A NEW RECONSTRUCTION OF TEMPERATURE VARIABILITY IN THE EXTRA-TROPICAL NORTHERN HEMISPHERE DURING THE LAST TWO MILLENNIA

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ABSTRACT. A new temperature reconstruction with decadal resolution, covering the last two millennia, is presented for the extra-tropical Northern Hemisphere (90–30°N), utilizing many palaeo-temperature proxy records never previously included in any large-scale temperature reconstruction. The amplitude of the reconstructed temperature variability on centennial time-scales exceeds 0.6°C. This reconstruction is the first to show a distinct Roman Warm Period *c.* AD 1–300, reaching up to the 1961–1990 mean temperature level, followed by the Dark Age Cold Period *c.* AD 300–800. The Medieval Warm Period is seen *c.* AD 800–1300 and the Little Ice Age is clearly visible *c.* AD 1300–1900, followed by a rapid temperature increase in the twentieth century. The highest average temperatures in the reconstruction are encountered in the mid to late tenth century and the lowest in the late seventeenth century. Decadal mean temperatures seem to have reached or exceeded the 1961–1990 mean temperature level during substantial parts of the Roman Warm Period and the Medieval Warm Period. The temperature of the last two decades, however, is possibly higher than during any previous time in the past two millennia, although this is only seen in the instrumental temperature data and not in the multi-proxy reconstruction itself. Our temperature reconstruction agrees well with the reconstructions by Moberg *et al.* (2005) and Mann *et al.* (2008) with regard to the amplitude of the variability as well as the timing of warm and cold periods, except for the period *c.* AD 300–800, despite significant differences in both data coverage and methodology.

Key words: Temperature reconstructions, temperature variability, Medieval Warm Period, Little Ice Age, Roman Warm Period, Dark Age Cold Period, global warming, climate change

Introduction

Considerable progress has been made in recent years in late-Holocene palaeoclimatology (for a review, see Wanner *et al.* 2008; Jones *et al.* 2009). This progress is partly a result of the challenge of the traditional concept of a distinct Medieval Warm Period (or Medieval Climate Anomaly) and Little Ice Age (e.g. Lamb, 1977) by Hughes and Diaz (1994), Jones *et al.* (1998), Mann *et al.* (1998, 1999) and Crowley and Lowery (2000) in their pioneering multi-proxy temperature reconstructions that encouraged further attempts at large-scale quantitative temperature reconstructions (e.g. Briffa 2000; Esper *et al.* 2002; Mann and Jones 2003; Cook *et al.* 2004; Jones and Mann 2004; Moberg *et al.* 2005; D'Arrigo *et al.* 2006; Osborn and Briffa 2006; Ammann and Wahl 2007; Hegerl *et al.* 2007; Juckes *et al.* 2007; Loehle 2007; Mann *et al.* 2008, 2009). The main objective with those reconstructions has been to place the observed twentieth-century warming in a long-term perspective. Much of the focus has thus been on comparing the amplitude of the warming during the Medieval Warm Period with that of the present in order to assess whether the recent warming is unprecedented either in magnitude or rate during the past one or two millennia (Crowley 2000; Bradley *et al.* 2001, 2003; Jones *et al.* 2001; Soon and Baliunas 2003; Huang *et al.* 2008; Esper and Frank 2009; Kaufman *et al.* 2009; The Copenhagen Diagnosis 2009; Trouet *et al.* 2009).

Despite significant improvement in our understanding of the temperature variability during the past one or two millennia, especially for the Northern Hemisphere, the controversial question whether Medieval Warm Period peak temperatures exceeded present temperatures remains unanswered. IPCC (2007) and NRC (2006) concluded that the data coverage still is too limited and unevenly distributed around the globe to say anything with reasonable certainty about temperatures on a global or hemispheric scale prior to *c.* AD 1600. The amplitude of the multi-decadal to centennial pre-industrial temperature variability constitutes a major uncertainty. The estimate of this variability ranges from *c.* 0.2 to 1°C in the different reconstructions. Those divergences are to some extent a result of the use of different methodological approaches, but the number and choice of proxy data seem to be of greater importance. Apart from the general limitations set by the overall scarcity of long quantitative palaeoclimate records, all large-scale reconstructions have furthermore been hampered to some degree by the dominance of proxy records from high latitudes. Many available proxy records also end sometime during the twentieth century and thus cannot be calibrated to the high temperatures during the last decades of the twentieth century. This may result in an underestimation of the true temperatures in earlier warm periods.

The number of long quantitative palaeotemperature records from across the globe, of which a majority are well suited for being used in large-scale temperature reconstructions, have been rapidly increasing in recent years (Ljungqvist 2009). As more and better data become increasingly available, it is essential to regularly make new multi-proxy reconstructions in order to gain as good and updated an understanding of large-scale pre-industrial temperature variability as possible. Here, we shall present a new temperature reconstruction for the extra-tropical Northern Hemisphere (90–30°N) with decadal resolution for the last two millennia. Our goal is to reassess the amplitude of the preindustrial temperature variability with the help of more data than have previously been utilized for this purpose and discuss what impact this additional data have on the overall results compared to earlier reconstructions.

Data and method

The new reconstruction presented in this paper consists of 30 temperature sensitive proxy records from the extra-tropical Northern Hemisphere (90–30°N), all of which reach back to at least AD 1000 and 16 all the way back to AD 1 (Table 1; Fig. 1). This is a considerable improvement in data coverage compared to previous large-scale quantitative temperature reconstructions on a global or hemispheric scale. This reconstruction is restricted to the extra-tropical Northern Hemisphere (90–30°N) since there still simply exist too little high quality palaeotemperature data from the low latitudes (e.g. tropical regions) of the Northern Hemisphere. A wide range of different kinds of proxies with annual to multi-decadal resolution have been used, as shown in Table 1: 2 historical documentary records, 3 marine sediment records, 5 lake sediment records, 3 speleothem $\delta^{18}O$ records, 2 ice-core $\delta^{18}O$ records, 4 varved thickness sediment records, 5 tree-ring width records, 5 tree-ring maximum latewood density records, and 1 $\delta^{13}C$ tree-ring record. Virtually all available high-quality palaeotemperature proxies with a reasonably high temporal resolution have been used. However, all tree-ring width records from arid and semi-arid regions, as southwest USA and Mongolia, have been excluded from the reconstruction. Since they may have been affected by drought stress, they possibly do not show a linear response to warming if higher summer temperatures also reduce the availability of water (D'Arrigo *et al*. 2006; Loehle 2009).

As shown in Table 1, the proxy collection is biased towards the warmer seasons of the year. Many proxy records are tree-ring width records and those, admittedly, capture only variations in growing season (e.g. summer) temperatures. However, considering the high correlation between seasons on decadal and longer time-scales in the period covered by instrumental measurements, it is justified to use them as annual proxies, as has also been done by Esper *et al*. (2002a) Cook *et al*. (2004), Moberg *et al*. (2005) and D'Arrigo *et al*. (2006). Since tree-ring records only reflect the growing season temperatures, their use as annual proxies is anyhow dependent on the assumption of a high degree of correlation between seasons that are stationary in time. It is, however, important in this context to acknowledge that there, for some regions, can be an anti-correlation between the seasons on inter-annual time-scales.

We use the common "composite-plus-scale" method for creating our multi-proxy reconstruction (von Storch *et al*. 2004; Lee *et al*. 2008). All records with less than annual resolution were linearly interpolated to have annual resolution before the records were normalized to zero mean and unit standard deviation, fitting the mean and variance AD 1000–1900 and then we calculated 10-year-mean values of the records. The arithmetic mean of all 30 records was then calculated to form a dimensionless index of Z-score units. This index was scaled to fit the decadal mean and variance over the period AD 1850–1989 in the variance adjusted CRUTEM3+HadSST2 90–30°N instrumental temperature record (Brohan *et al*. 2006; Rayner *et al*. 2006) and adjusted to have a zero equalling the 1961–1990 mean of this instrumental record. The decadal correlation between proxy and instrumental temperature is very high (*r*. 0.95, r^2 0.90) and the 2 standard deviation error bars only amount to ±0.12°C in the calibration period

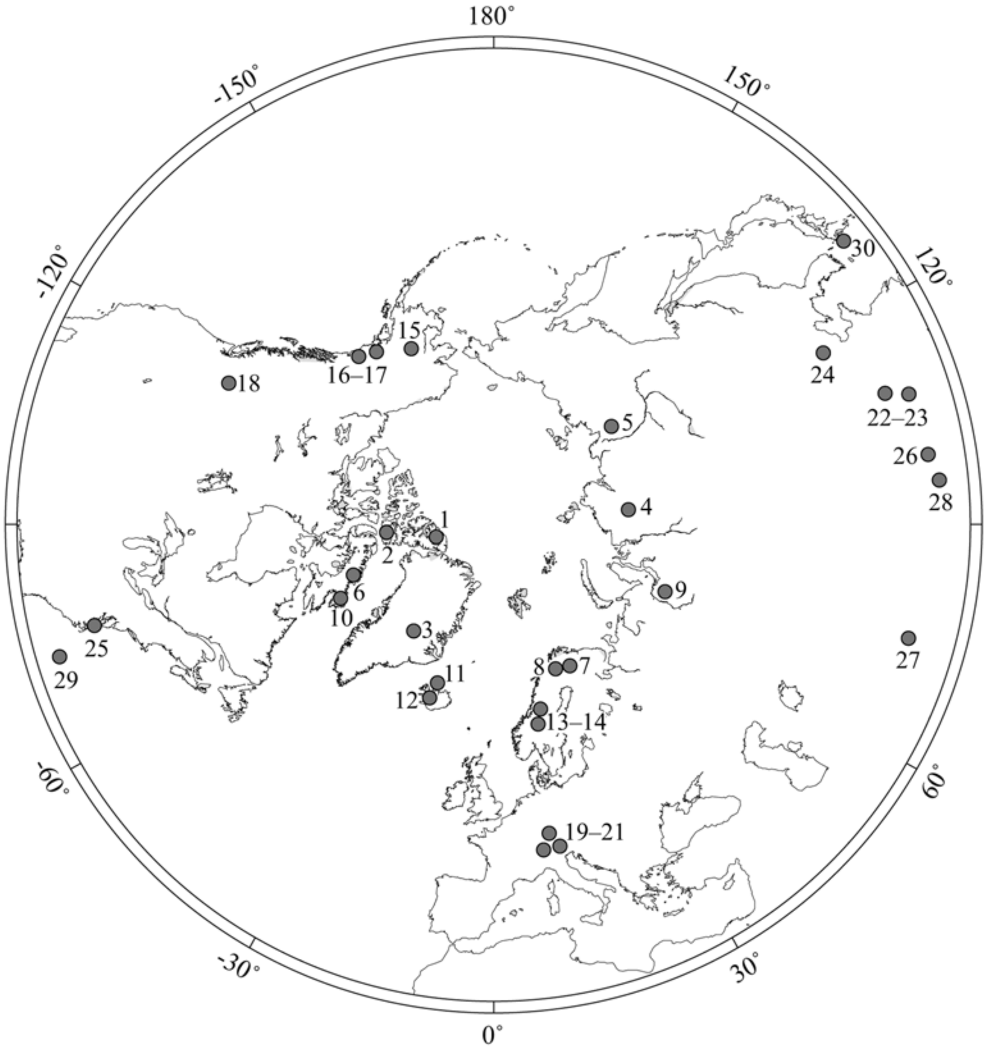

Fig. 1. The geographical locations of the records listed in Table 1.

AD 1850–1989. As would be expected from different sorts of proxy records deriving from different regions, there is a certain standard deviation between the decadal mean values of the records, as seen in Figure 2. This should, however, not be of concern for the accuracy of the reconstruction since the coherency between the records is rather stable in time back to *c*. AD 1000. The standard deviation is somewhat larger in the first millennium of the reconstruction, probably primarily because of the decreasing number of proxies covering this period, but even so this deviation is not much higher than in the calibration period. To account for changes in the standard deviation between the records in the error bars, we have increased the width of the confidence interval with the same percentage as the standard deviation between the records in a given decade exceeds the mean standard deviation during the calibration period AD 1850–1989.

Results

It is a rather conventional temperature history of the last two millennia, similar to that already outlined in Lamb (1977), that appears in our reconstruction,

Table 1. All temperature proxy records from across the extra-tropical Northern Hemisphere (90–30°N) used in our multi-proxy temperature reconstruction containing information such as geographical location, exact latitude and longitude, type of proxy, sample resolution, season bias, period covered by each record, and reference to the original publication. The proxy records are listed according to latitude from north to south. The geographical locations of the records are shown on the map in Fig. 1. Records marked with ‡ have never previously been used in any hemispheric or global multi-proxy temperature reconstruction.

Proxy location	Latitude	Longitude	Proxy type*	Sample resolution	Season bias	Period covered	Reference
‡ 1. Lower Murray Lake, N. Canada	81°21'N	69°32'W	V	Annual	Summer	1–1969	Cook *et al*. 2009
2. Devon Island, N. Canada	75°34'N	89°19'N	Ice-core $\delta^{18}O$	5 years	Annual	1–1969	Fisher *et al*. 1983
‡ 3. Greenland stack	75°N–65°11'N	38°3'–43°82'E	Ice-core $\delta^{18}O$	Annual	Annual	200–1969	Andersen *et al*. 2006
4. Taimyr peninsula, N. Siberia	73°00'N	105°E	TRW	Annual	Summer	1–1989	Naurzbaev *et al*. 2002
5. Indigirka, NE. Siberia	70°32'N	148°9'E	TRW	Annual	Summer	1–1989	Moberg *et al*. 2005
‡ 6. Big Round Lake, Baffin Island	69°52'N	68°50'W	V	Annual	Summer	980–1999	Thomas and Briner 2009
7. Lake Tsuolbmajavri, N. Fennoscandia	68°41'N	22°03'E	Lf	Multi-decadal to centennial	Summer	1–1989	Korhola *et al*. 2000
‡ 8. Torneträsk, N. Fennoscandia	68°12'N	19°27'E	MXD	Annual	Summer	510–1999	Grudd 2008
9. Polar Urals, NW, Siberia	66°52'N	65.38°E	MXD	Annual	Summer	780–1989	Esper *et al*. 2002a
10. Donard Lake, Baffin Island	66°40'N	61°21'W	V	Annual	Summer	800–1989	Moore *et al*. 2001
‡ 11. North Iceland Shelf	66°33'N	17°42'W	Md	2–5 years	Summer	1–1949	Sicre *et al*. 2008
‡ 12. Haukadalsvatn, W. Iceland	65°03°N	21°38°W	Lf	Decadal	Spring and summer	1–1999	Geirsdóttir *et al*. 2009
‡ 13. Korallgrottan , C. Sweden	64°54'N	14°8'E	Sp	Multi-decadal	Annual	1–1999	Sundqvist *et al*. 2010
‡ 14. Jämtland, C. Sweden	63°10'N	12°25'–13°35'E	TRW	Annual	Summer	1–870, 910–1999	Linderholm and Gunnarson 2005
‡ 15. Farewell Lake, C. Alaska	62°33'N	153°38'W	Lf	Multi-decadal to centennial	Summer	1–1959	Hu *et al*. 2001
16. Gulf of Alaska	61°N	146°W	MXD	Annual	Summer	730–1999	D'Arrigo *et al*. 2006
‡ 17. Iceberg Lake, Alaska	60°47'N	142°57'W	Lf	Annual	Summer	450–1989	Loso 2009
18. Canadian Rockies	52.9°N	117.9°W	MXD	Annual	Summer	950–1989	Luckman and Wilson 2005
‡ 19. Spannagel Cave, C. Alps	47°05'N	11°40'E	Sp	1–10 years	Annual	1–1929	Mangini *et al*. 2005
20. The Alps	47°00	7–13°E	MXD	Annual	Summer	760–1999	Büntgen *et al*. 2006
‡ 21. Lake Silvaplana, Switzerland	46°27'N	9°48'E	Lf	Annual to decadal	Summer	980–1999	Larocque *et al*. 2009
‡ 22. E. China	42°–27°N	110°–120°E	D	Decadal	Annual	20–1999	Yang *et al*. 2002
23. E. China	40°–27°N	107°–120°E	D	Decadal	Winter	20–1999	Ge *et al*. 2003
24. Shihua Cave, Beijing, China	39°54'N	116°23'E	Sp	Annual	Summer	1–1979	Tan *et al*. 2003

Table 1. Continued.

25. Chesapeake Bay, E. USA	38°89'N	76°40'W	Md	Multi-decadal	Spring	1–1989	Cronin *et al.* 2003
‡ 26. Lake Qinghai, Tibetan Plateau	37°N	100°E	Lf	Multi-decadal	Annual	1–1939	Liu *et al.* 2006
‡ 27. NW. Karakorum	37–35°N	74–76°E	TRW	Annual	Annual	620–1989	Esper *et al.* 2002b
‡ 28. Dulan, NE. Qinghai-Tibetan Plateau	36°N	98°E	TRW	Annual	Annual	1–1999	Zhang *et al.* 2003
29. Bermuda Rise, Sargasso Sea	33°41'N	74°26'W	Md	Multi-decadal to centennial	Annual	1–1969	Keigwin 1996
‡ 30. Yakushima Island, S. Japan	30°20'N	130°30'E	Tree-ring $\delta^{13}C$	Decadal	Annual	130–1949	Kitagawa and Matsumoto 1995

Notes: * D, documentary; Lf, lake/river fossils and sediments; MXD, tree-ring maximum latewood density; Md, marine sediments; Sp, speleothem isotopic analysis; TRW, tree-ring width; V, varved thickness sediments

with a Roman Warm Period *c.* AD 1–300, a Dark Age Cold Period *c.* AD 300–800, a Medieval Warm Period *c.* AD 800–1300 and a Little Ice Age *c.* AD 1300–1900, followed by the twentieth-century warming (Fig. 3). The highest decadal average temperatures in the reconstruction are encountered in the mid to late tenth century and the lowest towards the end of the seventeenth century. Although the highest reconstructed temperatures occurred during the Medieval Warm Period and in the twentieth century, the second century, during the Roman Warm Period, is the warmest century during the last two millennia according to our reconstruction. The Little Ice Age cooling, especially during the seventeenth century, appears to be more severe than the cooling during the Dark Age Cold Period. Our reconstruction is the first large-scale multi-proxy synthesis that shows that mean temperatures of the Roman Warm Period were higher than, or as high as, mean twentieth-century temperatures.

The decadal mean temperatures in the extra-tropical Northern Hemisphere seem to have equalled or exceeded the AD 1961–1990 mean temperature level during much of the Roman Warm Period and the Medieval Warm Period. The temperature since AD 1990 is, however, possibly higher than during any previous time in the past two millennia if we look at the CRUTEM3+HadSST2 90–30°N instrumental temperature data (Brohan *et al.* 2006; Rayner *et al.* 2006) spliced to the proxy reconstruction. The proxy reconstruction itself does not show such an unprecedented warming but we must consider that only a few records used in the reconstruction extend into the 1990s. Nevertheless, a very cautious interpretation of the level of warmth since AD 1990 compared to that of the peak warming during the Roman Warm Period and the Medieval Warm Period is strongly suggested.

Our new decadal temperature reconstruction for the extra-tropical Northern Hemisphere essentially confirms the results from those previous large-scale temperature reconstructions that have shown comparatively large low-frequency variability in the preindustrial period. The amplitude of the reconstructed temperature variability on centennial time-scales exceeds 0.6°C and is thus comparable to the variability in Moberg *et al.* (2005) and slightly larger than the variability in Mann *et al.* (2008). We should, however, keep in mind that our reconstruction is scaled against extra-tropical Northern Hemisphere (90–30°N) temperatures, whereas the Moberg *et al.* (2005) and Mann *et al.* (2008) reconstructions are scaled against the 90–0°N Northern Hemisphere temperatures.

Despite differences in both data coverage and methodology, our temperature reconstruction agrees well with Moberg *et al.* (2005) and Mann *et al.* (2008) with regard to the timing of warm and cold periods, but agrees somewhat less well, on longer time-scales, with the reconstructions by, for example, Briffa (2000), Esper *et al.* (2002a), Cook *et al.* (2004) and D'Arrigo *et al.* (2006). However, the period *c.* AD 300–800 shows considerably more variability in our reconstruction in contrast to the reconstructions by Moberg *et al.* (2005) and Mann *et al.* (2008). The amplitude of the temperature variability between the warmest and coldest century (prior to the twentieth century) in our reconstruction is 0.62°C. As a comparison, this amplitude is 0.22°C in Mann and Jones (2003), 0.58°C in Moberg *et al.* (2005), and 0.51°C in the 'error-in-variables' (EIV) regression method variant of

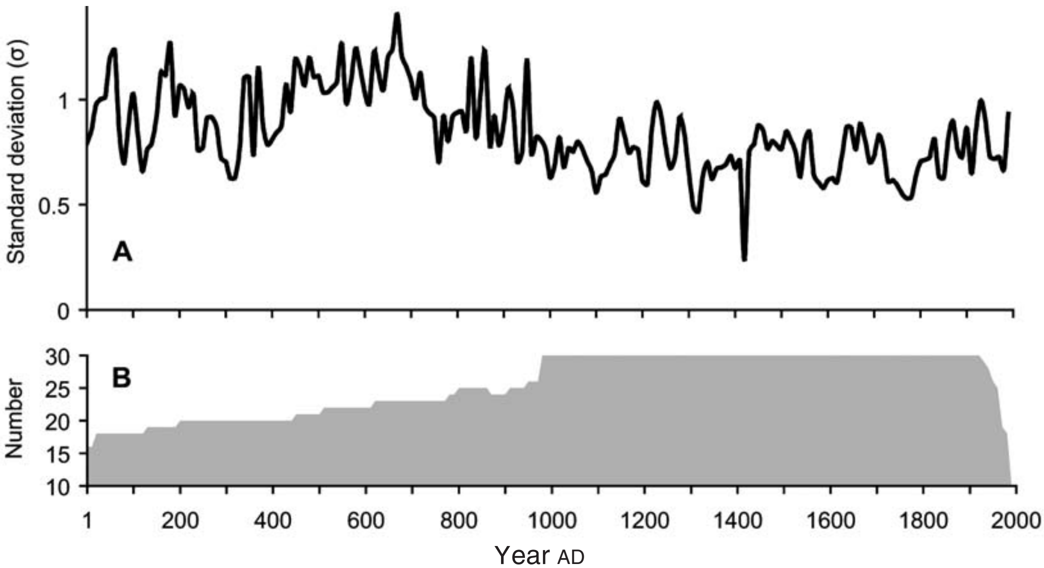

Fig. 2. A) Standard deviation between the decadal mean values of all proxy records used in the reconstruction; B) Total number of proxy records available for the reconstruction during different decades.

Mann *et al*. (2008) (Table 2). In our reconstruction the amplitude is 0.89°C between the warmest decade (the 950s) and the coldest (the 1690s) and thus *c*. 0.15°C smaller than in Moberg *et al*. (2005) and Mann *et al*. (2008), but much larger than the amplitude of 0.35°C in Mann and Jones (2003) (Table 3). These results should, however, be interpreted with some caution considering the estimated error bar of a minimum of ±0.12°C for any individual decade in our reconstruction.

Discussion

As already pointed out by Esper *et al*. (2005b), the broad picture of periods of relative warmth and cold of the last one to two millennia is rather well known. This fact is also evident in the review of long quantitative temperature reconstructions presented in the latest IPCC (2007) report. Our new reconstruction, utilizing a larger number of proxy records than most previous reconstructions, substantiates an already established history of long-term temperature variability. The remaining key uncertainty is related to the amplitude of low-frequency temperature variability and primarily to the magnitude of cooling during the Little Ice Age. Our new reconstruction shows a temperature variability on centennial time-scales exceeding 0.6°C, which is approximately similar to the amplitude of most more recent reconstructions. This amplitude is considerably larger than that in the pioneering reconstructions (e.g. Jones *et al*. 1998; Mann *et al*. 1999; Crowley and Lowery 2000) which were hampered by a very limited and unevenly distributed set of proxy data.

It is actually quite surprising that our results are so similar to those of other recent reconstructions, given the inclusion of much new data and a somewhat different methodological approach. It can therefore be concluded that, with present reconstruction techniques and limitations, the inclusion of additional data with similar limitation in temporal resolution and dating uncertainty will only have a minor effect on the reconstructed amplitude of the low-frequency variability. The minor differences compared to, for example, the reconstructions by Moberg *et al*. (2005) and Mann *et al*. (2008) can easily be attributed to differences in geographical data coverage and other statistical treatment of the data, although the substantially larger variability *c*. AD 300–800 in our reconstruction probably reflects a genuine signal originating from the use of more data.

The amplitude of the temperature variability on multi-decadal to centennial time-scales reconstructed here should presumably be considered to be the minimum of the true variability on those time-scales.

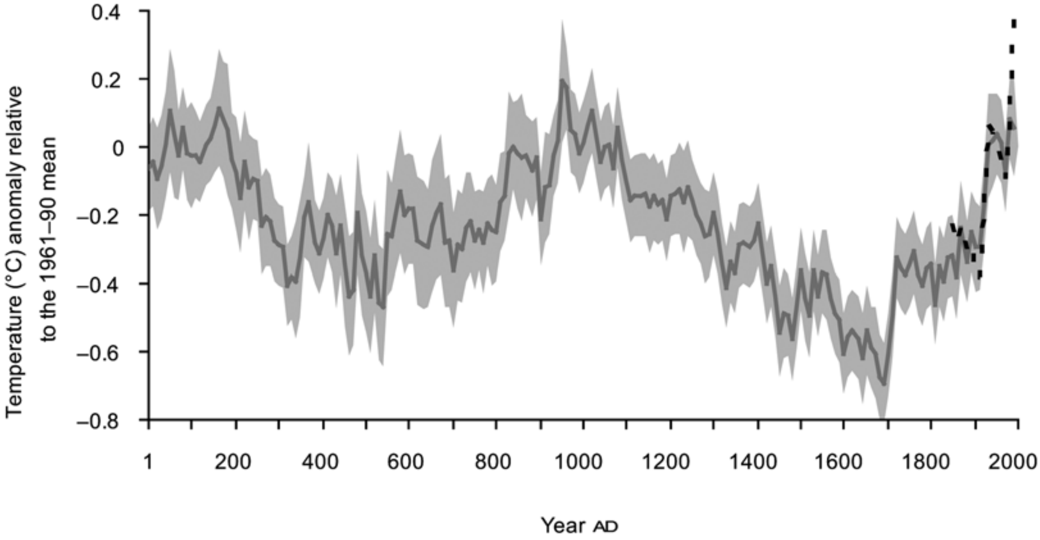

Fig. 3. Estimations of extra-tropical Northern Hemisphere (90–30°N) decadal mean temperature variations (dark grey line) AD 1–1999 relative to the 1961–1990 mean instrumental temperature from the variance adjusted CRUTEM3+HadSST2 90–30°N record (black dotted line showing decadal mean values AD 1850–1999) with 2 standard deviation error bars (light grey shading).

It is for several reasons likely that our reconstruction, together with most previous large-scale reconstructions, seriously underestimates the actual coldness of parts of the Little Ice Age (e.g. the seventeenth century) (Datsenko and Sonechkin 2008, 2009; von Storch *et al*. 2009). One circumstance that possibly has led to an underestimation of the true variability is that we must presuppose a linear response between temperature and proxy. If this response is nonlinear in nature, which is often likely the case, our interpretations necessarily become flawed. This is something that may result in an underestimation of the amplitude of the variability that falls outside the range of temperatures in the calibration period. The true amplitude of the pre-industrial temperature variability could also have been underestimated because of a bias towards summer temperatures among the proxies. If the magnitude of cooling during the Little Ice Age in the extra-tropical Northern Hemisphere was more pronounced during the colder seasons of the year, and the relationship between the seasons have not been stationary in time, our reconstruction of annual mean temperature underestimates the Little Ice Age cooling.

A major problem with many non-tree ring proxy records used in the reconstruction is their temporal uncertainty. For example, the marine sediments from the Bermuda Rise (Keigwin 1996) have an estimated dating uncertainty of ±160 years and the lake sediments from Lake Tsuolbmajavri (Korhola *et al*. 2000) of ±169 years. The dating uncertainty of proxy records very likely results in "flattening out" the values from the same climate event over several hundred years and thus in fact acts as a low-pass filter that makes us unable to capture the true magnitude of the cold and warm periods in the reconstruction (Loehle 2004). What we then actually get is an average of the temperature over one or two centuries.

Possible differences between various reconstructions can also arise from the use of certain scaling techniques and the choice of calibration time period. The variance and trend of the instrumental record during the calibration period is of significant relevance for the reconstructed temperature amplitude. The amplitude, for example, increases if sea surface data are excluded and decreases if warm season temperature data are used instead of annual data. Esper *et al*. (2005a) have shown that different scaling alone actually can result in changes in the temperature amplitude of up to *c*. 0.5°C in some cases.

A way to assess the low-frequency temperature variability, without the problems associated with calibration of proxy data to the relatively short instrumental temperature record, is to reconstruct the

Table 2. Centennial northern hemispheric mean temperatures relative to the AD 1000–1899 mean in large-scale quantitative temperature reconstructions reaching back to at least AD 500. Temperature values for the latter part of the twentieth century, usually not covered by the proxy reconstructions, are obtained from the variance adjusted CRUTEM3+HadSST2 record covering the same latitudes as the respective reconstruction. The amplitude of the temperature variability between the warmest and coldest century (prior to the twentieth century) is 0.62°C in our reconstruction, 0.22°C in Mann and Jones (2003), 0.58°C in Moberg *et al*. (2005), and 0.51°C in the 'error-in-variables' (EIV) regression method variant by Mann *et al*. (2008).

Century AD	This reconstruction	Mann and Jones (2003)	Moberg *et al*. (2005)	Mann *et al*. (2008)
1st	0.18	–	–0.03	–
2st	0.21	–	0.03	–
3rd	0.17	0.06	0.06	–
4th	0.11	0.02	–0.03	–
5th	0.15	0.00	–0.03	–
6th	0.15	0.01	–0.04	0.22
7th	0.14	0.03	0.03	0.18
8th	0.14	0.04	0.11	0.17
9th	0.19	0.12	0.12	0.27
10th	0.26	0.07	0.16	0.24
11th	0.29	0.10	0.31	0.32
12th	0.17	0.06	0.25	0.05
13th	0.10	0.01	0.06	0.13
14th	0.02	0.02	0.05	0.11
15th	–0.10	–0.03	0.00	–0.01
16th	–0.13	–0.05	–0.27	–0.14
17th	–0.17	–0.10	–0.25	–0.18
18th	–0.08	0.02	–0.12	–0.18
19th	–0.10	–0.04	–0.03	–0.10
20th	0.14	0.23	0.33	0.17

temperature history from composites of borehole measurements from the Earth's crust. Such reconstructions only show temperature variability on very long time-scales – centennial and longer – and the temporal resolution furthermore decreases back in time. They are, however, rather reliable on centennial time-scales for the last millennium and they indicate a considerably larger amplitude (*i.e.* magnitude of cooling during the Little Ice Age) of temperature variability – *c*. 0.8–1.2°C – for the Northern Hemisphere than most other large-scale proxy reconstructions (Shaopeng *et al*. 2000; Huang *et al*. 2000, 2008; Huang 2004). It is also possible to simulate such large low-frequency variability in the last millennium with some General Circulation Models and Energy Balance Models (von Storch *et al*. 2004). However, the reliability of the amplitude of temperature variability from borehole measurements is under discussion and has been called in question (González-Rouco *et al*. 2009).

An important object for further research must be to evaluate the true magnitude of cooling during the Little Ice Age and try to overcome the obstacles associated with this goal. One step towards doing so is to produce proxy records with smaller dating errors. At present, it is difficult to assess the true temperature amplitude due to limitations in the available proxy records and the limited knowledge of possible non-linear relationships between proxy and temperature over time. One approach would be to only use very accurately dated records with the highest correlation to temperature in the calibration period, but this would still leave us with all too few records for any reliable large-scale reconstruction.

We would like to briefly remark on the possible influence of variations in solar and volcanic forcing on the reconstructed temperatures. Little is known of the more high-frequency variance of solar and volcanic forcing before of *c*. AD 800, but our knowledge is more adequate regarding the past 12 centuries (Bard *et al*. 2000; Crowley *et al*. 2003; Mann *et al*. 2005). Our temperature reconstruction correlates reasonably well with the assumed low-frequency variability in solar forcing of the last millennium. During certain periods, especially the thirteenth century and the middle of the fifteenth century, our reconstruction also shows a significant correlation to volcanic forcing. Several of the periods with especially low solar activity are also visible in the reconstruction: the Wolf Minimum (*c*. AD 1280–1340), the Spörer Minimum (*c*. AD 1420–1530), and the Maunder Minimum (*c*. AD 1645–1715) (Eddy 1976). The Oort Minimum (*c*. AD

Table 3. The amplitude between the warmest and coldest decades respectively (prior to the twentieth century) in quantitative temperature reconstructions reaching back to at least AD 500.

	This reconstruction	Mann and Jones (2003)	Moberg *et al*. (2005)	Mann *et al*. (2008)
Warmest vs. coldest decade	0.89°C	0.35°C	1°C	1.02°C
Warmest decade	950–959	889–898	1104–1113	966–975
Coldest decade	1690–1699	1641–1650	1576–1585	1692–1701

1010–1050) and the Dalton Minimum (*c*. AD 1790–1820) are, on the other hand, not evident.

If a linear trend is superimposed on the reconstructed temperature pattern of the last two millennia, a small cooling trend of *c*. 0.2°C is visible, which likely represents the orbitally driven Neoglaciation. The reconstruction also shows manifestations of quasi-millennial climatic cycles – here represented by the Roman Warm Period, the Dark Age Cold Period, the Medieval Warm Period, the Little Ice Age and the twenthieth-century warming – that probably represent the much discussed quasi-cyclical *c*. 1470±500 Bond Cycles (Bond and Lotti 1995; O'Brien *et al*. 1995; Bond *et al*. 1997, 2001; Oppo 1997). Those oscillations were already in the early 1970s found to have affected both Scandinavia and northwest North America synchronically (Denton and Karlén 1973), but did not become firmly established until the 1990s and then primarily for the North Atlantic region. The Bond Cycles have, however, subsequently also been observed in China (Hong *et al*. 2009a, b), the mid-latitude North Pacific (Isono *et al*. 2009) and in North America (Viau *et al*. 2006), and have been shown to very likely have affected the whole Northern Hemisphere during the Holocene (Bütikofer 2007; Wanner *et al*. 2008; Wanner and Bütikofer 2008), or even been global (Mayewski *et al*. 2004). Whereas no known solar cycles operate on the same time-scale as the Bond Cycles, there are indications of similarities between those cycles and the long-term cycles in amount of cosmic ray flux (Franzén and Cropp 2007). Regardless of their cause, the occurrence of such quasi-cyclical oscillations indicates that substantial parts of the twentieth-century warming may be the result of natural climate variability, but the post-1990 warming in the instrumental record still seems to be outside the range of natural late-Holocene temperature variability.

Conclusions

Our new two-millennia long extra-tropical Northern Hemisphere (90–30°N) temperature reconstruction supports a distinct Medieval Warm Period and an even more distinct Little Ice Age, followed by a rapid twentieth-century warming. We also find a pronounced Roman Warm Period and support for the Dark Age Cold Period. Our reconstruction is actually the first to show a Roman Warm Period as warm on a hemispheric scale as the twentieth century. The amplitude of the reconstructed temperature variability on centennial time-scales exceeds 0.6°C and thus supports the conclusions of those previous reconstructions that have shown the largest low-frequency pre-industrial temperature variability. Substantial parts of the Roman Warm Period, from the first to the third centuries, and the Medieval Warm Period, from the ninth to the thirteenth centuries, seem to have equalled or exceeded the AD 1961–1990 mean temperature level in the extra-tropical Northern Hemisphere. Since AD 1990, though, average temperatures in the extra-tropical Northern Hemisphere exceed those of any other warm decades the last two millennia, even the peak of the Medieval Warm Period, if we look at the instrumental temperature data spliced to the proxy reconstruction. However, this sharp rise in temperature compared to the magnitude of warmth in previous warm periods should be cautiously interpreted since it is not visible in the proxy reconstruction itself.

Although partly different data and methods have been used in our reconstruction than in Moberg *et al*. (2005) and Mann *et al*. (2008), the result is surprisingly similar. The inclusion of additional records would probably not substantially change the overall picture of the temperature variability. The major uncertainty lies in the magnitude of cooling during the Little Ice Age. It is, for several reasons discussed earlier, quite likely that our reconstruction underestimates the actual cooling. This problem is probably partly connected to the fact that large dating uncertainties can 'flatten out' the temperature profile and decrease the amplitude. More accurately dated proxy records would be needed in order to solve this problem. Another difficulty, which possibly also contributes to an underestimate of variability, is the bias towards summer temperatures among the proxies, considering that the magnitude of cooling during the Little Ice Age in the extra-tropical Northern Hemisphere may have been more pronounced during the other seasons of the year.

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