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Extra-tropical Northern Hemisphere land temperature variability over the past 1000 years

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Abstract

The Northern Hemisphere (NH) temperature reconstruction published by Esper, Cook, and Schweingruber (ECS) in 2002 is revisited in order to strengthen and clarify its interpretation. This reconstruction, based on tree-ring data from 14 temperature-sensitive sites, is best interpreted as a land-only, extra-tropical expression of NH temperature variability. Its strongly expressed multi-centennial variability is highly robust over the AD 1200–1950 interval, with strongly expressed periods of "Little Ice Age" cooling indicated prior to AD 1900. Persistently above-average temperatures in the AD 960–1050 interval also suggest the large-scale occurrence of a "Medieval Warm Period" in the NH extra-tropics. However, declining site availability and low within-chronology tree-ring replication prior to AD 1200 weakens this interpretation considerably.

The temperature signal in the ECS reconstruction is shown to be restricted to periods longer than 20 years in duration. After re-calibration to take this property into account, annual temperatures up to AD 2000 over extra-tropical NH land areas have probably exceeded by about 0.3 °C the warmest previous interval over the past 1162 years. This estimate is based on comparing instrumental temperature data available up to AD 2000 with the reconstruction that ends in AD 1992 and does not take into account the mutual uncertainties in those data sets.

1. Introduction

A number of efforts have been made to reconstruct the Northern Hemisphere (NH) temperature variability over the past 1000 or more years using well-dated, high-resolution (mostly tree-ring) proxy records (e.g., Jones et al., 1998; Mann et al., 1999; Briffa, 2000; Crowley and Lowery, 2000; Briffa et al., 2001; Esper et al., 2002; Mann and Jones, 2003). Such long records are critically important in attribution studies that seek to determine the causes of the 20th century global warming (e.g., Jones et al., 1998; Crowley, 2000; Hegerl et al., 2003). See also IPCC (2001). Given the progress made to date, significant uncertainty still exists concerning the way in which NH temperatures have varied on multi-centennial time scales.

Briffa and Osborn (2002) highlighted this uncertainty in commentary associated with the publication of the somewhat controversial Esper et al. (2002) extra-tropical NH temperature reconstruction (hereafter referred to as ECS). They compared the ECS reconstruction with six other previously published NH temperature reconstructions (Overpeck et al., 1997; Jones et al., 1998; Mann et al., 1999; Briffa, 2000; Crowley and Lowery, 2000; Briffa et al., 2001). Each of the reconstructions was calibrated against the same observed land-only mean annual NH temperatures for the 20°–90°N latitude band and then smoothed with a 50-year low-pass filter. The result is shown in Fig. 1 (re-plotted from Briffa and Osborn, 2002), with the ECS reconstruction highlighted as the thick-black dashed curve. Over much of the past 1000 years, the expressed multi-centennial variability in the ECS reconstruction stands out from the others. This variability does not in general exceed the estimated uncertainty limits of other

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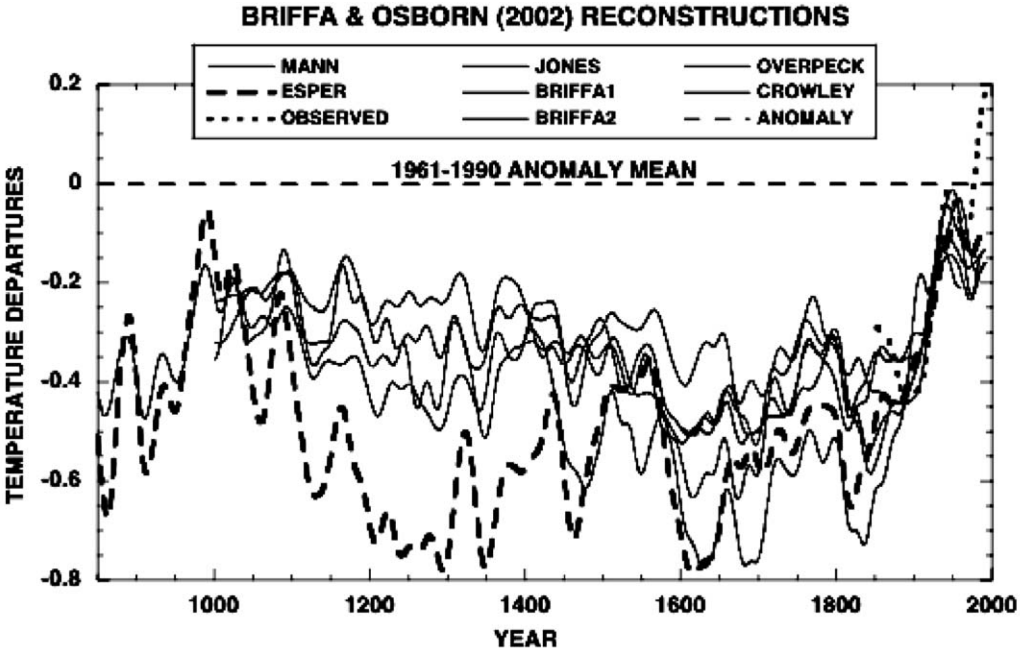

Fig. 1. Seven smoothed NH temperature reconstructions re-plotted from Briffa and Osborn (2002). All of the reconstructions have been re-calibrated identically with NH land-only mean annual temperatures north of 20°N and smoothed with the same 50-year low-pass filter. The ECS reconstruction is highlighted as a dashed curve to illustrate how it departs from the other NH temperature estimates.

large-scale temperature reconstructions (e.g., Fig. 1 in Mann et al., 2003), which suggests that there are few statistically meaningful differences between the NH reconstructions shown in Fig. 1. However, the amplified low-frequency variability in the ECS reconstruction does not appear to be random either. In this sense, it could also represent an emergent large-scale multi-centennial mode of NH temperature variability that is not well understood.

With this latter possibility in mind, we take this opportunity to clarify and tighten up the interpretation of the ECS reconstruction made somewhat incompletely in Esper et al. (2002), examine the robustness of its expressed multi-centennial variability, and address certain criticisms of it. It is also useful to first restate the origin of the Esper et al. (2002) study before proceeding, because the ECS reconstruction was in a sense a by-product of that paper's primary objective. Broecker (2001) argued that the apparent lack of a Medieval Warm Period (MWP) in the Mann et al. (1999) NH temperature reconstruction was due to the inability of long tree-ring records to preserve multi-centennial temperature variability. The Esper et al. (2002) paper sought to dispel that erroneous interpretation by demonstrating how tree-ring records from temperature-sensitive NH locations could preserve multi-centennial variability if the data were processed with that goal in mind. After showing how this could be done, Esper et al. (2002) then interpreted their extra-tropical NH tree-ring record as an alternative expression of past temperature variability that clearly differs in certain respects from the others shown in Fig. 1.

2. The ECS reconstruction and its interpretation

There are a number of possible reasons why the ECS extra-tropical NH temperature reconstruction differs as much as it does from the others shown in Fig. 1. Each expresses past temperature variability in somewhat different ways due to: (1) differences in the temperature proxies used and their NH locations; (2) differences in the properties of the temperature signals reflected in the proxies; (3) differences in the procedures used to develop the temperature proxies; and (4) differences in how the temperature reconstructions were created. We will address each of these issues with respect to how they relate to the ECS reconstruction, the robustness of its expressed low-frequency signal, and its overall interpretation.

2.1. What temperature proxies were used in the ECS reconstruction and where are they located?

As described in Esper et al. (2002), the ECS reconstruction is based on long, exactly dated, annual tree-ring chronologies from 14 sites in the NH (Fig. 2). The six longest tree-ring chronologies that all extend back to AD 831 are circled. The tree-ring sites are mostly located near the northern or upper-elevation

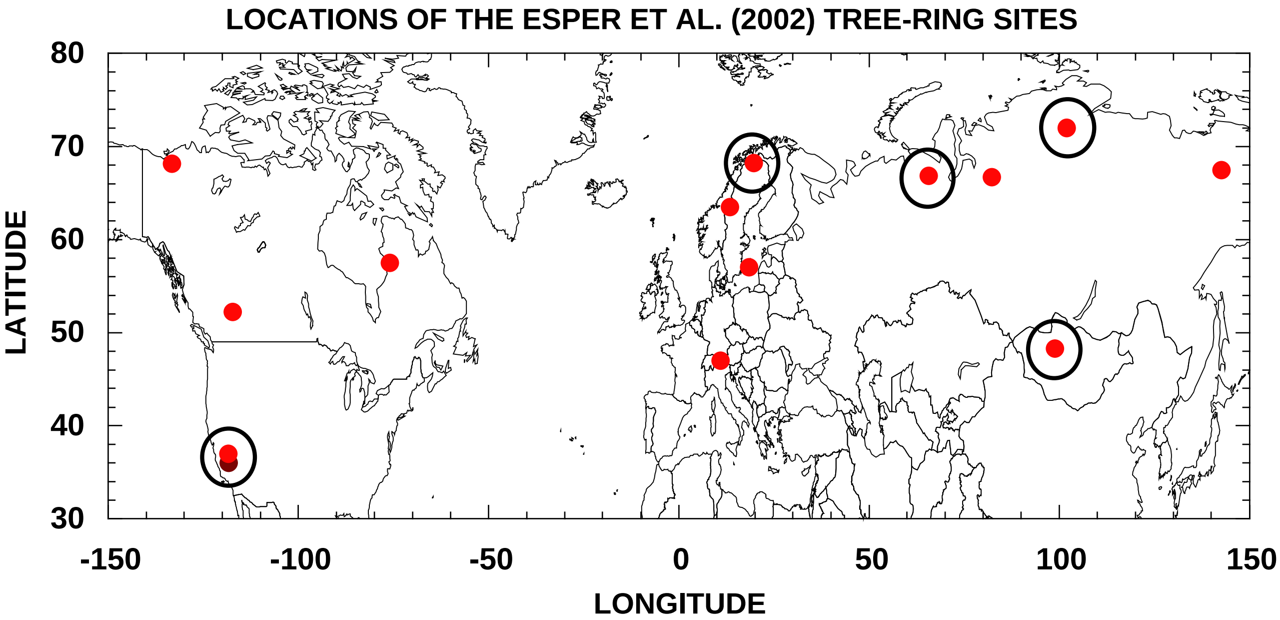

Fig. 2. Map of the Esper et al. (2002) tree-ring sites. Each solid red dot represents one of the 14 sites used. The six circled-sites are those that extend back to AD 831, the beginning of the ECS record.

limits of growth of the sampled tree species. At these locations, temperature variability commonly limits tree growth each year, and this annually changing limitation on growth is reflected in the radial ring-width variations of the tree. This has been shown to be the case for many site-level tree-ring reconstructions and inferred records of past temperatures covering the past millennium in the NH, e.g., northern Fennoscandia (Briffa et al., 1992), northern Polar Urals (Briffa et al., 1995), eastern Taimyr (Naurzbaev et al., 2002), Mongolia (D'Arrigo et al., 2001), and the Columbia Icefield in Alberta (Luckman et al., 1997). Significantly, of the 14 NH tree-ring sites used by Esper et al. (2002) in their study, tree-ring data from each of the five locations just referenced were also used in the ECS reconstruction. So, there is a significant amount of independent support for the expected temperature sensitivity of the tree-ring data at 35% of the sites used by Esper et al. (2002). The remaining sites have not been explicitly subjected to comparisons with local temperature data here and, indeed, some of the more xeric sites (e.g., in California; Lloyd, 1997) may have a mixed temperature/precipitation signal. However as stated earlier, their locations are broadly consistent with the kinds of tree-ring sites that are, from experience known to be sensitive to changing temperatures.

Note that the 14 sites in Fig. 1 are located in the 30–70°N latitude band. For this reason, Esper et al. (2002) also referred to their temperature reconstruction as *extra-tropical*. Interpretations of the ECS reconstruction must take this property into account. It is probably wise to tighten up this spatial interpretation even further. While it is arguable that some of the temperature information in the tree-ring chronologies extends beyond the continents to the oceans (e.g., Mann et al., 1999), the ECS site locations are almost certainly dominated by regional continentality effects, which would amplify their expressed low-frequency temperature signals over that in tree-ring chronologies from more ocean-dominated sites (e.g., western Tasmania; Cook et al., 2000). For this reason, the ECS reconstruction probably best reflects temperatures over *extra-tropical land areas* of the NH.

3. What temperature signals are in the ECS proxies?

The annual tree-ring chronologies used in the ECS reconstruction all derived from trees with constrained radial growth seasons that typically fall somewhere in the late-spring and summer months. This fact implies that the annual ring-width variations of the trees used in the ECS reconstruction (and in the other NH reconstructions as well) must only reflect warm-season temperatures. Although this would appear to be true, trees are physiologically active over a much broader time period than that associated with the radial growth season alone (Fritts, 1976). Consequently, temperatures outside of the radial growth season can affect longer-term tree growth processes such as foliage production/retention in evergreen conifers and fine root development (Jacoby et al., 1996). In addition, winter climate can have a preconditioning effect on subsequent growing season climate and tree growth through effects on land surface albedo, soil temperatures, and thawing of the root zone in the spring before radial growth commences. Finally, physiological preconditioning from the prior growth season is known to affect the potential for radial growth in the following year (Fritts, 1976). All this serves to broaden the temperature response window and make its interpretation in the ECS reconstruction more complicated and uncertain. Consequently, it is probably best described as a *warm-season-weighted* expression of temperature variability that includes information on temperatures outside of the summer radial growth season as well.

Even if we accept the admittedly nebulous *warm-season-weighted* temperature model in principle, would it have been possible to statistically differentiate it from a simple annual temperature average during the calibration phase of the ECS reconstruction? At the spatial scale that the ECS reconstruction represents and the temporal smoothing of the temperature signal contained within it, probably not. Land-only annual (January–December) and warm-season (April–September) temperatures for the 30–70°N latitude NH extra-tropics have a correlation of 0.87 over the period 1856–2000 without any smoothing and 0.93 after decadal smoothing (see also Esper et al., 2002 online Supplemental Data; http://www.sciencemag.org/cgi/content/full/295/5563/2250/DC1). Given these high correlations and the statistical uncertainty in the smoothed ECS tree-ring chronology used for reconstruction (see Fig. 3a), an annual temperature model is probably acceptably close to the ill-defined *warm-season-weighted* temperature model, even if the latter is closer to the truth in principle.

3.1. What procedure was used to develop the ECS temperature proxies?

With respect to the procedure used to develop the ECS temperature proxies, the annual tree-ring chronologies were all developed in a uniform way using the Regional Curve Standardization method (RCS; Briffa et al., 1992; Esper et al., 2003). The RCS method of detrending tries to preserve as much multi-centennial time-scale variability as possible in long tree-ring chronologies (Cook et al., 1995). The other NH temperature reconstructions shown in Fig. 1 have also used a variety of RCS tree-ring chronologies, including some used in the ECS reconstruction (e.g., Tornetrask and Polar Urals), but none pooled the site ring-width data together in the way that Esper et al. (2002) did.

In developing the ECS reconstruction, the ring-width data of the 14 sites were first pooled into two ring-width classes according to the shapes of their biological growth trends (non-linear and linear) that needed to be removed as part of the RCS procedure, with three sites mixing between the two trend classes (see Fig. 2 in the Esper et al., 2002 online Supplemental Data). This resulted in the initial development of two reasonably

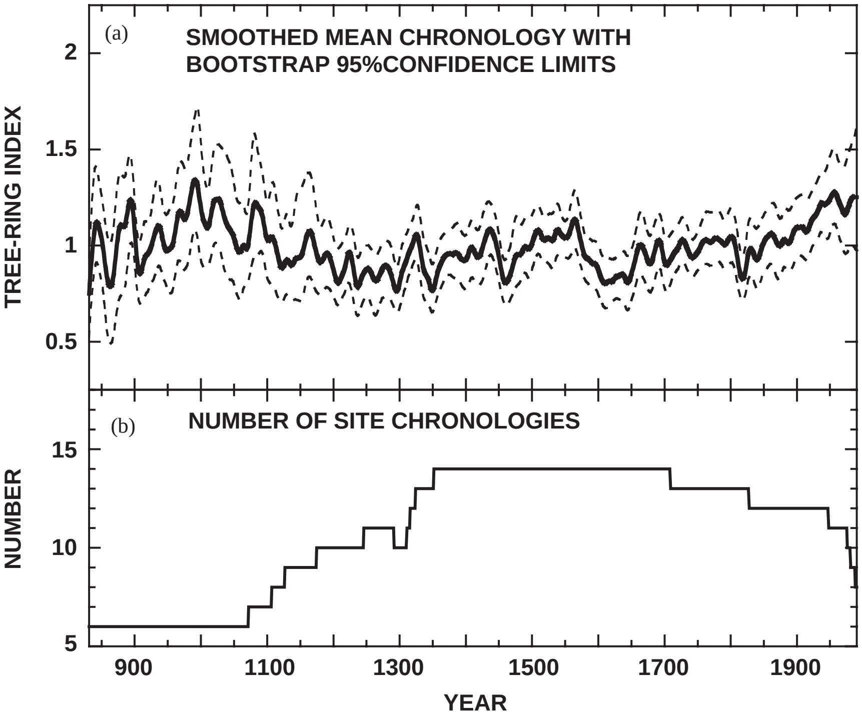

Fig. 3. The ECS mean tree-ring chronology (AD 831–1990) with bootstrap 95% confidence limits (a), all smoothed with a 20-year low-pass filter to highlight inter-decadal and longer fluctuations. The number of site chronologies available each year is shown in (b). They range from 6 to 14.

independent extra-tropical NH RCS tree-ring chronologies, each covering the period AD 831–1990. Over the AD 1200–1990 interval where site and series replication is relatively high in each growth trend class (see Figs. 2b and d in Esper et al., 2002), the two series are significantly correlated ($r = 0.523$; $p < 0.001$ corrected for lag-1 autocorrelation), and the correlation climbs to 0.732 after the series are smoothed with a 50-year low-pass filter. Before that time, the site and series replication decline in each trend class and the correlation between them correspondingly weakens: $r = 0.079$ before smoothing and 0.032 after smoothing.

While this breakdown could indicate a period of more spatially heterogeneous climate variability across the NH (Crowley and Lowery, 2000), a more likely cause is the decline of site and ring-width series replication prior to AD 1200. Further interpretation of this apparent breakdown is hampered by the fact that there is unequal pooled site replication in each trend-class chronology over time, which means that certain sites will dominate certain time periods (e.g., Mongolia, Tornetrask, and Polar Urals in the non-linear class and Taimyr and Upper Wright in the linear class for the AD 900–1100 interval; see Fig. 2 in the Esper et al., 2002 online Supplemental Data). To counteract this uneven weighting effect over time, the grand mean RCS chronology used by Esper et al. (2002) was based on the 14 site RCS chronologies, with each site weighted by the cosine of the latitude band it was located in (centered in either 30°–50°N or 50°–70°N) to provide more realistic regional weighting (again see the Esper et al., 2002 online Supplemental Data). Therefore, the loss of correlation between the non-linear and linear trend classes prior to AD 1200 may not be as severe when the site chronologies are used to calculate the grand mean RCS chronology. Regardless, the pre-1200 interval of the ECS reconstruction needs to be interpreted cautiously, a point that was illustrated by Esper et al. (2002) in their Fig. 2a that showed the linear and non-linear chronologies and their dissimilarities prior to AD 1200.

Fig. 3a shows the grand mean of the 14 RCS tree-ring chronologies for the AD 831–1990 interval with bootstrap 95% confidence limits, each smoothed with a 20-year low-pass filter, *after* the annual values were estimated. The smoothing highlights the inter-decadal and longer fluctuations that are of primary interest here. The number of chronologies available for each year is shown in Fig. 3b. It ranges from 6 to 14. This plot is very similar to the one shown in Fig. 2c in Esper et al. (2002), who regarded it as “compelling evidence” for large-scale low-frequency climate variability over the extra-tropical NH.

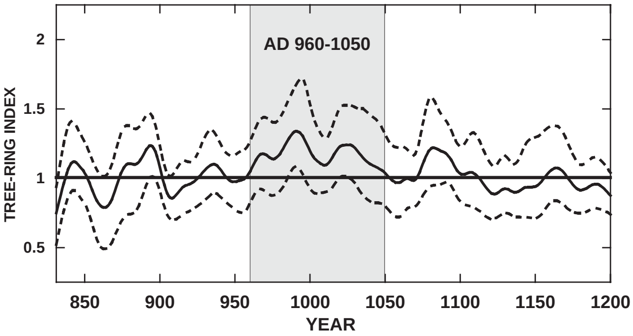

Fig. 4. The weakly replicated AD 831–1200 interval of the ECS mean chronology. The number of site chronologies available each year is shown in Fig. 3b. Note the persistent above-average period in the AD 960–1050 interval that hints at the existence of a spatially coherent temperature signal.

Fig. 4 zooms in on the weakly replicated AD 831–1200 interval for easier examination. The number of tree-ring sites available each year ranges from 6 to 10 out of the original total of 14 (see Fig. 3b). The AD 960–1050 interval highlighted in the shaded rectangle is persistently above average in this smoothed record, with two brief periods that also exceed the 95% confidence level. The sites represented are widely scattered, ranging from the western United States to northern Fennoscandia, the northern Polar Urals, the Taimyr Peninsula, and Mongolia (see Fig. 2). This result suggests the existence of a spatially coherent low-frequency signal among these six sites, which Esper et al. (2002) interpreted to be an expression of the MWP, hence their statement that it “supports the large-scale occurrence of the MWP over the NH extratropics”. This statement has been strongly criticized by R.S. Bradley (pers. comm.), and indeed it does not fit into the Euro-centric definition of “High Medieval” time (AD 1100–1200) used by both Lamb (1965) and Bradley et al. (2003) in their sensu strictu definition of the MWP. In contrast, the MWP sensu lato is regarded by some as having occurred between the 9th and 14th centuries (e.g., see http://www.ngdc.noaa.gov/paleo/globalwarming/medieval.html), but this is at best an educated guess.

The sensu lato definition of the MWP is more consistent with what the mean RCS chronology shows. However, its suggested 600-year duration also allows for a large range of global climate phenomena to be included, which may not be causally related to the MWP (Bradley et al., 2003). Thus, the MWP sensu lato is susceptible to a variant of “suck-in and smear” (Baillie, 1991), in which a broad time period assigned to an ill-defined climate epoch allows for unrelated climate anomalies to be sucked into it. We do not believe that this is necessarily the case for our mean RCS chronology because of its likely temperature dependency. On the other hand, its weak replication in the AD 831–1200 interval requires more cautious interpretation of MWP warming than that stated by Esper et al. (2002). Little more can be said about the likelihood of a MWP in the ECS data without improving the site chronologies used

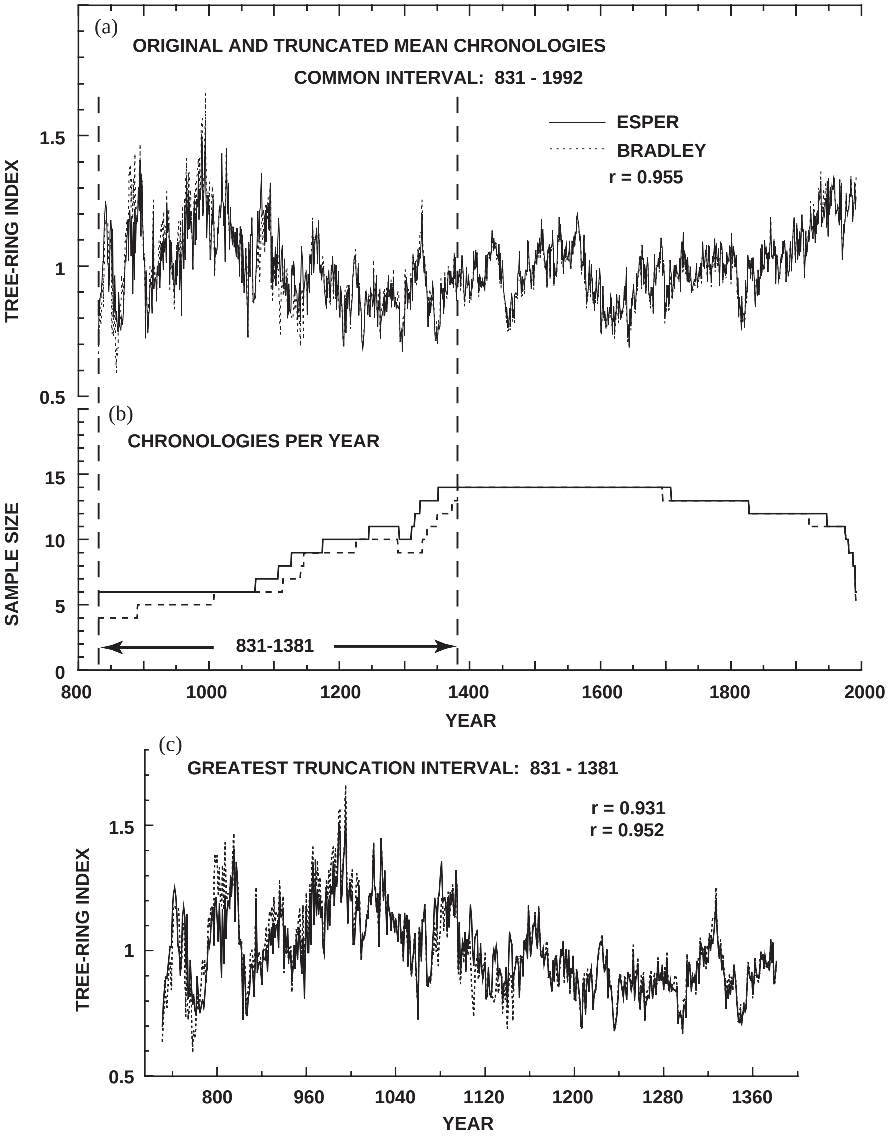

Fig. 5. Test of the effect of truncating weakly replicated portions of the chronologies used by Esper et al. (2002). Portions of chronologies with fewer than five measurements per years were deleted. This resulted in the loss of some chronology replication in the mean series, as indicated by the dashed line in the sample size plot (Fig. 3b). The two correlations in Fig. 3c are for unsmoothed and 40-year low-pass filtered data (in parentheses).

in this and other studies (e.g., better early replication and increased length in some cases) and, more so, in improving the spatial coverage of millennia-long temperature-sensitive tree-ring chronologies (Bradley et al., 2003).

The greater uncertainty of the pre-1200 interval and even the apparent expression of the MWP in the ECS reconstruction could also be related to low replication in the early portions of some of the tree-ring chronologies used (R.S. Bradley, pers. comm.). To investigate this possibility, we truncated the early portions of all chronologies with fewer than five ring-width measurements per year. This cutoff is admittedly somewhat arbitrary, but it serves as a useful demonstration nonetheless. Fig. 5 shows the chronologies before and after truncation over their full lengths (Fig. 5a) and the change in the number of chronologies per year (Fig. 5b). Most of the truncation occurs in the AD 831–1381 period which causes the number of chronologies to drop to as low as four. Yet, the correlation between the two RCS chronologies remains very high: $r = 0.955$ over the full AD 831–1992 length. Even when we compare only the AD 831–1381 period most affected by truncation (Fig. 5c), the correlation between the mean RCS records remains very high: $r = 0.931$ unfiltered and $r = 0.952$ after 40-year low-pass smoothing. These high correlations, even after losing some sites due to truncation, may be due to the fact that there is still a reasonably good degree of spatial representation in the truncated mean chronology (western United States, northern

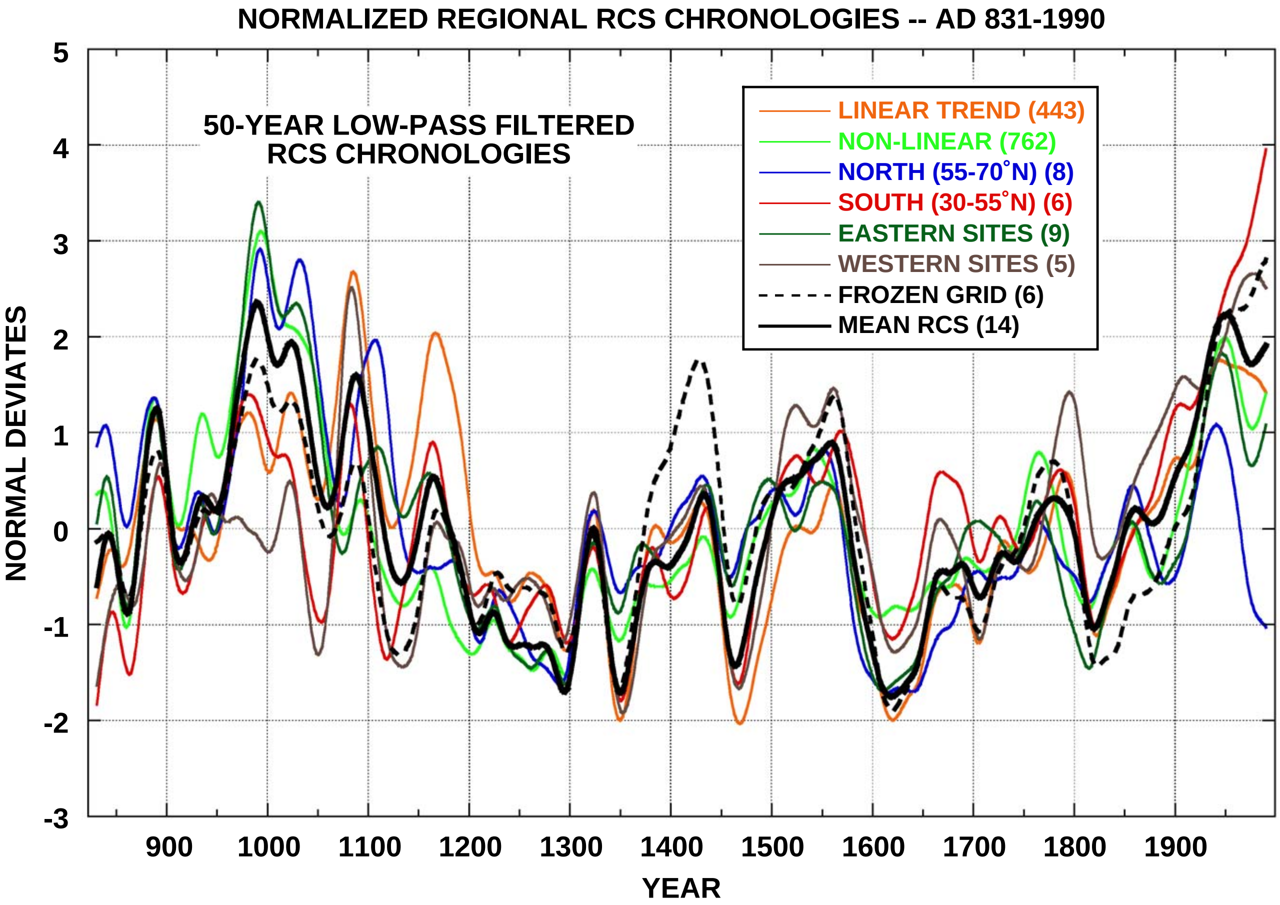

Fig. 6. Testing the regional robustness of the ECS tree-ring data. The "linear" and "non-linear" chronologies are the same as those shown in Esper et al. (2002). The other chronologies have been grouped by geographic location of the sites. The number of sites in each geographic group is provided in parentheses in the plot legend.

Fennoscandia, Taimyr Peninsula, Mongolia). Although the concern of R.S. Bradley (pers. comm.) was well justified, low chronology replication does not appear to have been responsible for creating the persistently above-average period in Fig. 4 that Esper et al. (2002) interpreted as an expression of the MWP sensu lato in their temperature reconstruction.

The robustness of the low-frequency land-only extra-tropical NH signal shown in Fig. 3a is further illustrated in Fig. 6. Besides the "linear" and "non-linear" groupings shown in Esper et al. (2002), the RCS-detrended data were grouped geographically into northern (55–70°N) and southern (30–55°N) bands, by eastern and western hemispheres, and as the mean of only the six longest chronologies (their locations circled in Fig. 2) extending back to AD 831. The latter is a form of "frozen grid" analysis (Jones et al., 1986; Duffy et al., 2001) that tests for the loss of fidelity when data during certain time periods are missing. These chronologies have all been smoothed with a 50-year low-pass filter and normalized to zero mean and unit variance.

Two points are worth making here. First, the low-frequency signal in the mean RCS chronology and the various subset chronologies is generally robust, particularly over the AD 1200–1950 interval. The average correlation between the mean RCS chronology and the subset chronologies is 0.82 for the full AD 831–1990 period and 0.87 for the AD 1200–1950 period. Prior to AD 1200, there is more separation between the subset chronologies, which is consistent with the significant decline in replication described earlier. After AD 1950, there is clear divergence, particularly between the "North" and "South" subset chronologies. This is probably an expression of the well-documented large-scale loss of growth sensitivity to climate in boreal forest conifers (Briffa et al., 1998a, b), a phenomenon that is not yet fully understood. The "South" chronologies may also show evidence of abnormally accelerated growth in the 20th century (Briffa et al., 1998a, b). So it appears that the data used by Esper et al. (2002) contain a geographically robust low-frequency signal over the period AD 1200–1950 that is almost certainly reflecting large-scale temperature forcing on tree growth. Prior to AD 1200, the evidence for robustness is again weakened by low replication and, perhaps, a period of greater regional climate variability.

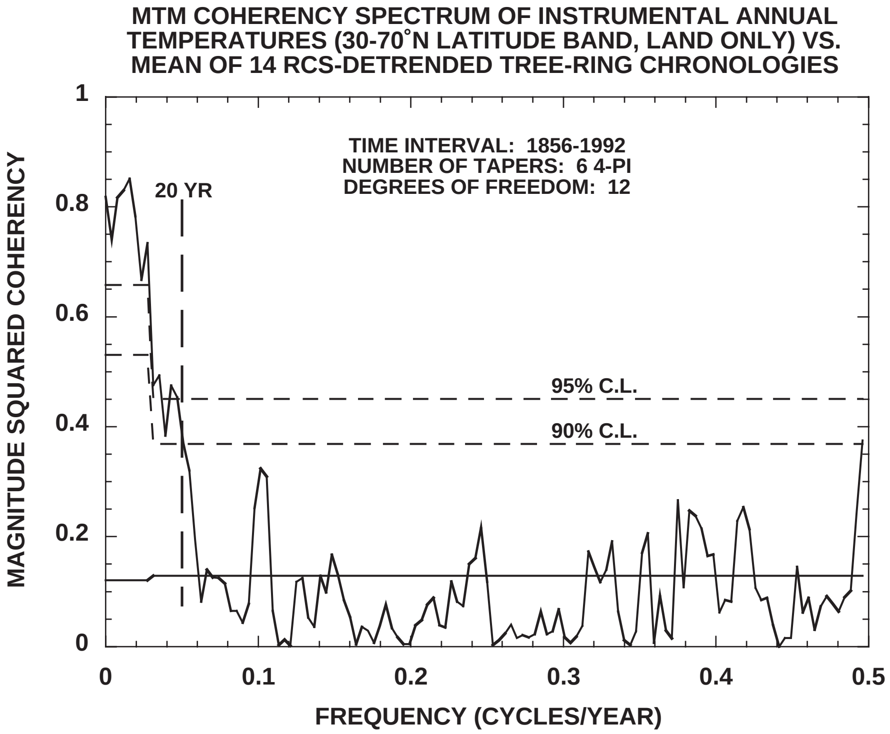

Fig. 7. The magnitude squared coherency spectrum between mean annual extra-tropical NH temperatures and the mean RCS chronology.

Second, the long-network chronology used for the "frozen grid" test correlates well with the mean RCS chronology ($r = 0.85$ over the full AD 831–1990 period and 0.82 over the AD 1200–1950 period). So overall the "frozen grid" chronology based on six sites captures most of the low-frequency variance found in the mean RCS chronology based on 14 sites. Nonetheless, some differences between the two are strongly apparent, especially around AD 1400. While it is tempting to use the "frozen grid" chronology alone as a useful expression of past land-only NH temperature variability, its geographic signal may be spatially biased at times by more geographically restricted effects. This argues again for caution in interpreting the pre-1200 period as a large-scale expression of the MWP and the need for additional long, spatially distributed, tree-ring records covering the past 1000 or more years.

4. How was the ECS temperature reconstruction created?

The ECS reconstruction differs from most of the others shown in Fig. 1 in that it is based on the grand mean of the 14 extra-tropical NH site chronologies *before* it was calibrated with instrumental temperature data. This is not necessarily the optimal way to reconstruct large-scale temperatures. However, the original point of the Esper et al. (2002) paper was to dispel the claim made by Broecker (2001) that long tree-ring series were largely incapable of reconstructing multi-centennial temperature variability. For this reason, the large-scale low-frequency features of tree growth were purposely emphasized in the Esper et al. (2002) paper at the expense of any higher-frequency local temperature signals in the individual site chronologies. Indeed, the way in which Esper et al. (2002) aggregated their data made it difficult, if not impossible, to reconstruct high-frequency temperature changes, which tend to be much more local compared to the multi-decadal and centennial changes (Jones et al., 1997).

To illustrate this point, Fig. 7 shows the magnitude squared coherency (MSC) spectrum between annual temperatures and the mean RCS tree-ring chronology for the common interval 1856–1992. The temperature data are "land-only" in the same 30–70°N latitude band as the tree-ring sites. This differs from the full NH annual average temperature series used by Esper et al. (2002), but that result would be very similar. In this case, the coherency spectrum clearly shows that the only useful temperature signal in the mean RCS chronology occurs at periods greater than 20 years in duration where the MSC exceeds the 90% confidence level. This result fits in nicely with our expectation.

Fig. 8 shows the mean RCS chronology, after 20-year low-pass filtering and calibration in terms of the similarly filtered land-only 30°–70°N annual temperature series used in the coherency spectrum analysis.

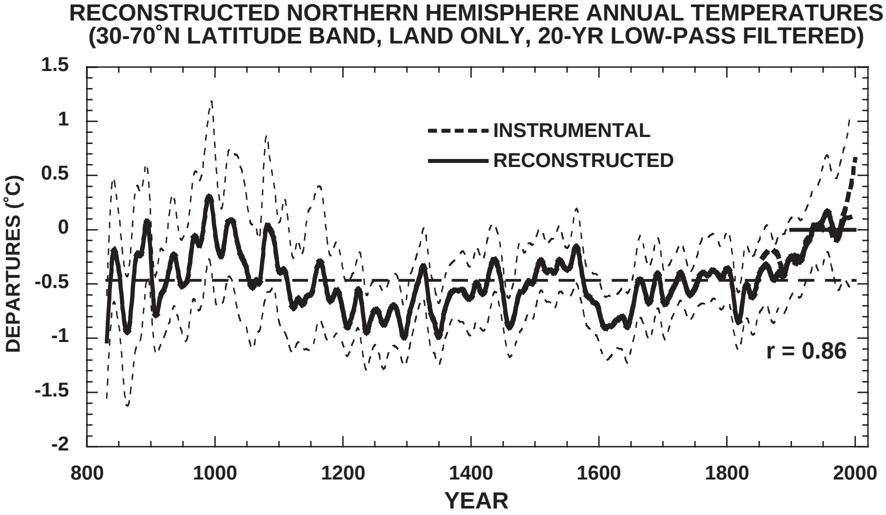

Fig. 8. The temperature-calibrated mean RCS tree-ring chronology, AD 831–1990 (thick solid curve). The thin dashed curves are bootstrap 95% confidence intervals, and the thick dashed curve represents the instrumental data up to 2000. The temperature values are anomalies from the full 20th century instrumental mean anomaly (1900–1999). The difference between the 20th century zero anomaly and the long-term anomaly mean (~0.47 °C) is indicated by the long-term mean (thick dashed horizontal line).

Calibrating on the 20-year low-pass filtered estimates makes sense from a signal processing perspective, a point also made by Osborn and Briffa (2000) and Timm et al. (2004) in their papers on timescale-dependent reconstruction of past climate from tree-ring chronologies. Over the 1856–1992 interval, the instrumental and proxy series have a correlation of 0.86, which based on the coherency spectrum results is statistically significant ($p < 0.05$). The reconstruction is expressed as temperature anomalies from the full 20th century mean of the instrumental record and covers the period AD 831–1992. The zero anomaly period contrasts with the mean anomaly of the entire record, with a difference of −0.47 °C. This difference is clearly related to reconstructed cool periods in the AD 1200–1850 interval that probably represents a large-scale expression of the Little Ice Age (LIA; Grove, 1988) and its various forcings over extra-tropical NH land areas.

The re-calibrated reconstruction in Fig. 8 is effectively the same as the ECS reconstruction shown in Fig. 1 because the same mean RCS chronology was linearly rescaled to temperatures in each case. The main difference is in how the scaling of tree growth in terms of temperature was done. This is a significant issue because it can strongly affect the amplitude of the resulting reconstruction. Briffa and Osborn (2002) performed all of their re-calibrations of the existing reconstructions using annually resolved data. They then low-passed filtered the re-calibrated reconstructions for comparison purposes. In so doing, differing amounts of variance were inevitably lost due to regression, which could explain some of the differences in the expressed amplitudes of the temperature reconstructions in Fig. 1. This procedure also reduced the amplitude of the ECS reconstruction compared to that published in Esper et al. (2002) because the latter was directly calibrated on 40-year low-pass filtered data, a frequency band with a better signal-to-noise ratio for estimating temperature. This property is illustrated in the MSC spectrum (Fig. 7), which shows that there is little useful temperature information in the mean RCS chronology at periods less than 20 years in duration. For this reason, we argue that the amplitude of the extra-tropical temperature reconstruction produced here, with its approximately 1 °C range over the past 1000 years, is a reasonable estimate of past temperature change within the uncertainty of the data and procedures that we are using here.

5. Other interpretational issues

The re-calibrated mean RCS tree-ring record probably represents the best reconstruction of past land-only, extra-tropical NH annual temperatures that is practical to extract from it at this time. Note that it does very well at tracking the instrumental data on inter-decadal and longer timescales up to about 1982, after which the tree-ring estimates systematically under-estimate the actual warming. This departure probably reflects the loss of climate sensitivity noted earlier in the ''North'' chronology shown in Fig. 6. Whether or not a similar loss of sensitivity has occurred in the past is unknown with any certainty, but no earlier periods of similar divergence are apparent between the ''North'' and the other regional chronologies. This result suggests that the large-scale loss of climate sensitivity documented by Briffa et al. (1998a, b) is unique to the 20th century, which argues

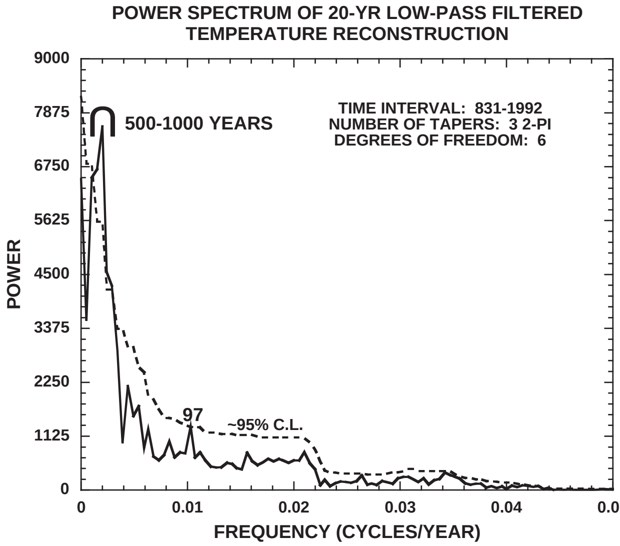

Fig. 9. The multi-taper power spectrum of the land-only, extra-tropical NH annual temperature reconstruction.

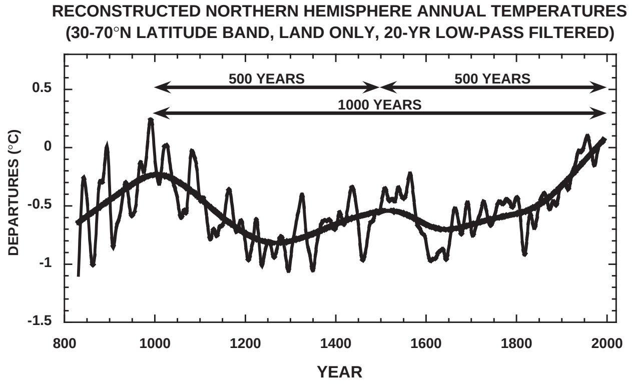

Fig. 10. The extra-tropical NH annual temperature reconstruction showing possible quasi-500 and 1000-year periods, which are visibly apparent in the series.

for an anthropogenic cause. After 1992, smoothed instrumental temperatures (up to 2000, our last available year of data, and scaled to reflect lost variance due to regression in the reconstruction) have increased rapidly and now exceed our warmest estimated past temperature epoch (ca AD 1000) by about 0.3 °C. This estimate is based on comparing instrumental temperature data available up to AD 2000 with the reconstruction that ends in AD 1992 and does not take into account the mutual uncertainties in those data sets.

Based on what we now show here, it appears that late-20th century land-only extra-tropical NH temperatures are warmer than at anytime over the past 1162 years. This conclusion is consistent with other evaluations of recent global warming and its cause(s) (e.g., Jones et al., 1998, 2001; Mann et al., 1999; Crowley, 2000; Mann and Jones, 2003). Even so, our proposed expression of the MWP, with all its caveats, appears to be a period of significant warmth as well. Esper et al. (2002) stated that the MWP in their reconstruction "approached, during certain intervals, the magnitude of 20th century warming at least up to AD 1990". Given the new results in this paper, that earlier statement requires some clarification and correction. Fig. 8 shows that 20th century temperatures since the early 1980s have exceeded those during our proposed expression of the MWP. The separation of the instrumental temperature record from our re-calibrated reconstruction is clearly evident only after 1984 however. Up to that date, the reconstructed warm epoch centered on AD 1000 (with its greater uncertainty) is comparable to that estimated for most of the 20th century. The subsequent divergence between the two records after 1984 up to 1990 may reflect the loss of climate sensitivity in some of the tree-ring records noted earlier. After 1990, the instrumental temperatures steadily increase to the point where they clearly exceed the peak warmth of the earlier warm epoch by about 0.3 °C. Therefore, our present results indicate that our estimate of MWP warming over extra-tropical NH land areas was comparable to that over most of the 20th century, but only up to the early 1980s as best as we can estimate here. Whether or not the MWP was a global phenomenon is still hotly debated (e.g., Hughes and Diaz, 1994; Bradley, 2000; Bradley et al., 2001; Broecker, 2001; Bradley et al., 2003). This question cannot be answered with any certainty either way because, as stated earlier, the global coverage of well-dated, high-resolution, millennial-length temperature proxies is still insufficient.

Given the stated uncertainties in the ECS reconstruction and its re-calibrated version shown in Fig. 8, it is still useful to examine the series in the frequency domain for evidence of band-limited multi-decadal/centennial variability. Fig. 9 shows the power spectrum of the temperature reconstruction shown in Fig. 8. This analysis is necessarily restricted to periods > 20 years in duration. The spectrum is clearly dominated by significant spectral power in the 500–1000 year band, with a slight indication of additional significant power at around 97 years. The source of this indicated 500–1000 year spectral power is indicated in Fig. 10. Of course, with only 1162 years of data, it is impossible to claim that the variability seen in this reconstruction is representative of longer-term NH temperature variability during the Holocene. At this time it must be viewed only as an estimate of multi-centennial temperature variability over extra-tropical NH land areas for the past 1,162 years. Whether or not this kind of behavior reflects an intrinsic mode of internally or externally forced variability also cannot be determined with any certainty at this time. Variability at similar time scales has been described for the North Atlantic by Bond et al.

(1997, 2001), and also by Chapman and Shackleton (2000). Therefore, it is possible that the suggested quasi-periodic behavior in the temperature reconstruction reflects a mode of long-term variability and forcing that has operated throughout the Holocene. There is, however, a reasonably strong association between certain cold epochs in the reconstruction (e.g., in the AD 1200s and 1600s; see Fig. 8) and explosive volcanism as well (M.E. Mann, pers. comm.). See Briffa et al. (1998c) and Zielinski (2000) for records of past explosive volcanism that support this interpretation, and Shindell et al. (2003) for modeling results that demonstrate the dynamical and radiative effects of volcanic forcing on NH temperatures. So this kind of episodic internal climate forcing must also be considered as an important potential contributor to the indicated multi-decadal variability in our land-only, extra-tropical NH temperature reconstruction.

6. Concluding remarks

The Esper et al. (2002) temperature reconstruction and the data used to develop it have been revisited in this paper in order to clarify and tighten up some of the interpretations made about it. We have argued that this reconstruction is best interpreted as an expression of land-only, extra-tropical NH temperature variability. It probably best reflects warm-season-weighted temperatures, but an annual temperature model can also be used as a reasonable approximation. In the process, we also examined the robustness of its expressed multi-centennial variability and addressed certain criticisms of it. Within the limits of the data and methods used in the original ECS paper, we have determined that the multi-centennial variability evident in the mean RCS chronology used for reconstruction is highly robust over the AD 1200–1950 interval. Prior to AD 1200, site and within-chronology replication weakens considerably, thus making the interpretation of that early period more tenuous. After 1950, a loss of climate sensitivity in the northern boreal zone of the Esper et al. (2002) network is also evident, which weakens the use of these data for climate interpretations.

The temperature signal in the mean RCS tree-ring chronology used by Esper et al. (2002) for reconstruction is largely restricted to periods longer than 20 years in duration. Consequently, the mean RCS chronology was re-calibrated after applying a 20-year low-pass filter to both it and the instrumental record. In so doing, it was determined that annual temperatures over extra-tropical NH land areas have now exceeded earlier reconstructed warm intervals by approximately 0.3 °C. There is also a strongly expressed LIA cooling in the reconstruction, which is the main cause of its separation from the other reconstructions shown in Fig. 1. The challenge now is to determine why this is so. Three likely candidates are: (1) differences in how the tree-ring chronologies were developed, (2) differences in the methods used to calibrate the tree-ring chronologies for temperature reconstruction, and (3) differences in the regional expressions of the temperature signals recorded in the tree-ring chronologies used for reconstruction. This detailed review and critique of how the ECS reconstruction was developed is a step in that direction.

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