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Summer temperature variations in Lapland during the Medieval Warm Period and the Little Ice Age relative to natural instability of thermohaline circulation on multi-decadal and multi-centennial scales

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ABSTRACT: New tree ring-based analysis for climate variability at a regional scale is presented for high latitudes of Europe. Our absolutely dated temperature reconstruction seeks to characterise the summer temperatures since AD 750. The warmest and coolest reconstructed 250-year periods occurred at AD 931–1180 and AD 1601–1850, respectively. These periods share significant temporal overlap with the general hemispheric climate variability due to the Medieval Warm Period (MWP) and the Little Ice Age (LIA). Further, we detect a multi-decadal (ca. 50- to 60-year) rhythm, attributable to instability of the North Atlantic Deep Water, in the regional climate during the MWP but not during the LIA. Intensified formation of the North Atlantic Deep Water further appeared coincident to the initiation and continuation of MWP, the mid-LIA transient warmth occurring during the period AD 1391–1440, and to recent warming. Our results support the view that the internal climate variability (i.e. thermohaline circulation) could have played a role in the earlier start of the MWP in several proxy reconstructions compared to the externally forced model simulations. Copyright © 2009 John Wiley & Sons, Ltd.

KEYWORDS: climate change; dendrochronology; Finland; North Atlantic Deep Water.

Introduction

Climate trends and fluctuations can be obtained from several types of natural and human archives. However, instrumental climate records are not long enough to resolve the full spectrum of climate variability, especially concerning the long-term behaviour of climate. Indirect proxy estimates of past climate elongate the climatic records retrospectively over past centuries and millennia (Bradley, 1999). Typical proxy records over the continents are recent and subfossil tree rings that can be used for larger-scale and regional reconstructions of past climates (Fritts, 1976; Briffa, 2000; Esper *et al.*, 2002; D'Arrigo *et al.*, 2006; Grudd, 2008). In the present study, we present a tree ring-based reconstruction of palaeotemperature variability at the high-latitudes of Europe over the past millennium. As a regional temperature reconstruction, this record is expected to depict the climate variations inherent to the North Atlantic more clearly than the spatially extended reconstructions that typically mask the details concerning the spatial patterns of climate variations and their causes (Jones and Kelly, 1983; Wanner, 2005).

In the North Atlantic sector, the natural climatic changes originating from the Atlantic Ocean have recently been shown to drive multi-decadal variations over the past centuries (Enfield *et al.*, 2001; Knight *et al.*, 2005; Sutton and Hodson, 2005; Linderholm *et al.*, 2009). These variations are of importance regarding the future climate since the ongoing and future changes in the deep water formation in the northern North Atlantic could abruptly change the continental climate similarly to their past influences (Clark *et al.*, 2002; Alley *et al.*, 2003). Consequently,

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the obtained temperature reconstruction was compared to changes in the sedimentary proxy of the thermohaline circulation through the past millennium (Bianchi and McCave, 1999). We hypothesise that synchrony between the temperature reconstruction and thermohaline circulation would indicate an oceanic influence on regional climate through the classical climate stages of the 'Medieval Warm Period' and the 'Little Ice Age' (Lamb, 1965, 1982; Bradley and Jones, 1993; Grove, 2004; Matthews and Briffa, 2005). Given that such relationships have existed during the past millennium, similar constraints could be expected shaping the 21st-century climate evolution, thus playing a role alongside the external and/or anthropogenic forcings.

Material and methods

Our reconstruction was derived from the dataset of Scots pine (*Pinus sylvestris* L.) tree ring series of living and subfossil wood from forest limits of Finland and Norway, within 70° to 68° N, and 30° to 20° E (Eronen *et al.*, 1999, 2002; Helama *et al.*, 2004b, 2008). Living pines in this chronology were cored in the autumn of 2000. The initial tree ring dataset of Eronen *et al.* (2002) was later processed by Helama *et al.* (2005c) and this tree ring width chronology was adopted here since AD 750. Previously, the biological trends were removed from the individual tree ring series using an indexing approach that largely resembled the regional curve standardisation (Briffa *et al.*, 1992) with an exception that the concavity of the growth trend, that has for long known to vary with the stand density changes (Mikola, 1950; Helama *et al.*, 2005a,b,c), was adjusted for the known past changes in the pine population density in the study region (Helama *et al.*, 2005b,c). In so doing, we obtained tree ring indices that were more reliable concerning their low-frequency variations than could be retrieved using the conventional regional curve standardisation method (Helama *et al.*, 2005c). The chronology performs expressed population signal statistics (Wigley *et al.*, 1984) well above the level of reliable chronology variability (i.e. above 0.85), indicating potential for proxy record of excellent data quality. Variance in the chronology was further adjusted for temporally varying sample size (Osborn *et al.*, 1997). The ubiquitous climatic signal, detected in Scots pine tree rings in the study region, is that of mid-summer (i.e., July) temperature variability (Hustich and Elfving, 1944; Mikola, 1950; Sirén, 1961; Lindholm, 1996; Helama *et al.*, 2005a). Several calibration and verification exercises have demonstrated the reliability of these tree rings for reconstructions of past temperatures with a high level of statistical significance by differently partitioned spatiotemporal subsets of the data (Lindholm and Meriläinen, 1995; Lindholm *et al.*, 1995, 1996a,b, 1997; Lindholm, 1996; Lindholm and Eronen, 2000; Helama *et al.*, 2002). Importantly, the tree ring widths not only of living trees but also those originating from subfossil wood (retrieved from lake sediments) were previously shown to correlate with mid-summer temperatures (Helama *et al.*, 2004a). In the present study, the instrumental monthly climatic data from meteorological stations of Karasjok in northern Norway (69° 28′ N; 25° 31′ E) was used in the regression-based transfer functions. The mean temperature of July (AD 1876–1998) was used as a predictand. Calibration between the meteorological data and ring width time series was processed between the years AD 1876 and 1998. Estimates of summer temperature variability were obtained using linear regression. The time series of predictand and predictor were July mean temperatures and ring width indices, respectively. A model using two lagged ($t-2$, $t-1$), one concurrent (t) and two leading years ($t+1$, $t+2$) of normalised tree ring width (TRW) was used. Leading and/or lagging tree ring values are included in the model to correct for statistical autocorrelation effects that arise from physiological processes (inherent to growth) carrying the concurrent climatic signal over a multitude of years (Fritts, 1976). That is, growth is influenced by the concurrent climate but also results from climatic forcings of previous years that, in turn, are reasonably imprinted in the leading values of tree rings. Similarly, the signal of concurrent climate is stored in the growth over a number of subsequent years, this influence becoming registered by the lagging values of tree rings. Validity of the model was proven by comparing independent climate data to reconstructed temperatures. The model was first calibrated using the data between AD 1876 and 1937; these results were verified with data between AD 1937 and 1998. A similar examination was then repeated using the reversed intervals. Standard methods used frequently in dendroclimatic and palaeoclimatic studies – reduction of error, coefficient of error and sign test (Fritts, 1976; Gordon *et al.*, 1982; Briffa *et al.*, 1988) – were used as tests of reconstruction skill through a calibration verification exercise. The anomalous climate phases were quantified by computing the four warmest and coolest 50-year periods, the three warmest and coolest 100-year periods and the warmest and coolest 250-year periods. These periods were reported with the two-standard-error limits about the period mean (Briffa *et al.*, 1990, 1995). Concentration of climate variability at different periodicities was estimated by multi-taper methods (MTM) (Thomson, 1982, 1990; Ghil *et al.*, 2002).

Results

All the statistics (reduction of error, coefficient of error, sign test) indicated that the reconstruction exhibited reasonable accuracy for both verification periods (Table 1). The actual calibration period was AD 1876–1998. The final transfer function takes the following form:

$$T_t = -0.190\mathrm{TRW}_{t-2} - 0.150\mathrm{TRW}_{t-1} + 0.914\mathrm{TRW}_t - 0.100\mathrm{TRW}_{t+1} - 0.142\mathrm{TRW}_{t+2} \quad (1)$$

The bi-decadal and longer variations in tree ring indices and temperature series were extracted from the annually based series of observed and estimated temperatures using a 30-year cubic spline (with 50% cut-off) as a 'low-pass' filter. The reconstruction accounted for more than 40% of the total summer temperature variation and roughly 60% of the

Table 1 Calibration and verification statistics for construction. The calibration period was divided into two subperiods for cross-validation to ensure reliability of the transfer function

Calibration period	1876–1937	1937–1998	1876–1998
Verification period	1937–1998	1876–1937	
Calibration			
Correlation (*R*)	0.715	0.597	0.636
Sign test (correct/incorrect)	45/16	44/17	86/36
Verification			
Correlation (*r*)	0.547	0.643	
Reduction of error (RE)	0.315	0.420	
Coefficient of error (CE)	0.284	0.397	
Sign test (correct/incorrect)	44/17	45/16	

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temperature variation at bi-decadal and longer timescales. Considering the temporal length of the calibration period, these figures would indicate that the range of simulated temperature values equal or exceed the average the 95% confidence interval inherent in the model (Lucy *et al.*, 2008), with potential timescale dependency. Cross-spectral analysis (Howell, 2001) indicated that there was statistically significant ($P < 0.05$) coherence at all periods greater than 30 years (not illustrated).

Reconstruction indicates a highly variable late Holocene climate with oscillations of warmer and cooler climatic phases through the record (Fig. 1(a)). Climatic variability has taken place from inter-annual to sub-millennial timescales. The warmest and coolest 250-year periods occurred during the periods AD 931–1180 and AD 1601–1850, respectively. These periods were superimposed by the extreme variations of shorter timescales (Fig. 1(b)). In general, the warm climates were predominantly experienced during the multi-centennial warming at the start of the record (AD 931–1180) or in connection with recent warming that seems to have taken place in the region since the end of the 19th century (Fig. 1(b)). Thereafter, the majority of the cool climate periods occurred roughly between AD 1300 and 1850. The only exceptions found were the cool half-centennial period AD 775–824 and the warm period of the same length between the years AD 1391 and 1440. The recent climatic conditions appeared anomalous in the context of the full reconstruction but not markedly warmer (in terms of overlapping error limits) than the warmest periods at the beginning of the record.

Discrete periodicities at ca. 120, 80, 50 and 30 years were all evident above 95% confidence level (Fig. 2(a)). More precisely, the warmest multi-centennial period was characterised by multi-decadal periodicities (Fig. 2(b)), whereas the coolest multi-centennial period experienced multi-annual periodicities in temperature variability (Fig. 2(c)). Especially well-developed

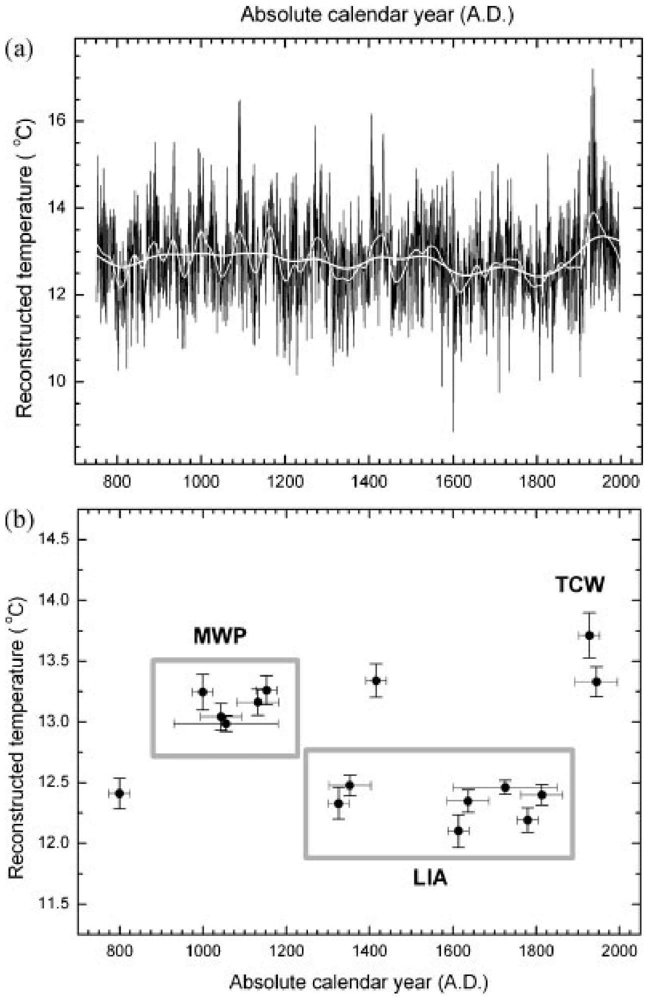

Figure 1 Climatic evolution in Lapland since AD 750. Reconstructed temperature variability depicts total variations (black line), decadal (thin white line; 25-year spline, Cook and Peters, 1981) and centennial (thick white line; 75-year spline) variations (a). The anomalous climate phases were quantified by four warmest and coolest 50-year periods, three warmest and coolest 100-year periods and the warmest and coolest 250-year periods. Horizontal bars indicate the duration of the period; vertical bars indicate the 2-standard error limits about the period mean. Grey boxes depict the intervals of increased probability to obtain extremely warm or cool periods due, respectively, to conditions of the Medieval Warm Period (MWP), the Little Ice Age (LIA) and the Twentieth Century Warming (b)

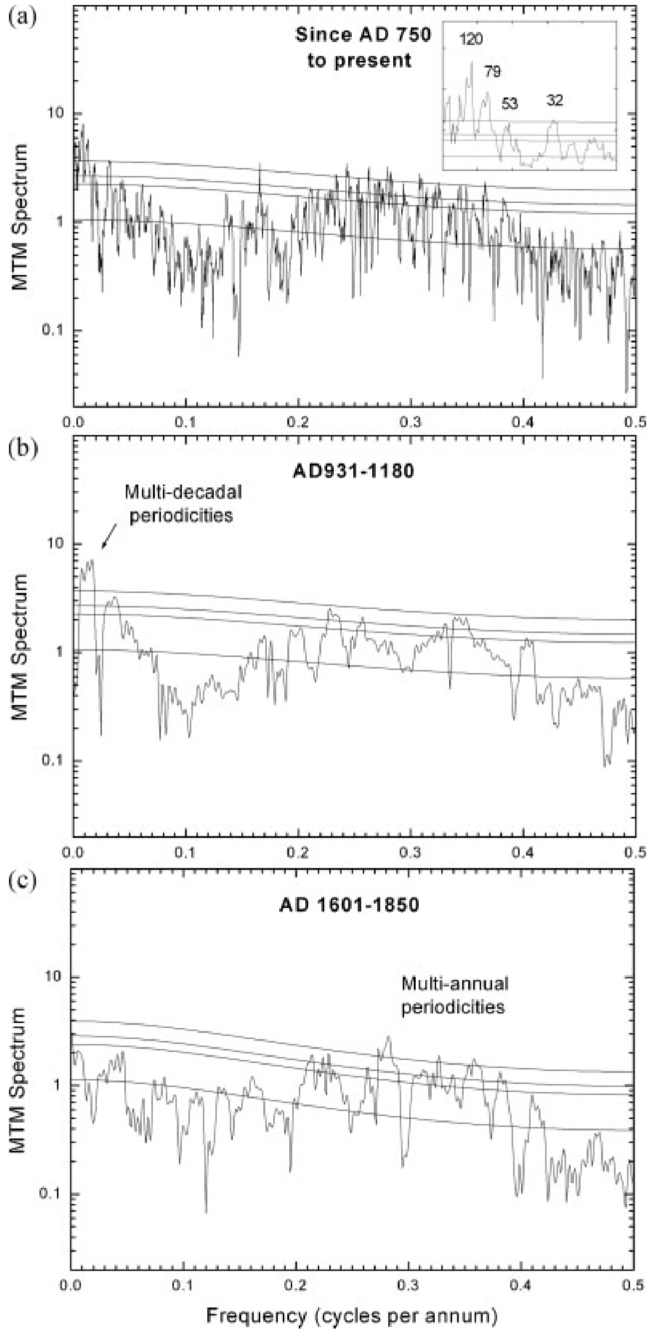

Figure 2 Spectral characteristics of reconstructed climate, estimated as MTM spectrum (Thomson, 1982, 1990; Ghil *et al.*, 2002): (a) over the full period (AD 750–1998); (b) during the warmest interval (AD 931–1180); and (c) during the coolest interval (AD 1601–1850). Shown as horizontal lines are the median, 90%, 95% and 99% significance levels relative to the red noise

periodicity was found at 60-year timescales during the warm spell (Fig. 2(b)).

Discussion and conclusions

Periodic temperature variations

Previous studies conducted in the region and adjacent areas have found dendroclimatic periodicities similar to our findings (Boman, 1927; Sirén and Hari, 1971; Briffa and Schweingruber, 1992; Ogurtsov *et al.*, 2001, 2002, 2008). With special regard to potential climatic forcings, the century-scale temperature variability over Fennoscandia was tentatively connected to the Gleissberg (1944) cycle of solar activity by Briffa and Schweingruber (1992). Later, it was demonstrated that the regional tree ring-based temperature variations could be statistically correlated both with the observed variations in sunspot numbers (i.e. Gleissberg cycle) and with variations in the reconstructed Northern Hemisphere temperatures (Mann *et al.*, 1999) at centennial scales and through the past millennium, that is, when all the records were filtered to exhibit roughly the 80- to 120-year band of variations (Ogurtsov *et al.*, 2001, 2002, 2008). In this study, we discuss our results in the context of the observed multi-centennial (50- to 60-year) temperature variability that bears a potential link to oceanic origins (Schlesinger and Ramankutty, 1994; Delworth and Mann, 2000) and that is under discussion in the recent palaeoclimatic literature (e.g. Enfield *et al.*, 2001; Latif *et al.*, 2004; Sutton and Hodson, 2005; Knight *et al.*, 2005; Parker *et al.*, 2007; Sicre *et al.*, 2008a,b).

The warm–cool–warm cycle

The present reconstruction depicted multi-centennial warmth that spanned from the 10th to the 12th century. This observation could be seen as synchronous with some recent proxy-based hemispheric climate records that show evidence concerning the relative warmth during the same centuries (Esper *et al.*, 2002; Moberg *et al.*, 2005; D'Arrigo *et al.*, 2006; Osborn and Briffa, 2006; Grudd, 2008). For example, Osborn and Briffa (2006) found positive temperature anomalies for the Northern Hemisphere between AD 890 and 1170. Of note, our reconstruction did not show any extremely cool periods during this interval. By contrast, the concentration of the coolest periods was recorded from the 14th to the 19th century. Also this observation was parallel to the general palaeoclimatic views that have shown a long-term decline in European temperatures over these centuries (Bradley and Jones, 1993; Matthews and Briffa, 2005). This is the warm–cool–warm cycle of the past millennium that has actually stood as a rough benchmark for climatic history since the studies of Lamb (1959, 1963, 1965, 1982), at least in western Europe, but more broadly in the North Atlantic sector. Still today, a similar cycle can be comprehended as a common feature among several proxy and model-based temperature reconstructions spanning the past millennium (Jones and Mann, 2004). The periods of the past climate that constitute this cycle have been termed the Medieval Warm Period (MWP), the Little Ice Age (LIA) and the Twentieth-Century Warming (TCW). The MWP was likely introduced first by Lamb (1965) in regard to his conclusions about the relatively warm climates in some parts of western Europe during the 12th–13th centuries. The LIA has become used for the period of cool climates after the MWP but before the TCW (Bradley and Jones, 1993; Grove, 2004). According to Matthews and Briffa (2005), the LIA culminated during the period AD 1570–1900 when Northern Hemisphere summer temperatures dropped significantly below the AD 1961–1990 mean. To this end, the temporal correlation between the MWP and LIA and the climatic extreme periods of our reconstruction appeared evident. It can be concluded that the forcings (internal and external) responsible for the MWP and LIA conditions that have been influential on a wide geographical scale have likewise constrained regional climate conditions towards warmer and cooler conditions, respectively. These conditions were then observed as the general climate instability of Lapland and adjacent areas during the past millennium (Fig. 1(b)).

Thermohaline circulation

The North Atlantic sedimentary record of Bianchi and McCave (1999) indicates the speed of deep ocean flow (Iceland–Scotland Overflow Water), which is an important component of the thermohaline circulation (THC). The sedimentary record thus indicates the production of North Atlantic Deep Water (NADW) (Bianchi and McCave, 1999). It is known that the variations in THC and sea surface temperatures over the North Atlantic are closely linked. The THC transports warm saline surface water towards high latitudes, thus keeping the surface temperatures over the North Atlantic Ocean and western Europe higher than those of areas with comparable latitudes in the Pacific realms. Likewise, weakening of the THC would result in a concomitant decrease in the formation of NADW and modulation of the climate to reduce air temperatures over the regions under these influences (Weaver *et al.*, 1999; Manabe and Stouffer, 1999; Latif *et al.*, 2004). We observed that the interval characterising the positive temperature anomaly in the study region during the MWP was strikingly coexistent with increased formation of the NADW (Fig. 3). More precisely, the temperature rise during the early MWP (from cool climate during the AD 800s to warmer climate during the AD 900s) seemed to coincide with increasing formation of the NADW. Likewise during the MWP, spectral analysis revealed a dominance of multi-decadal temperature variations with a 50- to 60-year periodicity (Fig. 2(b)). Interestingly, temperature variations of similar timescales (ca. 50–90 years) have previously been associated with recent changes in the THC-related climate variability particularly over the Atlantic region (Schlesinger and Ramankutty, 1994; Delworth and Mann, 2000; Knight *et al.*, 2005). These proxy-based findings would augment the view that the THC may have influenced warming of the climate during the MWP (Bond *et al.*, 2001; Broecker, 2001), especially during the initiation of the MWP.

Additional evidence for the influence of THC on continental summertime climate has been gathered for the beginning of the 15th century. It was found that anomalous warming during the first half of the 15th century coincided with the concurrently intensified formation of the NADW (Fig. 3). Thereafter, during the culmination phase of the LIA, spectral analysis did not show significant periodic behaviour at low frequencies that could be associated with oceanic origins as there seemed to be no evidence for a periodic climatic signal at multi-decadal scales (Fig. 2(c)). During the culmination of the LIA, the most developed periodic behaviour of temperature variability occurred at multi-annual timescales.

Last, the most recent phase of intensified formation of the NADW occurred parallel to the 20th-century warmth (Fig. 3).

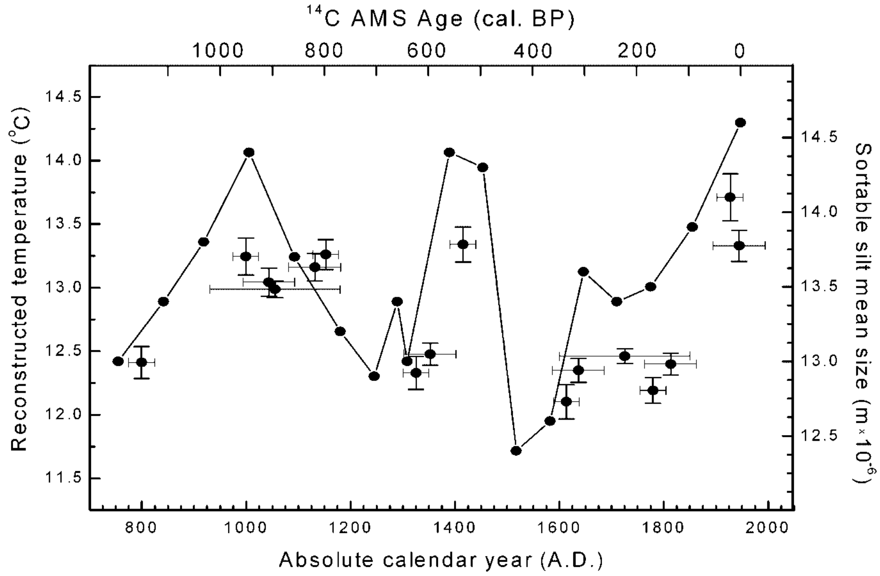

Figure 3 Reconstructed temperature variability indicated by anomalously positive and negative temperature intervals presented with estimated changes in the speed of deep ocean flow (Iceland–Scotland Overflow Water) (line with dots), which is an important component of the thermohaline circulation (THC) and indicates the production of North Atlantic Deep Water, by sortable silt mean size (10–63 μm) (Bianchi and McCave, 1999). Horizontal axes give dendrochronological calendar years (AD) for reconstruction and calibrated radiocarbon years before present (cal. BP) for sediments. Age uncertainties concerning radiocarbon years are up to ±35 a (Bianchi and McCave, 1999; Chapman and Shackleton, 2000)

To conclude, the three warm periods recorded here – AD 931–1180, AD 1391–1440 and AD 1895–1994 – all correlated temporally with the three intensification phases of the THC over the past millennium. In addition, MWP climatic variability showed spectral characteristics similar to expected timescale-dependent behaviour of the THC, whereas the culmination phase of the LIA exhibited absence of climate variability at corresponding timescales. This could imply that the multi-decadal periodicities of oceanic origins are introduced to regional climate notably during intervals of intensified production of the NADW. All these findings concerning ocean–climate interactions confirm and throw more light on previous results by palaeoceanographers (Keigwin, 1996; Bianchi and McCave, 1999; deMenocal *et al.*, 2000; Andersson *et al.*, 2003; Sicre *et al.*, 2008a,b) in the North Atlantic sector, with special reference to the climate of Lapland and adjacent areas of northern Europe.

Medieval solar activity maximum

As noted previously by D'Arrigo *et al.* (2006), several dendroclimatic temperature reconstructions show an earlier peak in the MWP temperatures than the model simulations. More precisely, North American and Eurasian tree rings were found to show high-index values around AD 950 and AD 1000, respectively (D'Arrigo *et al.*, 2006). Also the multi-proxy compilation of Osborn and Briffa (2006) evidenced positive temperature anomalies for the Northern Hemisphere as early as AD 890 (with continuation roughly to AD 1170). This view was supported by our reconstruction (Fig. 1). By contrast, the externally forced climate model simulations typically indicate the highest MWP-related temperatures no earlier than after AD 1100 (see reviews in Jones and Mann, 2004, and Goosse *et al.*, 2005). A major contribution to the positive model-based temperatures during this time originates from estimates of solar activity showing a concurrent positive anomaly (ca. AD 1100–1250) (Jirikowic and Damon, 1994; Crowley, 2000; Solanki *et al.*, 2004). Obviously, the influence from medieval solar activity postdates the rise of the early MWP temperatures in proxy reconstructions. As speculated already by D'Arrigo *et al.* (2006), it is possible that the model–proxy deviation could originate from internal climate dynamics unattainable by externally forced models. Meanwhile, multi-decadal variations in North Atlantic sea surface temperatures have been shown to drive adjacent continental climate variations over past centuries (Enfield *et al.*, 2001; Sutton and Hodson, 2005; Knight *et al.*, 2005). Our example supports these views with a proposition that changes in the formation of the NADW could have played a role in the initiation of the relatively warm state of climate during the MWP, as well as other long-term summer temperature variations thereafter. These findings would further indicate that ongoing changes in the North Atlantic hydrology (Curry *et al.*, 2003; Curry and Mauritzen, 2005) could be comprehended as a realistic forcing towards cooler climates in the region.

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