer temperatures, but the first reconstruction of summer temperatures in Fennoscandia using tree-ring data was not made until the 1980s. Aniol and Eckstein (1984) used tree-ring width (TRW) data sampled by Bartholin and Karlén (1983) at four locations around Lake Torneträsk, in northernmost Sweden, to reconstruct July temperatures from 1680 to 1983. A few years later, Schweingruber et al. (1988) published the first radiodensitometric-dendroclimatological analysis of Fennoscandian tree-rings using Scots pine data from Torneträsk dating back to AD 441 (Bartholin, 1987). Using part of this maximum latewood density (MXD) tree-ring data set, together with a network of TRW chronologies from northern Fennoscandia, Briffa et al. (1988) reconstructed regional July–August temperatures back to AD 1700. Briffa et al. (1988) concluded that although the year-to-year variability in observed temperatures could be reconstructed with fidelity, the low-frequency fluctuations, above 50 years, could not be reconstructed because of limitations in the standardization technique. The limitations concerned the standardization of each tree-ring series individually to create a common index series (henceforth referred to as individual standardization (IS)). Using this approach, the maximum wavelength of recoverable climatic information is a function of the lengths of the individual tree-ring series, the so called "segment length curse" (see Cook et al. (1995) for an in-depth discussion).

The summer temperature reconstruction from 1988 was further developed by Briffa et al. (1990), extending the target seasonal window to April–August, using tree-ring data only from the Torneträsk area. The reconstructed period spanned AD 500–1975, and when interpreted, they found no evidence of a homogeneous Medieval Warm Period (MWP). A short Little Ice Age (LIA) was inferred to have occurred around 1570–1650. Again, the weaknesses of the standardization method made it difficult to retrieve centennial to multi-centennial variation in the reconstruction. An effort to enhance the low-frequency variation was made by Briffa et al. (1992), where a modified standardization method was applied to the same dataset used by Briffa et al. (1990) together with some additional tree-ring width series. Instead of standardizing every tree-ring series with an individual function, all series were standardized using one common function derived from all individual series; a regional growth curve. This method was named Regional Curve Standardization (RCS), and can be described as a modification of the method earlier developed by Erlandsson (1936). A consequence of using the RCS method was a lowered common signal among the trees, but the low-frequency variability was greatly enhanced. Thus, one of the significant results of the new reconstruction was a longer and more coherent period of temperatures below the 1951–1970 normal in ca 1570–1750, compared to the old reconstruction.

In Finland, Lindholm et al. (1996) utilized Scots pine TRW data from the northern timberline to reconstruct July temperatures back to 1720. They noted pronounced decadal variability in mid-summer temperatures, where two periods displayed prolonged below average temperatures; ∼1760–1820 and ∼1860–1910, and warm decades in the 1750s,

Table 1. Fennoscandian temperature reconstructions described in the text. The numbers accompanying the location names refers to Fig. 1a The heading SM refers to standardization method, where IS is individual standardization and RCS = Regional Curve Standardization. R^2 = variance in observations explained by the reconstruction. The proxy parameter TRW refers to tree-ring width, MXD to maximum latewood ensity, LW to latewood and EW to earlywood. t refers to the current year, $t-1$ to the previous year and $t+1$ to the following year and so on.

No.	Location Reference	Lat. Long.	Interval	SM	Calibration period	Proxy	Summer temp. parameter	R^2
1	Torneträsk, (Aniol and Eckstein, 1984)	68° N, 20° E	1680–1983	N.A.	1901–1980	TRW (t, $t-1$, $t-2$, $t-3$)	Jul	0.34
–	Northern Fennoscandia (Briffa et al., 1988)	59–69° N, 9–28° E	1700–1851	IS	1852–1925, 1891–1964	TRW (t, $t+1$), MXD (t, $t+1$).	Jul–Aug	0.69 0.56
1	Torneträsk, (Briffa et al., 1990)	68° N, 20° E	500–1975	IS	1876–1975	TRW (t, $t+1$), MXD (t, $t+1$).	Apr–Aug	0.51
1	Torneträsk, (Briffa et al., 1992)	68° N, 20° E	500–1975	RCS	1876–1975	TRW (t, $t+1$), MXD (t, $t+1$).	Apr–Aug	0.55
2	Femundsmarka, (Kalela-Brundin, 1999)	62° N, 12° E	1500–1985	IS	1872–1993	TRW (t, $t-1$, $t+1$, $t+2$), EW (t, $t+1$), LW (t, $t+1$)	Jul and Jul–Aug	0.52 0.49
3	Vikran	69° N, 18° E	1700–1989,	IS	1875–1989	TRW (t, $t+2$, $t+3$)	Jul–Aug	0.49
	Stonglandseidet	69° N, 17° E	1548–1989,			TRW (t, $t+1$, $t+2$, $t+3$)		0.33
	Forfjorddalen (Kirchhefer, 2001)	69° N, 15° E	1358–1989			TRW ($t-1$, t, $t+1$)		0.34
1	Torneträsk, (Grudd et al., 2002)	68° N, 20° E	BC 5407– AD 1997	RCS	1869–1997	TRW (t)	Jun–Aug	0.36
4	Jämtland, (Linderholm and Gunnarson, 2005)	63° N, 12–13° E	BC 1632– AD 887 907–2002	RCS	1861–1946	TRW (t, $t-1$)	Jun–Aug	0.4
5	Finnish Lapland (Helama et al., 2002)	68–70° N, 20–30° E	BC 5634– AD 1992	RCS	1879–1992	TRW (t, $t+1$)	Jul	0.37
6	Dividalen, (Kirchhefer, 2005)	68° N, 19° E	587–980, 1507–1993	IS	1921–1992	TRW (t, $t+1$)	Jul	0.28
7	Laanila/Utsjoki (Gagen et al., 2007)	69° N, 27–28° E	1640–2002	None	1958–2002	Isotope δ^{13}C	Jul–Aug	0.52
–	Fennoscandia (Gouirand et al., 2008)	59–69° N, 9–28° E	1700–1970	IS/ RCS	1901–1970	TRW, MXD. PC from these proxies	Jun–Aug	0.8
1	Torneträsk, (Grudd, 2008)	68° N, 20° E	500–2004	RCS	1860–2003	TRW (t, $t+1$) MXD (t)	Jul–Aug	0.64
5	Northern Finland and Norway. (Helama et al., 2009a)	68–70° N, 20–30° E	750–2000	RCS	1876–1998	TRW ($t-2$, $t-1$, t, $t+1$, $t+2$)	Jul	0.41
7	Kessi, (Hilasvuori et al., 2009)	68° N, 28° E	1600–2002	–	1907–2002	Isotope δ^{13}C, TRW (t)	Jul–Aug	0.59
8	Sivakkovaara, (Hilasvuori et al., 2009)	62° N, 31° E	1600–2002	–	1909–2002	Isotope δ^{13}C	Jul–Aug	0.33

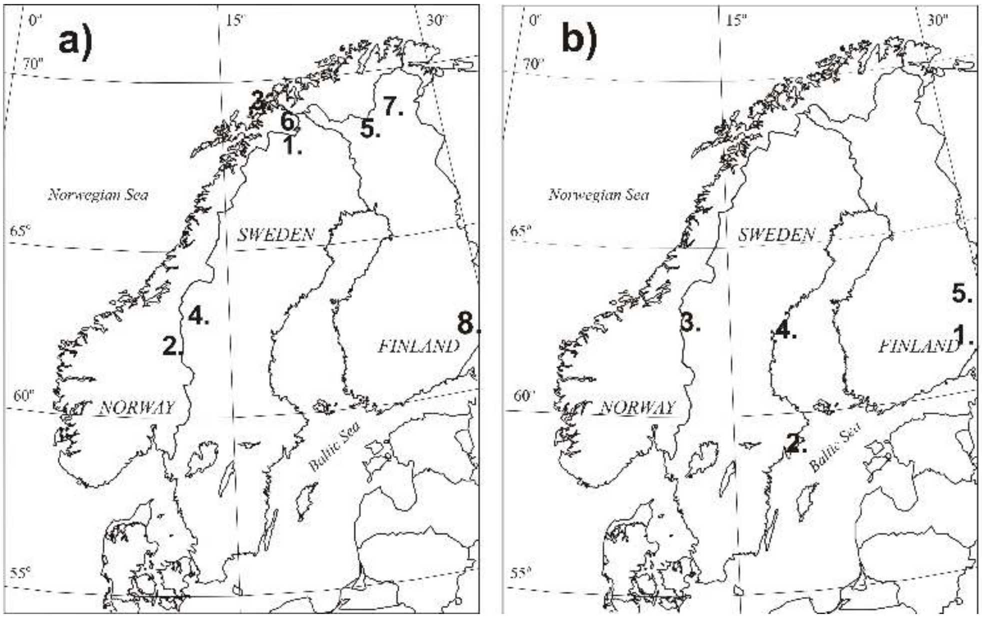

Fig. 1. Maps showing the locations of the Fennoscandian tree-ring based climate reconstructions mentioned in the text. **(a)** Temperature reconstructions 1. Torneträsk, 2. Femundsmarka, 3. Vikran, Stonglandseidet and Forfjorddalen, 4. Jämtland, 5. Finnish Lapland, 6. Dividalen, 7. Laanila/Utsjoki and 8. Sivakkovaara. Further information of the temperature reconstructions is found in Table 1. **(b)** Precipitation/drought reconstructions 1. South-Eastern Finland, 2. Tyresta, 3. West-Central Sweden, 4. Härnön, 5. Sivakkovaara. Further information of the precipitation/drought reconstructions is found in Table 2.

Table 2. Precipitation reconstructions from Scot pine described in the text. The numbers accompanying the location names refers to Fig. 1b. The heading SM refers to standardization method, where IS is individual standardization and RCS = regional curve standardization. R^2 = variance in observations explained by the reconstruction. The proxy parameter TRW refers to tree-ring width, LW to latewood and EW to earlywood. t refers to the current year, $t-1$ to the previous year and $t+1$ to the following year and so on.

No.	Location Reference	Lat. Long.	Interval	SM	Calibration period	Proxy	Summer temp. parameter	R^2
1.	South-East Finland (Helama and Lindholm, 2003)	61–62° N, 29–30° E	874–1993	IS	1918–1985	TRW (t)	May–Jun	0.31
2.	East-Central Sweden (Linderholm and Molin, 2005)	59° N, 18° E	1750–1999	IS	1901–1999	TRW (t, $t+1$)	(SPI) Jun–Aug	0.24
3.	West-Central Sweden (Linderholm and Chen, 2005)	63° N, 10–16° E	1500–1990	IS	1905–1994	TRW, PC from this proxy	Sep–Apr	0.45
4.	Mid-East Sweden (Jönsson and Nilsson, 2009)	62° N, 18° E	1560–2001	IS	1890–2001	TRW, EW, LW. PC from these proxies	May–Jun	0.46
1.	South-East Finland (Helama et al., 2009a)	61–62° N, 28–29° E	670–1993	RCS	1909–1993	TRW	May–Jun	0.40
5.	Sivakkovaara Finland (Hilasvuori et al., 2009)	63° N, 31° E	1600–2002	Various	1909–2002	Isotope δ^{18}O	Jul–Aug	0.21

around 1830, 1850 and from ∼1910 to 1960 could be distinguished. More recently, Helama et al. (2009b) reconstructed regional summer temperatures in Lapland (Norway and Finland, 68–70° N, 20–30° E). Over the last 1250 years, they found that the warmest and coolest 250-year periods had occurred from AD 931–1180 and AD 1601–1850 respectively.

Until the 1990s, most efforts in building tree-ring chronologies for climate reconstruction purposes had been focused on inland northern Fennoscandia. However, Kalela-Brundin (1999) turned southwards to reconstruct summer temperatures from Scots pine TRW data sampled in Femundsmarka, east-central Norway. In addition to whole tree-ring widths, Kalela-Brundin (1999) measured the width of early wood and late wood separately and made a reconstruction of July and July–August temperatures 1500–1985 based on combinations of these. Another effort to expand the diversity of locations in Fennoscandia was made by Kirchhefer (2001), who investigated Scots pine tree-ring widths from three coastal sites in northern Norway; Vikran (northernmost), Stonglandseidet and Forfjorddalen (southernmost). Due to the variable landscape, where mountains locally reach to elevations of up to 1000 m a.s.l. raising straight from the sea, climate varies across relatively short distances. Consequently, differences in tree responses to climate were evident, where tree-growth at Vikran was associated with a shorter growing period than at the two more southerly sites. Based on these chronologies, a set of July–August temperature reconstructions were made, where the longest, based on data from Forfjorddalen, spanned 1358–1989. Selecting one of the driest locations in Norway, Dividalen in the north-western part of the country, Kirchhefer (2005) compiled two chronologies from living and and dead Scots pines. The chronologies covered AD 320–1167 and 1220–1994 and July temperatures were reconstructed over AD 587–980 and 1507–1993. Kirchhefer (2005) found prolonged warm periods between ca. 819–957 and from 1915 and onwards, while longer cold spells were noted in 769–818, 1573–1624, 1785–1826 and 1864–1914.

Despite the relative wealth of dendrochronological data from Fennoscandia, few attempts have been made to make regional climate reconstructions based on networks of tree-ring chronologies. Briffa et al. (2001) reconstructed temperatures for northern Europe (NEUR), partly based on MXD data from Fennoscandia. The MXD data were standardized using "age band decomposition" (ABD), which is another technique for preserving long-term variability. The individual MXD series were used to produce a regional ABD chronology, which was then used to reconstruct April–September mean temperatures for a north European region back to 1588. When the NEUR reconstruction is correlated with observed temperatures (Fig. 2), it displays its highest correlations ($r \approx 0.6$) in eastern Finland along the border to Russia, while correlations are in general below 0.5 west of the Baltic Sea. Since the NEUR was a regional average of all available MXD chronologies from the northern Europe domain, Gouirand et al. (2008) argued that possibly some of the chronologies used were not really suitable for reconstructing summer temperatures, as the trees' temperature/growth relationship at some sites was weak. Gouirand et al. (2008) used another approach to reconstruct summer temperatures exclusively for Fennoscandia. From a network of TRW and MXD chronologies, they selected those having the strongest temperature information, to obtain a strong common climate signal suitable for a regional-scale reconstruction. Depending on the number of tree-ring chronologies available through time, seven separate reconstructions were created, the longest covering the period AD 442–1970. They showed that it was possible to get a good spatial representation of the reconstructions back to around AD 1700, with correlations of ≥ 0.7 with observed summer temperatures for nearly the whole of Fennoscandia, and even higher correlations (≥ 0.85) over much of central-northern Fennoscandia (Gouirand et al. (2008), Fig. 2). When the NEUR and Gouirand et al. (2008) reconstructions are compared to April–September temperatures (the target season for NEUR) over a larger domain (Fig. 2), it is striking how they complement each other spatially in terms of high correlations. This suggests that it would be possible, by appropriate selection of tree-ring chronologies, to make a high-quality reconstruction of warm season temperatures for western Eurasia based on existing data. One additional important conclusion from Gouirand et al. (2008) was that summer temperatures in Fennoscandia could be represented by a relatively small number of temperature-sensitive chronologies. The implication of this was that, in order to extend a spatially strong reconstruction back in time, rather than sampling a large number of new sites, focus should be on improving (extending samples back and forward in time) the existing key sites included in the reconstruction.

4.2 Multimillennial temperature reconstructions

Globally, less than 30 tree-ring chronologies extend back over the past 1000 years (Jansen et al., 2007) and less than 20 extend over the past two millennia (Ljungqvist, 2009). However, to investigate large-scale averages and spatial patterns of climate variability on millennial timescales, a dense network of multi-millennial long tree-ring chronologies is needed (Jones et al., 2009). One main challenge in constructing millennial-long chronologies is to find trees that cover such a long timespan; either living or dead trees that have been preserved through time. Scots pine in Fennoscandia can reach ages of 700–800 years (Häggström, 2005) but such old-living specimens are very rare. Hence, in order to develop "supra long" tree-ring chronologies, data from living, recently dead and preserved wood from protective environments such as peat bogs or river and lake sediments, so called subfossil wood, is needed, and potential sites with known subfossil material are limited (Jones et al., 2009). Although the number of available millennial-long

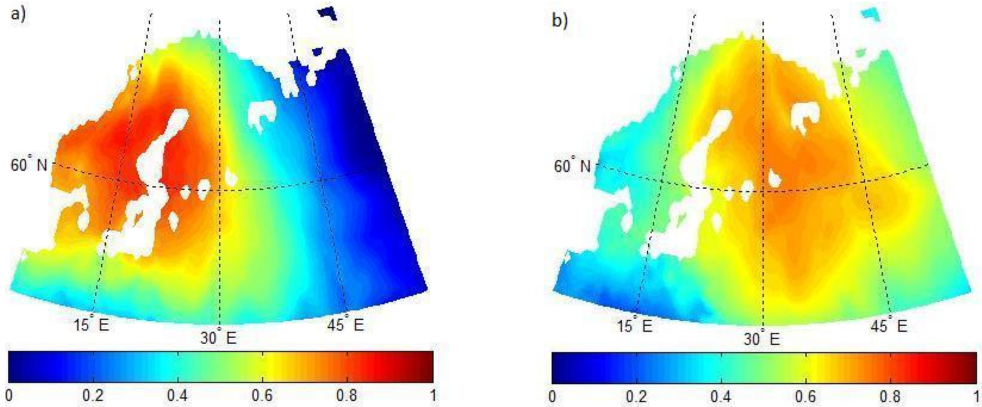

Fig. 2. Spatial correlations between observed (gridded) April–September temperatures 1901–1970 (Mitchell et al., 2004) and **(a)** reconstructed Fennoscandian June–August temperatures (Gouirand et al., 2008) and **(b)** reconstructed northern Europe April–September temperatures (Briffa et al., 2001).

tree-ring chronologies is increasing, it still remains small and the efforts of developing these are fully justified. Northern Fennoscandia has been shown to be suitable for developing long tree-ring chronologies, because of its richness in natural forests with old living trees, dead trees (called snags, which in some areas resist decomposition for many centuries) as well as subfossil logs and stumps found in small mountain lakes and peat bogs. Presently, three multi-millennial tree-ring width chronologies have been developed, spanning more than 6000 years (Fig. 3), which will be described below.

4.2.1 Torneträsk

The Torneträsk chronology has been developed from a region surrounding Lake Torneträsk, located in the northernmost part of Sweden (Fig. 1). The Scots pine material consists of living trees, snags preserved on land and subfossil wood preserved in lakes and lake sediments. As mentioned above, extensive sampling in the area was undertaken in 1970s and 1980s (Bartholin and Karlén, 1983; Bartholin, 1984). A selection of the material collected by Bartholin and Karlén was used to produce a MXD chronology covering AD 441–1980 (Schweingruber et al., 1988) and the data was later used in a reconstruction of summer temperature spanning AD 540–1980 (Briffa et al., 1990, 1992). In the mid 1990s, the Torneträsk TRW chronology was updated and extended within the ADVANCE-10K project (Briffa and Matthews, 2002) to cover the last 7400 years (Grudd et al., 2002). Recently, the maximum density data was updated by Grudd (2008) so that it now covers the period AD 441–2004 and is presently the longest density record in the world. The updated MXD chronology shows generally higher temperature variability than previously reconstructed from the region and also suggests that the late-twentieth century is not exceptionally warm in a 1500-year context. Moreover, Grudd (2008) argues that the MWP in northern Fennoscandia was warmer than previously thought.

The Torneträsk tree-ring data have been used in many large-scale climate reconstructions (e.g., Jones et al., 1998; D'Arrigo et al., 1999; Mann et al., 1999; Briffa et al., 2002; Moberg et al., 2005). The Torneträsk MXD data, in particular, have been demonstrated to have an exceptionally strong temperature signal (Briffa et al., 1992; Grudd, 2008). Consequently, Torneträsk MXD data have played an important role in reconstructions of Northern Hemisphere temperatures for the last millennium (e.g. Fig. 6.10 in Jansen et al., 2007).

4.2.2 Finnish Lapland

In Finnish Lapland, subfossil pines were collected in the beginning of 1970s in order to study pine forests history and tree-line variability (Eronen, 1979; Eronen and Hyvärinen, 1982). The tree-ring width chronology contained series from a rather wide region approximately between 68–70° N and 20–30° E, with altitudes ranging between 75–515 m a.s.l. The chronology was extended and updated within the Finnish Research Programme on Climate Change (SILMU) and later in the ADVANCE-10K project, with the goal to build a more than 7000-year long tree-ring width chronology for dendroclimatological purposes (Zetterberg et al., 1994; Eronen et al., 1999, 2002). Presently, the Finnish record is the longest conifer tree-ring chronology in Eurasia, extending back to 5634 BC (Helama et al., 2008). These data have been used in several summer temperature reconstructions and for different time periods (Lindholm et al., 1996; Lindholm and Eronen, 2000; Helama et al., 2002, 2008). However, because samples were collected from a wide geographic area, the homogeneity and the robustness of the data, especially in the older part of the record, may be weak (Eronen et al., 2002).

4.2.3 Jämtland

In Jämtland, a province in west-central Sweden, Schweingruber and colleagues collected tree-ring data in the 1970s,

Table 3. North Atlantic Oscillation (NAO) reconstructions described in the text. SM = standardization method, IS = individual standardization, RCS = regional curve standardization, R^2 = variance in observations explained by the reconstruction.

Location Reference	Interval	SM	Calibration period	Proxy	Summer temp. parameter	R^2
Chronologies from around the North Atlantic Ocean (Cook et al., 1998)	1701–1980	various	1874–1980	TRW (t)	Winterphase	0.41
Fennoscandian, Russian and Estonian Chronologies (Lindholm et al., 2001)	1750–1999	various	1893–1981	TRW (t, $t+1$)	Winterphase	0.25
Northwestern Europe (Linderholm et al., 2008)	1441–1976	various	1850–1976	TRW, MXD. PC from these proxies	Summerphase	0.46
Great Britain and Western Norway (Folland et al., 2009)	1706–1976	IS	1850–1976	TRW, MXD. PC from these proxies	Summerphase	0.38

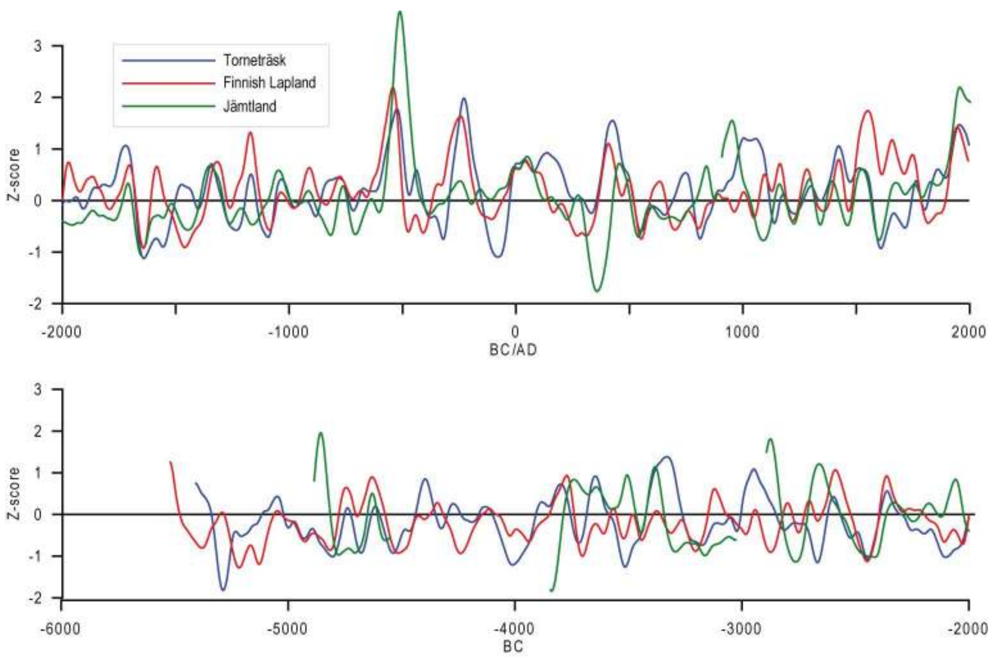

Fig. 3. Comparison of standardized and z-score transformed tree-ring width (TRW) chronologies from Torneträsk (Grudd et al., 2002), Finnish Lapland (Helama et al., 2002) and Jämtland (Gunnarson, 2008). All records have been RCS standardized (see text) and filtered with 100-year splines to show centennial variability.

producing TRW and MXD series covering large parts of the last millennium (AD 1107 to 1827 (with a gap between 1293–1316), data available from the International Tree-Ring Data Bank; http://www.ncdc.noaa.gov/paleo/treering.html). This data set has been included in reconstructions of large-scale temperatures by Esper et al. (2002) and D'Arrigo et al. (2006). However, part of this material has likely been collected from historical buildings, not necessarily from high elevation sites, and consequently the climate information in the original data set may be ambiguous (Gunnarson et al., 2010).

In the late 1990s, the Jämtland tree-ring data was updated and extended in order to build a multi-millennial tree-ring chronology which could reflect climate variability in central Scandinavia, thus decreasing the gap in tree-ring data coverage between northern Fennoscandia and chronologies from Central Europe. The selected area, east of the main dividing line of the Central Scandinavian Mountains, seemed ideal: close to the tree line, Scots pines of up to 700 years can be found and areas of old-growth forests virtually untouched by man still exist. But most importantly, large quantities of old pines, preserved for centuries to millennia, were frequently found in small mountain lakes (Gunnarson, 2001; Gunnarson and Linderholm, 2002). During the last decade, large efforts have been made to collect Scots pine tree-ring data from living and subfossil wood at a number of sites in the area, (Gunnarson, 2001, 2008). Trees from the last ca. 7000 years have been found and amalgamated into chronologies, spanning the time period from 4868 BC to AD 2006 with two minor gaps near 1600 BC and AD 900 and one larger gap near 2900 BC. The TRW data has been used to reconstruct summer temperatures back to 1600 BC (Linderholm and Gunnarson, 2005). Furthermore, the temporal distribution patterns of subfossil wood found in various lakes has been used as proxy for lake level fluctuations, which in turn could be tentatively associated with changes in precipitation and changes in the atmospheric circulation (Gunnarson et al., 2003; Gunnarson, 2008). Recently, progress has been made to produce new MXD data for tree-line sites in Jämtland and to use these data in combination with previously collected data (ITRDB) to create new and improved reconstructions of summer temperatures in this region (Gunnarson et al., 2010).

4.2.4 A regional comparison

The fact that dendrochronological cross-dating is possible between Torneträsk and Finnish Lapland, as well as between Jämtland and Torneträsk, indicates a common high-frequency variability in tree-ring growth more than 600 km apart (Gunnarson, 2001; Grudd et al., 2002). However, when the three TRW records are filtered to show century-timescale variation they display a much more complicated story (Fig. 3). There are some periods when all three records vary in phase, e.g. around 2500 BC and 1700 BC. Other common features are a warm period in the first centuries AD, and the cold conditions in the mid-6th century AD, which have been tentatively linked to a large volcanic eruption near the equator in AD 536 (Larsen et al., 2008). However, there are also significant differences between the records, most noticeable in the medieval times around AD 1000 and in the 16th and 17th centuries. The two Swedish records do show evidence of a warm conditions around AD 1000, although not synchronous, while the Finnish record shows no evidence of warmth around this time. In the 16th and 17th centuries the Torneträsk and the Jämtland records indicate cold conditions, while the Finnish record shows high temperatures which is clearly not comparable to other evidence of a cold period at this time (e.g., Weckström et al., 2006). The TRW records, also, lack variability on the longer, i.e. millennial to multi-millennial, time scales. A general lack of variability on the longest time scales is a common problem shared by most tree-ring chronologies. The problem is related to the need for removing non-climatic, biological growth trends in each series associated with changing tree age and tree size. In the process of de-trending there is always a risk of removing some of the low-frequency climatic signal. Although the RCS de-trending method used here is designed to circumvent this problem, this method has some demanding requirements in terms of data distribution (Esper et al., 2003) that are not fully met with. The numbers of tree samples that are used to construct each of the three chronologies change quite dramatically through time, with the largest sample replication in the most recent time. Hence the disagreement between the series may partly be explained by low sample replication and associated large confidence limits around the mean chronology, especially in the older parts of the records. When extending tree-ring records as far back in time as several millennia there is also the risk of violating one of the most fundamental principles in proxy climate reconstruction, namely the principle of "uniformitarianism" which, in the case of dendroclimatology, states that tree growth/climate relationships must have been the same in the past as in the present (Fritts and Swetnam, 1989). The long chronologies from Torneträsk, Jämtland and Finnish Lapland (Fig. 3) are for the most recent millennium based mainly on living and dead "land" wood from ordinary forest environments, and for the earlier millennia based on subfossil wood from lakes. The subfossil lake samples present a potential problem in terms of ecological heterogeneity; first, because their climatic response may differ from the living trees used for calibration, and secondly because they originate from a large number of small lakes with potential differences in their hydrological history that may have affected tree growth. However, some of the differences between the records may also be attributed to real differences in century-timescale temperatures between Jämtland, Torneträsk and Finnish Lapland.

The problems with retaining low-frequency variability in long tree-ring records imply that their multi-millennial trends can not be trusted. When compared to other long proxy records that do not suffer from de-trending problems, e.g. pollen data, it is clear that the long Fennoscandian tree-ring records do not show the long-term cooling summer temperature trend that is observed since the mid-Holocene in the other data (e.g., Seppä et al., 2009).

Fennoscandian TRW and MXD chronologies have different seasonal response windows, where TRW typically capture mid-summer (July) temperatures while MXD has a strong association to temperatures over the full length of the growing season (McCarroll et al., 2003; Grudd, 2008; Gunnarson et al., 2010). A comparison between the low-frequency variation in two Swedish MXD based reconstructions of summer temperature from Torneträsk (Grudd, 2008) and Jämtland (Gunnarson et al., 2010) shows broad agreement in some periods, but also notable dissimilarities in other periods (Fig. 4). It should be noted, however, that the Jämtland chronology for the first ca. 200 years is likely based on historical buildings and that the source area for these samples may differ from the latter material, which originate from living and subfossil samples (Gunnarson et al., 2010). Hence, the conspicuously high temperatures in Jämtland in the 12th century as reconstructed from MXD are probably not real. There is also no evidence of corresponding high temperatures in the TRW records (Fig. 3). From about AD 1250 the TRW and MXD records from Jämtland and Torneträsk show a common broad picture; slightly rising temperatures up to about AD 1550 followed by a cooling trend to around AD 1600. The prominent increase in temperature in the latter half of the 18th century and the very low temperatures around 1900 in the Torneträsk record are not seen in the Jämtland data. The Jämtland record instead shows a more gradual increase in warm-season temperatures. These discrepancies may be due to differences in replication between the two sites, varying sample provenance in Jämtland, or reflect regional differences in large-scale climate.

4.3 Precipitation/drought

Few reconstructions of precipitation or drought have been developed from tree-ring records in Fennoscandia. As noted in Sect. 2, the geographical location of Fennoscandia does not, in general, provide the dry conditions needed for trees to be strongly dependent on precipitation, which is the case in many semi-arid to arid regions. Since the precipitation influence on tree growth usually is weaker than that of temperature, the importance of selecting a suitable site is highly important when seeking precipitation information from Fennoscandian tree-ring data. However, in recent years, several attempts have been made to explore past precipitation/drought variability in Fennoscandia.

Helama and Lindholm (2003) used Scots pine TRW to reconstruct annual May–June rainfall variability in southeastern Finland back to AD 874. They found evidence for longer periods of severe drought in 1173–1191, 1664–1680 and 1388–1402, while wet periods were encountered in 1081–1095, 1433–1447 and 1752–1765. Scots pine TRW data from xeric sites in Tyresta national park, east-central Sweden, was used to reconstruct the Standardised Precipitation Index (SPI) for June-August, back to 1750 (Linderholm and Molin, 2005). Compared to the Finnish study, where 31% of the variance in precipitation was explained by the tree-ring data, the precipitation information was slightly weaker at Tyresta; the reconstruction could only account for ca. 25% of variance in the observed SPI data. The most pronounced dry period interpreted from the tree-ring record was found in the beginning of the 19th century, between 1810 and 1835. That this was a period of particularly dry summers was corroborated by evidence from a local farmer's diary, although the limited interval of the diary makes difficult to assess the drought in a long-term context. This period was also indicated as a dry period in the Helama and Lindholm (2003) record. Using Scots pines from Härnön, on the east coast of the northern part of central Sweden, Jönsson and Nilsson (2009) reconstructed May–June precipitation back to 1560. Rather than using the only whole ring widths, they based their reconstruction model on early and late wood, as well as the entire ring width. Using this approach, they were able to improve the precipitation signal provided by previous studies in Fennoscandia (see Table 2). The Jönsson and Nilsson (2009) reconstruction indicated dry periods in ∼1560–1590, ∼1660–1680 and ∼1694–1750, while wet periods were encountered around 1650, ∼1750–1815, around 1870 and in the 1920s. The long period with below average precipitation and low variability between 1694 and 1751 was tentatively associated with the Late Maunder Minimum, a period of low solar activity (Eddy, 1976). Also targeting May–June precipitation, Helama et al. (2009a) used 563 living and dead Scots tree-ring records from moisture-sensitive sensitive sites across 61–62° N and 29–28° E in Finland to make a precipitation reconstruction back to AD 670. Perhaps the most striking feature of this reconstruction was the distinct and persistent drought, "megadrought", from the early 9th century to the 13th century, supporting the concept of a Medieval Climate Anomaly (Stine, 1994). Wetter conditions were found in 720–930, and in the early 13th and 16th centuries. The north European "megadrought" seems to have been synchronous with severe droughts in North and South America and Africa, and was suggested to be associated with interactions between the El Niño-Southern Oscillation (ENSO) and the NAO (Helama et al., 2009a).

Most attempts to gain climate information from tree-rings in Fennoscandia have focused on the warm season. However, Linderholm and Chen (2005) showed that in addition to the summer temperature – Scots pine growth relationship on interannual timescales in west-central Scandinavia, there was an association between winter precipitation and tree growth on semi-decadal timescales. The winter precipitation signal in the Scots pines was believed to result from a sensitivity to the duration of snow cover and soil moisture variability, which would have impact on the initiation of cambial activity. They developed a 400-year long winter (September-April) precipitation reconstruction with 5-year resolution, based on TRW data. In a multidecadal perspective, periods of above average winter precipitation were indicated in ∼1520–1560, ∼1730–1850 and ∼1950 to present, while dry winters were encountered in ∼1565–1620, ∼1690–1730 and ∼1890–1950. The driest winters, disregarding the absolute beginning of the record, were found in the beginning of the 18^{th} century, while the last half of 20th seemed to be the wettest, at least over the past 400 years.

Scots pine has hitherto been the only species utilized for reconstruction precipitation/drought in Fennoscandia.

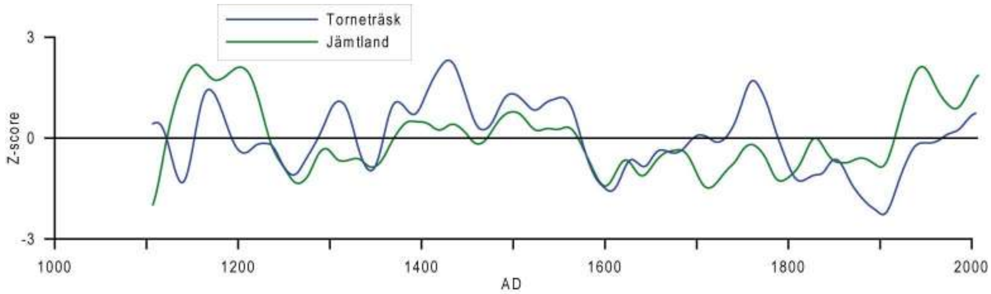

Fig. 4. Temperature reconstructions from Fennoscandia based on maximum latewood density (MXD) from Torneträsk (blue) (Grudd, 2008) and Jämtland (green) (Gunnarson et al., 2010). The reconstructed seasonal temperature target is June–August for Torneträsk and April–September for Jämtland. The records have been z-score transformed and filtered by a 50 year spline.

However, in the southern parts of this region, pedunculate oak (*Quercus robur* L.) is another tree species which could potentially be promising for precipitation reconstructions. Oak growth is strongly influenced by early growing season precipitation and the spatial pattern of growth anomalies have been shown to follow the spatial pattern of major regional weather anomalies (Drobyshev et al., 2008). Multi-century oak chronologies developed in this region (Bartholin, 1975) may therefore prove to be a useful proxy for historical growing season precipitation.

It can be concluded that there exist a potential for making further regional precipitation/drought reconstructions in Fennoscandia, and the work of Helama et al. (2009b) suggests that to achieve this, data from a regional network should be utilized. It is unlikely, though, that such reconstructions will be as reliable as those of temperature. Nevertheless, it is of importance to understand past precipitation variability, especially in relation to large-scale forcings such as the AMO, NAO or ENSO, so that we may quantify how future changes in climate may affect this region.

4.4 Large-scale circulation patterns

From investigations cited in Sect. 2, it is evident that the NAO has a significant impact on climate variability over Fennoscandia, and several studies have shown associations between tree-growth and NAO. Like other observed records, NAO indices (based on station or regional data, Hurrell et al., 2003), in general only cover the last 150 years. The strong link to climate over the North Atlantic region, as well as recent indications of its possible role as a pacemaker of global climate shifts (Wang et al., 2009), makes it highly desirable to extend the NAO index back in time. Because strong links between NAO and climate have been established for the cold season, and because the NAO is less dynamically active during summer, most reconstructions have focused on the winter NAO. Analysing Scots pine TRW data from Norway and Finland, D'Arrigo et al. (1993) found associations between above/below average ring-width departures and positive/negative December–February sea-level pressure (SLP) anomalies related to the Icelandic low. Thus, after cold winters, associated with negative NAO, the trees responded with low growth, and vice versa. This was a first indication that tree-rings could be used to reconstruct winter NAO. Consequently, Cook et al. (1998) used an extensive tree-ring data set from eastern North America and north-western Europe, including Fennoscandia, to reconstruct the winter NAO. The reconstruction spanned 1701–1980 and it was concluded that the oscillatory character of the NAO is a long-term feature of the North Atlantic climate system. Further improvements of the winter NAO reconstructions were made in subsequent years, combining tree rings and ice core data, extending the index back to the beginning of the 15th century (Glueck and Stockton, 2001; Cook et al., 2002). One of the more interesting outcomes was that the persistent positive phase of the NAO seen in the latter half of the 20th century was not anomalous in a 600-year context; comparable periods of persistent positive-phase NAO had occurred in the past, especially before 1650 (Cook et al., 2002).

Folland et al. (2009) showed strong associations between the NAO and climate over the western North Atlantic region during high-summer (July–August) on interannual to interdecadal timescales. This summer NAO (SNAO) was derived from the first EOF of mean sea level pressure (MSLP) over the extratropical North Atlantic in July and August. The SNAO exerts a strong influence on northern European rainfall, temperature, and cloudiness through changes in the position of the North Atlantic storm tracks (Folland et al., 2009). A positive SNAO index is associated with warm and dry conditions over North West Europe but cooler and wetter conditions over southern Europe and the Mediterranean, and vice versa. Using tree-ring data from Great Britain and western Norway, Folland et al. (2009) reconstructed the SNAO back to 1706, and the skill of the reconstruction was indicated by a strong relationship with observed Central England temperatures over that period. Using an increased data set (both in number and spatial distribution) the SNAO reconstruction was further extended back to AD 1441 (Linderholm et al., 2008). Over the last 550 years the SNAO has been in a negative phase during the majority of the record. Periods of relatively low SNAO in 1650–1750 and around 1800 coincide with periods of very low solar activity (Linderholm et al., 2009), and the strong positive phase of the SNAO around 1970–1995 seems unprecedented in the last 550 years. Also focusing on summer, D'Arrigo et al. (2003) inferred changes in the Arctic Oscillation (AO), which is defined as the spatial pattern of interannual variability of Northern Hemisphere sea level pressure centred over the Arctic (Thompson and Wallace, 1998), using tree-ring data from the North Atlantic sector. They presented a reconstruction of AO-related surface air temperatures for April-September, as well as one of July–August AO sea level pressure, spanning 1650–1975. The trends of their reconstructions resembled those of Arctic temperatures, and the positive values of the 20th century were equal to or exceeding those in the earlier parts of the record.

Increasing evidence has indicated the important role of SSTs as a multidecadal forcing of climate over much of the Northern Hemisphere (see Sect. 2). To investigate if the multidecadal variability seen in the observational record continued further back in time, Gray et al. (2004) reconstructed North Atlantic SSTs back to AD 1567, using tree-ring data, in part from Fennoscandia. They concluded that the low-frequency variability of the AMO had indeed persisted for the last five centuries. Analyzing the reconstruction of high-latitude Fennoscandian temperatures (described in Sect. 4.1), Helama et al. (2009b) noted a multidecadal periodicity of ca. 50–60 years which they attributed to variations related to North Atlantic deep water (NADW) formation, which in turn is associated with the THC. This multi-decadal variability seemed, however, to be lacking during the LIA, suggesting a link between NADW stability and climate in the region.

The influence of the atmospheric circulation and North Atlantic SSTs on climate in Fennoscandia makes tree-ring data from this region useful proxies to reconstruct large-scale climate patterns. The present reconstructions of, mainly, the NAO have indeed furthered our knowledge of past variability, showing that the oscillations of the NAO is not only a feature of the past 150 years. Moreover, they have also put the positive phase of the NAO in the late 20th century in a long term context. Extending also time series of AMO or THC variability back in time will enable us to further understand how the short and long-term changes in large-scale climate patterns affect climate in Fennoscandia, as well as relate this to features elsewhere in the world. Thus, we may be able to explain why prolonged periods of warming or cooling, such as the MWP and LIA, are more strongly manifested in some parts of the world, but less obvious in others.

4.5 The "divergence" problem

One of the basic principles of dendroclimatology is that if a growth-climate relationship can be established, it is assumed to be time-invariant so that climate can be reconstructed back in time (Fritts, 1976). However, using a high-latitude Northern Hemisphere conifer MXD network, Briffa et al. (1998b) discovered that the chronologies appeared to lose some of their sensitivity to temperature towards the end of the 20th century. A "divergence" between tree-ring proxies and temperature coinciding with the period when reconstructions are calibrated could lead to reconstructions of past temperatures being overestimated, but also that estimates of future atmospheric CO_2 levels, based on carbon-cycle models which are sensitive to high-latitude warming, could be too low (Briffa et al., 1998b). No conclusive evidence of the cause of this divergence has yet been found, but factors such as increasing CO_2, increased nitrogen fertilization and increased UV-B levels (Briffa et al., 1998a), an increasing trend in winter precipitation in subarctic regions (Vaganov et al., 1999), or increased drought stress due to increased temperatures (Barber et al., 2000) have been suggested.

However, divergence may also be an effect of the standardization method. The RCS method has been shown to retain low-frequency variability in the tree-ring data. Nevertheless, this procedure requires some basic conditions to be met. For instance, a long-term trend extending longer than the length of the chronology causes the RCS standardisation to over- or underestimate the chronology in the beginning or the end (Briffa and Melvin, 2010). For northern Fennoscandia, a cooling trend has been observed over the last several millennia in analysis of various types of proxy records (Kaufman et al., 2009). Since this millennial trend is longer, than what can be captured by the century-scale variability in the tree-ring data, it may actually lead to an overestimation of temperatures in the most recent part of a chronology (Briffa and Melvin, 2010). The number and temporal distribution of trees in the chronology is of very high importance when applying RCS to tree-ring data. For the RCS method to be most powerful trees should preferably be equally distributed through time (Briffa et al., 1992). Moreover, if only living trees of approximately the same diameter are sampled in natural forests, it is likely that the resulting RCS chronology will have positive bias in the end (Melvin, 2004). It is worth noting that when updating the Torneträsk density chronology, Grudd (2008) included relatively young trees in the most recent period and by doing so the apparent loss of temperature sensitivity in an earlier version was eliminated.

In summary, the "divergence" in the late 20th century may not be a universal problem, caused by a changing response of trees to a warmer climate or altered environment. It is likely that at some sites, the response to climate has changed in association with a warmer and drier climate. However, it is plausible that some of the observed occurrences have been due to methodological reasons, like sampling strategies or the standardization. Thus, by careful processing of the data, biased trends in the tree-ring data may be eliminated. Nevertheless, there exist occasional divergences between tree-ring data and climate prior to the end of the 20th century that needs to be further investigated. One such example is an anomalous growth increase around the 1950s in pine growing intra-alpine valleys in western Fennoscandia, which does not correspond to observed temperatures (Linderholm, 2002; Kirchhefer, 2005). This growth "surge" has been related to an extended growing season and likely drier conditions, anomalies in the atmospheric circulation or SSTs. Moreover, Grudd (2008) found a loss of temperature sensitivity in the Torneträsk tree-ring width in the early 19th century, possibly related to changes in stand dynamics due to a strong regeneration period at that time. If trees in certain growth environments are occasionally more sensitive to environmental changes, these must be detected and taken into consideration when interpreting a reconstruction.

5 Isotope dendroclimatology

While various non-climatic factors may influence the growth of a tree, the isotopic ratios in wood are influenced by a limited range of relatively simple physiological controls (McCarroll and Loader, 2004). This makes stable isotopes in tree-rings potentially powerful paleoclimate proxies. In Fennoscandia, dendroclimatological studies using isotopes have almost exclusively been restricted to the stable isotopes of carbon from trees growing at high-latitude sites in Finland. The added value of isotopes to that of TRW and MXD is that they may provide additional climate information, but also there is no long-term trend trend in the isotope records related to the ageing of the tree. This means that it is not necessary to detrend isotope series from trees, so they have the potential to retain climate information on a range of time scales (Gagen et al., 2007). At high latitude cool and moist sites, the $^{13}C/^{12}C$ ratio ($\delta^{13}C$) is dominated by variables controlling the assimilation rate, that is temperature and sunshine during summer (McCarroll and Pawellek, 2001; McCarroll et al., 2003). At dry sites, the climate signal in $\delta^{13}C$ is related to stomatal conductance which is dependent on air humidity and soil moisture (Gagen et al., 2004). Analysing $\delta^{13}C$ extracted from Scots pine tree rings in northern Finland (site 7 in Fig. 1), Gagen et al. (2007) observed high correlations ($r = 0.72$) between summer temperatures and $\delta^{13}C$, and subsequently reconstructed July–August temperatures for the period 1640–2002. The reconstruction captured cold/warm periods previously seen in other reconstructions from the region. However, when compared to instrumentally observed Tornedalen summer temperatures (Klingbjer and Moberg, 2003), from northern Sweden, the $\delta^{13}C$ reconstruction indicated slightly warmer temperatures in most of the 19th century, indicating differences between northern Sweden and Finland in temperatures at that time, or that either the instrumental record or the reconstruction is biased in the 19th century. Hilasvuori et al. (2009) reconstructed temperatures for northern Finland, and temperature and precipitation for eastern Finland using 400-year long records of carbon and oxygen isotopes (the $^{18}O/^{16}O$ ratio: $\delta^{18}O$) and TRWs from Scots pine. Examining the temperature sensitivity of $\delta^{13}C$ and $\delta^{18}O$ throughout the 20th century, it was found that the $\delta^{13}C$/temperature association in northern Finland was stable throughout the century, while a weakening in the temperature relationship for both $\delta^{13}C$ and $\delta^{18}O$ in the latter part of the century was evident in the eastern region. This change in isotope/temperature relationship was likely caused by increased spring temperatures and associated changes in the seasonality. The isotope and TRW data were subsequently used to reconstruct summer climate. In northern Finland, July–August temperatures were reconstructed from spline-detrended $\delta^{13}C$ and TRW residuals. The reconstruction showed good skill, but due to the detrending the low-frequency variability was omitted. In eastern Finland, $\delta^{13}C$ was used to reconstruct July-August temperature and $\delta^{18}O$ to reconstruct July–August precipitation. Here the reconstructions showed more uncertainty then that from the north. Further south, Robertson et al. (1997) investigated the influence of climate on $\delta^{13}C$ in tree-ring cellulose from oak growing at sites with different hydrological characteristics close to the species northern limit of distribution in southwestern Finland. They found a strong negative relationship between summer precipitation/relative humidity and $\delta^{13}C$, and a positive relationship for summer temperature.

Tree-ring carbon isotope values often show a declining trend from the start of the industrial period (∼1850), due to incorporation of ^{13}C-depleted CO_2 primarily released by the burning of fossil fuels (Freyer and Wiesberg, 1973; McCarroll and Loader, 2004). A correction procedure that attempts to calculate $\delta^{13}C$ values that would have been obtained under pre-industrial conditions was proposed by McCarroll et al. (2009). The procedure, which essentially is a nonlinear detrending of the low frequency changes in the $\delta^{13}C$ based on the physiological response of trees to rising CO_2, was tested on the $\delta^{13}C$ cellulose data obtained from northern Finland and North-West Norway. In each case the correction improved the correlation with local meteorological records (McCarroll et al., 2009). Using highly replicated $\delta^{13}C$ chronologies of Scots pine from a number of sites in northern Finland, Gagen et al. (2008) investigated non-climatic trends in the tree-ring $\delta^{13}C$ series. After a correction for changes in $\delta^{13}C$ of atmospheric CO_2, the chronologies, comprised of 32 trees of several age classes, displayed juvenile trends in absolute $\delta^{13}C$ values lasting for approximately the first 50 years of the tree-growth. The authors showed that the RCS approach could be used to identify and remove the juvenile phase, as an alternative to simply omitting the juvenile portion of the stable carbon isotope series. McCarroll and Pawellek (1998) measured the variability and signal strength of $\delta^{13}C$ in late wood cellulose of Scots pine trees growing at sites located along a latitudinal transect, extending from the Arctic Circle to the northern limit of pine distribution, in northern Finland. A strong within and between site signal was observed. However, different trees yielded absolute $\delta^{13}C$ values offset by $\geq 2‰$, which is similar in magnitude to the variability within individual series that includes the effect of climate. The authors thus concluded that the common strategy of pooling four cores from four trees is inadequate for paleoclimate research.

6 Future prospects

It is clear that dendroclimatology has come a long way in Fennoscandia but great potential remains concerning the use of tree-ring data to improve our knowledge of past climate variability in the region. In this section we outline some possible future directions which Fennoscandian dendroclimatology could take in the coming years.

6.1 Utilizing the Fennoscandian tree-ring data

In the last two decades, quite a few reconstructions of Fennoscandian climate have been published. Still, a large number of tree-ring chronologies are not freely accessible and have not be included in regional paleoclimatic syntheses. Brought together this material would, likely, provide opportunities to improve our knowledge of climate variability in Fennoscandia. As shown by Gouirand et al. (2008), it is possible to reconstruct summer temperatures with good accuracy with a limited number of chronologies. Although their temperature record spanned from 442 to 1970, before ca. 1700 the reconstruction was only based on a handful of sites, resulting in a reduced spatial signal (and increased uncertainty). Although it would need some effort, it is not beyond reach to extend the tree-ring data from the key sites (or similar) up to the present and back to ca AD 1000. By careful sampling, in terms of number of trees and age distribution, and standardizing all data with the RCS method, which was not the case for most tree-ring data in Gouirand et al. (2008), it would be possible to obtain a regional, high-quality, reconstruction of summer temperatures in Fennoscandia for the last millennia.

Three of the world's longest tree-ring width chronologies are obtained from Fennoscandia, and they have contributed to an improved understanding of summer temperature variability in the Holocene. However, there still has been no thorough inter-comparison among the chronologies. From Fig. 3 such a comparison would potentially provide additional information on short- and long term climate variability, as well as give an insight into rapid shifts in climate, such as when considerable changes in temperature occur over a few years. This could provide valuable information on the occurrence of "tipping points", critical thresholds in the climate system (Lenton et al., 2008), over the last millennia. Moreover, in these three chronologies, the sample size varies through time. Scrutinizing these temporal changes in tree availability may also provide knowledge about past stand dynamics in the far north. Such analyses have been made at the individual sites (Eronen et al., 2002; Gunnarson et al., 2003; Gunnarson, 2008; Grudd, 2008), but not on a regional scale in a joint effort.

It would be interesting to see a similar approach as the one Helama et al. (2009a) had for reconstruction precipitation/drought for the whole of Fennoscandia. Such a study could provide information of regional changes in large-scale precipitation patterns related to changes in the oceanic influence as well as in the large-scale circulation, especially when combined with other precipitation proxies. Moreover, in the light of a changing climate, where summers in Fennoscandia are expected to become warmer and drier (IPCC, 2007), there may be an increased risk of summer droughts, especially in the southern parts of the region (e.g., Folland et al., 2009). Thus, by assessing the magnitude and frequency of droughts in the past and their relation to the prevailing (large-scale) climate conditions, it may be possible to provide useful information for making predictions for the future.

6.2 Climate versus past human impact

Current climatic reconstructions based on tree-ring data have failed to include the effects of long-term human impacts, because there has been a lack of analytical tools for identifying broad-scale, low intensity land-use patterns in northern alpine or sub-alpine boreal areas. In forest ecosystems, climatic variations acting over the same time-frame as human impacts make it difficult to differentiate anthropogenic and environmental factors. The productivity and biodiversity of forest stands are affected by both anthropogenic and climatic factors acting at local, regional and global scales. In order to extract non-biased climatic proxy data from tree-rings and to improve the resulting quality of climatic reconstructions, there is a need to quantify and filter out the effects of low intensity human impacts. The major benefit of this is to allow a non-biased climatic signal from tree-ring data, facilitating better climatic reconstructions from these ecosystems. Interdisciplinary approaches involving archaeological, historical, palaeoecological and palaeoclimatological components are necessary to fully detect understand and quantify past human forest use. Long-term, low intensity land use is substantially influencing forest structure and composition that in turn reverberate through the ecosystem for many centuries (Josefsson, 1969). To quantify and obtain a gradient of human impact, chronologies from areas with little or minor human activity should be compared with chronologies more strongly affected by human activity.

6.3 Combining proxies

One clear potential for paleoclimatology in Fennoscandia is to combine several proxies to better understand past climate variability. Tree-ring data may provide a variety of climate information depending on the temporal scale that is considered. Consequently, the low-frequency variability of TRW data from selected sites could be compared to proxies for humidity or precipitation, such as lake sediments and peat stratigraphies, to get a more complete picture of long-term changes in the atmospheric circulation.

The influence of the North Atlantic Ocean on climate variability in Fennoscandia needs to be further studied. Preferably, both marine and terrestrial proxies should be combined. Looking at high resolution there seems to be very good opportunities to combine tree-ring data and the annual increments in skeletal growth of molluscs (sclerochronology). Previous research have shown that bivalves may contain useful information of climate variability related to their growth environments, such as summer temperatures (Schöne et al., 2005) or the NAO (Helama et al., 2007) or the Pacific Decadal Oscillation (PDO, which is a pattern of Pacific climate variability on inter-decadal time scales) (Nielsen et al., 2008). In a pioneering study in northern Norway, Helama et al. (2007) compared growth variability in marine and terrestrial ecosystems using dendrochronological and sclerochronological records, showing common responses to the specific phases of the NAO. A more regional study of this kind would most likely provide more insight into the influence of large-scale climate variability on different ecosystems.

6.4 Teleconnections

Teleconnections, i.e. strong statistical relationships between weather in different parts of the world, in the climate system are associated with the large-scale circulation of the atmosphere and the oceans. In the atmosphere, climate signals can be transferred to regions far from the physical source of the variability, while in the oceans teleconnections are associated with the global thermohaline circulation (e.g., Chase et al., 2005). Tree rings, with their large spatial coverage and high resolution, are highly useful proxies for studies of spatiotemporal stability of observed climate patterns, and associated teleconnections. An increasing amount of evidence suggests strong links between regional climate and weather features such as NAO, ENSO etc. As an example, Linderholm and Bräuning (2006) noted that millennium-long tree-ring records from Jämtland and Tibet showed similar evolution in tree-growth variability, on decadal and longer time scales, between ca. 1100 and 1550, but around 1550 the two chronologies diverged. The change in common response was tentatively related to the strengthening of the Asian monsoon around that time. Such a teleconnection between the North Atlantic Region and Asia has been proposed to result from AMO variability and associated changes in the atmospheric circulation (Feng and Hu, 2008). Possibly the NAO is teleconnected to the East Asian jet (Branstator, 2002), where the strength of the East Asian jet affects weather downstream in Asia (Yang et al., 2002). A new 2.5 millennia long tree-ring record from Tibet (Liu et al., 2009) will facilitate the study of possible teleconnections between Asia and Fennoscandia during the late Holocene. Additionally, the work of (Helama et al., 2009a) suggests teleconnections between Fennoscandia and the ENSO system in the Pacific Ocean, and similar ideas have been put forward by Trouet et al. (2009). It is evident that more work is required to determine if these associations really are robust, but the large networks of tree-ring data available for the Northern Hemisphere provide a good opportunity to study temporal teleconnections between climate over northern Europe and other parts of the world.

6.5 Combining tree-ring data and climate models

Because of the great advances in climate modelling science in the recent few decades, our understanding of climate change, and the mechanisms behind those, has been greatly improved (Randall et al., 2007). In addition to being able to simulate present-day climate more realistically and predict future climate change with less uncertainty, a challenging topic of climate modelling is to simulate climate variations of the past. This enables us to better estimate the sensitivity of the climate system to external forcings (such as solar variability) and to understand the driving mechanism behind climate change. The only surrogates to validate results from simulation of past climates of global climate models are climate proxies from various sources (e.g. the Paleoclimate Modelling Intercomparison Project, phase II, http://www.cgd.ucar.edu/ccr/paleo/pmip2/). One example from a proxy-climate model comparison from Fennoscandia is the work by Moberg et al. (2006). They used output from a global climate model to provide boundary conditions used to drive a regional model simulation for long periods during the last millennium, to study temperature, precipitation and runoff for the northern and southern parts of Sweden. The Scandinavian climate, as simulated by the model, was compared with proxy and instrumental data, to obtain an understanding for how realistically the model behaved. Comparing summer temperatures simulated by the model and reconstructed from tree-ring data provided some evidence on the performance of the model. It was shown that, simulated year-to-year variations were likely too small, but that the long-term variations likely slightly too large. Still, Moberg et al. (2006) argued that the regional climate simulation could be used to approximate the possible range of summer temperatures in Sweden for the last millennium. Thus, analyses of Fennoscandian climate simulated with global and regional models and reconstructed from proxies can provide understanding of the important processes for regional climate variability. Moreover, due to the possibility to extract information of a number of climate parameters with annual resolution as well as their wide spatial distribution across the world, tree-ring chronologies are highly useful proxy records when validating climate models' performances in simulating multi-decadal (e.g., PDO, AMO, the Asian Monsoon) to multi-centennial climate variation (Delworth and Mann, 2000; Collins et al., 2002). Although there are uncertainties both in tree-ring records and climate models, it has been suggested that if tree-ring based reconstruction and instrumental records are applied to constrain climate model simulations, the uncertainties in predicting future climate change can be greatly reduced (Hegerl et al., 2006). Today, many climate models incorporate a vegetation model which simulates growth of plants. Tree-ring records from Fennoscandia as well as other regions could be looked upon as direct indicators of vegetation growth, which is a key variable in vegetation-coupled climate models. This implies a possibility that tree-ring records could be utilized to constrain model of spatiotemporal vegetation variability, which possibly would reduce the uncertainty in climate model simulations of the past due to interaction between vegetation and the overlying climate.

7 Concluding remarks

We have shown the strength and weakness of dendroclimatology in Fennoscandia as a high-resolution proxy of regional climate variability. While temperature has been the most frequently investigated climate parameter, new efforts are being made to look into other features as well, such as precipitation, drought and the large-scale circulation. Naturally there exist limitations in tree-ring based climate reconstructions, since other processes than climate affect tree-growth, and this will influence the climate information derived from tree-ring data. However, in combination with other climate proxies and climate models, tree-ring data can provide more information of past climate variability and change. One obvious future direction is for the Fennoscandian dendroclimatologists to collaborate more closely and utilize the vast spatially distributed tree-ring chronology data set that exist to extend our knowledge about regional climate variability and set it into a global perspective.

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