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Variability and extremes of northern Scandinavian summer temperatures over the past two millennia

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ABSTRACT

Palaeoclimatic evidence revealed synchronous temperature variations among Northern Hemisphere regions over the past millennium. The range of these variations (in degrees Celsius) is, however, largely unknown. We here present a 2000-year summer temperature reconstruction from northern Scandinavia and compare this timeseries with existing proxy records to assess the range of reconstructed temperatures at a regional scale. The new reconstruction is based on 578 maximum latewood density profiles from living and sub-fossil *Pinus sylvestris* samples from northern Sweden and Finland. The record provides evidence for substantial warmth during Roman and Medieval times, larger in extent and longer in duration than 20th century warmth. The first century AD was the warmest 100-year period (+0.60 °C on average relative to the 1951–1980 mean) of the Common Era, more than 1 °C warmer than the coldest 14th century AD (−0.51 °C). The warmest and coldest reconstructed 30-year periods (AD 21–50 = +1.05 °C, and AD 1451–80 = −1.19 °C) differ by more than 2 °C, and the range between the five warmest and coldest reconstructed summers in the context of the past 2000 years is estimated to exceed 5 °C. Comparison of the new timeseries with five existing tree-ring based reconstructions from northern Scandinavia revealed synchronized climate fluctuations but substantially different absolute temperatures. Level offset among the various reconstructions in extremely cold and warm years (up to 3 °C) and cold and warm 30-year periods (up to 1.5 °C) are in the order of the total temperature variance of each individual reconstruction over the past 1500 to 2000 years. These findings demonstrate our poor understanding of the absolute temperature variance in a region where high-resolution proxy coverage is denser than in any other area of the world.

1. Introduction

Millennial-length temperature reconstructions became an important source of information to benchmark climate models (IPCC, 2007), detect and attribute the role of natural and anthropogenic forcing agents (Hegerl et al., 2006), and quantify the feedback strength of the global carbon cycle (Frank et al., 2010b). Newer approaches are using palaeoclimatic reconstructions to assess the likelihood of simulation ensemble members, and thus help to constrain future climate scenarios (Yamazaki et al., 2009). These efforts are, however, limited by the number of high quality reconstructions and their ability to properly quantify the absolute range of past temperature variations (Esper et al., 2002), adding considerable uncertainty to hemispheric scale reconstructions that combine multiple regional proxy records (Frank et al., 2010a). At this point, we seem to have a fairly good understanding of the course of temperature change over the past millennium, i.e. the Medieval Warm Period (MWP), cooling into the Little Ice Age (LIA), and subsequent warming into the 20th century. However, the absolute variance (or amplitude) of temperature change (in degrees Celsius) is more poorly constrained, and might range from less than 0.5 °C to more than 1 °C over the past 1000 years at hemispheric scales (Frank et al., 2010b and references therein). The situation is even less clear prior to medieval times, as only few high-resolution reconstructions are available for the Common Era (Jones et al., 2009) complicating assessments of the absolute temperature amplitude during the Roman and subsequent Migration periods (Büntgen et al., 2011).

While discrepancies in hemispheric scale reconstructions have received considerable attention over the past decades (Frank et al., 2010a), less debate has been centred on the uncertainties of regional reconstructions and their abilities to properly estimate the evolution and amplitude of temperatures over the past centuries to millennia. This is surprising for a variety of reasons including the fact that large-scale reconstructions are often a simple aggregation of these regional reconstructions. It should thus be clarified how large errors at

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the regional level may be, and how these regional errors contribute to large-scale uncertainties.

Northern Scandinavia is one of the core regions from where multiple tree-ring based summer temperature reconstructions spanning the past 1–2 millennia are available (overview in Gouirand et al., 2008). The most widely cited (and integrated in hemispheric scale reconstructions) of these records is the timeseries derived from tree-ring maximum latewood densities (MXD) from the Tornetraesk region in northern Sweden (Schweingruber, 1988, updated in Grudd, 2008). Reasons for this extensive consideration include the length of the reconstruction (back to AD 500), as well as the robust climate signal of MXD data (correlation against summer temperatures typically > 0.7) that is generally stronger than for traditional tree-ring width (TRW) data (typically < 0.5). The Tornetraesk MXD data have also been combined with TRW data from the same trees to form an alternative reconstruction reaching back to AD 500 (Briffa et al., 1992). Since then, three additional reconstructions from Fennoscandia have been developed – all based on TRW, spanning the past two millennia, but partly relying on the same raw measurement series (Grudd et al., 2002; Briffa et al., 2008; Helama et al., 2010) – so that multiple, independently developed records can be used to assess the variability of summer temperatures over the past 1500 to 2000 years at a regional scale.

We here address this issue by *(1)* introducing a new summer temperature reconstruction that is longer and much better replicated than any other published MXD-based record, *(ii)* using this timeseries to derive estimates of the absolute range of regional summer temperature variation considering extremely cold and warm reconstructed years and periods over the past two millennia, *(iii)* comparing these estimates with existing tree-ring based reconstructions, and finally *(iv)* using the differences among these various records to assess the uncertainty of reconstructed temperatures within a confined region.

2. Material and Methods

We developed 587 high-resolution density profiles (Frank and Esper, 2005) from living and sub-fossil *Pinus sylvestris* in northern Sweden and Finland to form a long-term MXD record (N-Scan) spanning the 138 BC to AD 2006 period (Table 1). The living-tree samples were obtained from pines growing at the shores of three lakes to ensure data homogeneity with the sub-fossil samples obtained from 14 lakes in the region (Fig. 1). Spatial data homogeneity was assessed using a total of nine *Pinus sylvestris* MXD chronologies from northern Sweden, Finland, and Russia ($r_{1812-1978} = 0.72$; not shown) validating the integration of data throughout the region (Eronen et al., 2002). All MXD measurements were derived from high-precision X-ray radiodensitometry (Schweingruber et al., 1978).

Table 1
Living-tree and sub-fossil pine sites integrated in the long-term N-Scan reconstruction.

	Location	Lon.	Lat.	No. Series	Start	End
Living	Ket	24.05	68.22	49	1596	2006
	Kir	20.10	67.90	87	1656	2006
	Tor	19.80	68.20	79	1800	2006
Sub-fosssil	Aka	24.20	67.70	8	1311	1782
	Hae	27.50	67.50	2	1342	1533
	Hal	29.00	66.80	6	691	1282
	Kal	24.80	68.50	10	271	1553
	Koi	27.50	68.70	10	−47	1767
	Kol	29.00	66.80	6	1686	1916
	Kom	28.00	68.50	83	−215	1906
	Kul	23.00	68.50	49	488	1704
	Luo	28.00	68.50	68	-4	1897
	Nak	23.50	68.70	37	372	1822
	Pel	24.80	68.50	5	171	1743
	Pet	27.00	69.50	10	883	1792
	Pit	27.50	67.50	16	−6	1749
	Rie	28.00	68.50	59	301	1770

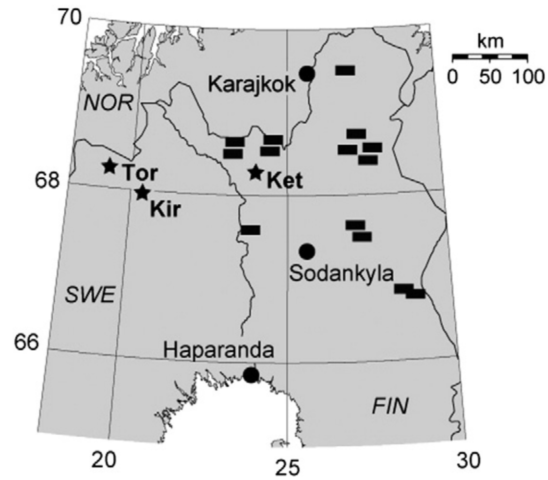

Fig. 1. Map showing the three living-tree (stars) and 14 sub-fossil (rectangles) pine sites integrated in the N-Scan record, together with the long-term meteorological stations in Haparanda, Karasjok, and Sodankyla (circles).

Biological age trends inherent to the MXD data were removed using RCS (Esper et al., 2003), a detrending method that preserves high-to-low frequency variance in the resulting indices. MXD series were combined using the arithmetic mean. Variance changes, such as those that can arise from temporally changing replication and inter-series correlation (Frank et al., 2007), were adjusted. The new MXD record was calibrated against mean JJA temperatures derived from the long-term instrumental stations in Haparanda, Karasjok, and Sodankyla (Fig. 1) over the 1876–2006 period, and transferred into summer temperature estimates using ordinary least squares (OLS) regression (with MXD as the dependent variable) (Cook and Kairiukstis, 1990).

N-Scan was used to identify temperature extremes over the 138 BC to AD 2006 period including exceptionally cold and warm summers, 30-year periods, and centuries. The 30-year periods were additionally considered for comparison with existing temperature reconstructions from the region, including a combined TRW-plus-MXD record by Briffa et al. (1992) from northern Sweden (hereafter Briffa92), a TRW-based record by Grudd et al. (2002) from northern Sweden (hereafter Grudd02), a TRW-based record by Briffa et al. (2008) from northern Finland and Sweden (hereafter Briffa08), a MXD-based record by Grudd (2008) from northern Sweden (hereafter Grudd08), and a TRW-based record from Helama et al. (2010) from northern Finland (hereafter Helama10). Of the six reconstructions considered here, four reach back to AD 1 and earlier (N-Scan, Grudd02, Briffa08, Helama10), and two back to AD 500 (Briffa92, Grudd08). Whereas some of these records share data (e.g. Briffa92 and Grudd02, Briffa92 and Grudd08,) others are fully independent (e.g. Grudd02 and Helema10). All records were, however, independently derived and as such individually treated and considered in large-scale reconstructions. Due to data overlap, uncertainties defined by the spread amongst reconstructions should be considered as conservative estimates.

Temperature differences among the various proxy records were assessed after re-calibrating each of the six reconstructions against JJA temperatures over the common 1876–1993 period (except for the Briffa92 record that only extends until 1980) and transferring the records into summer temperatures using OLS regression with the tree-ring data as the independent variable. These calibrated and transferred timeseries were used to calculate the range of reconstructed temperatures during extremely cold and warm years. We also smoothed the six proxy records using 30-year filters prior to the calibration against JJA temperatures (over the 1891–1979 period) and analyzed the difference between the reconstructions during