A 2000-YEAR GLOBAL TEMPERATURE RECONSTRUCTION BASED ON NON-TREERING PROXIES

by

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A 2000-YEAR GLOBAL TEMPERATURE RECONSTRUCTION BASED ON NON-TREERING PROXIES

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ABSTRACT

Historical data provide a baseline for judging how anomalous recent temperature changes are and for assessing the degree to which organisms are likely to be adversely affected by current or future warming. Climate histories are commonly reconstructed from a variety of sources, including ice cores, tree rings, and sediment. Tree-ring data, being the most abundant for recent centuries, tend to dominate reconstructions. There are reasons to believe that tree ring data may not properly capture long-term climate changes. In this study, eighteen 2000-year-long series were obtained that were not based on tree ring data. Data in each series were smoothed with a 30-year running mean. All data were then converted to anomalies by subtracting the mean of each series from that series. The overall mean series was then computed by simple averaging. The mean time series shows quite coherent structure. The mean series shows the Medieval Warm Period (MWP) and Little Ice Age (LIA) quite clearly, with the MWP being approximately 0.3°C warmer than 20th century values at these eighteen sites.

Keywords: anthropogenic climate impacts, historical climate trends, hockey stick model, time series

INTRODUCTION

Historical data provide a baseline for judging how anomalous recent climate changes are and for assessing the degree to which organisms are likely to be adversely affected by current or future warming. Numerous regional to global climatic time series have been constructed (e.g., Crowley, 2000; Crowley and Lowery, 2000; Jones, 1998; Jones et al., 1999; Mann and Jones, 2003; Mann et al., 1995, 1998, 1999; Moberg et al., 2005; Overpeck et al., 1997; Viau et al., 2006). However, a number of questions have arisen about the validity of dendroclimatic methods when applied to periods greater than a few hundred years (see below). Data from numerous sites give the impression that the Medieval Warm Period (MWP) was a real climatic episode (see reviews in Loehle, 2006; Soon and Baliunas, 2003 and below), but reconstructions from tree-ring data do not show this episode very well. The purpose of this paper is to develop a 2000-year temperature reconstruction that is not based on tree-ring data in order to see whether the MWP and Little Ice Age (LIA) can be detected from these records.

Climate histories are commonly reconstructed from a variety of sources, including ice cores, tree rings, and sediment. There are reasons to believe that tree ring data may not capture long-term climate changes (100+ years) because tree size, root/shoot ratio, genetic adaptation to climate, and forest density can all shift in response to prolonged climate changes, among other reasons (Broecker, 2001; Falcon-Lang, 2005; Loehle, 2004; Moberg et al., 2005). Most seriously, typical reconstructions assume that tree ring width responds linearly to temperature, but trees can respond in an inverse parabolic manner to temperature, with ring width rising with temperature to some optimal level, and then decreasing with further temperature increases (D'Arrigo et al., 2004; Kelly et al., 1994). This response is most likely due to water limitation at higher temperatures, because higher temperatures increase evaporation rates. The result of this violation of linearity is to introduce tremendous uncertainty or bias into any reconstruction, particularly for temperatures outside the calibration range. For example, tree rings in many places show recent divergence from observed warming trends, even showing downward trends (Briffa et al., 1998a,b; Pisaric et al., 2007). In a recent circumpolar satellite survey covering 1982 to 2003 (Bunn and Goetz, 2006), it was found that tundra areas showed increased photosynthetic activity, but forested areas showing a change evinced decreased photosynthesis and this effect was greater where tree density was higher. This effect probably reflects moisture limitations. If the temperature remained at the present level, over time the forest would adjust its density to come into equilibrium with available water and this decreased growth effect would dissipate. Trees may also respond more to precipitation (e.g., Gedalof et al., 2004) than to temperature, respond to seasonal temperature and moisture shifts as well as to annual means, or shift their response from temperature to precipitation at different times. If climate is reconstructed from tree ring data, therefore, the response will primarily reflect noise, with the average response being flat, which will make it look like past climates have been stable. An additional problem with the use of tree ring data is that there is no agreed upon method for calibrating the tree series against temperature. Because in any given set of trees many will not track temperature very well, methods have been developed to pick the trees that "work best," but this leads to issues of subjectivity. Over the 20th century, CO_2 has increased in concert with temperature. Tree growth has been repeatedly shown to respond to CO_2 enrichment. This is particularly true for trees at high elevations where low atmospheric pressure makes CO_2 particularly limiting (Idso, 1989). Such trees are often used in tree ring studies because it is assumed that they are temperature limited. Using the 20th century as the calibration period for the growth ring vs. temperature transfer function thus potentially confounds temperature response and CO_2 enrichment response. It has been found that the assumption of independence of tree response to climate with age can be violated (Carrer and Urbinati, 2004; Szeicz and MacDonald, 1994). Until these and other issues are resolved, it is reasonable to ask whether a reconstruction without tree ring data might produce a different result than those produced in past studies. To date, only two long-term reconstructions have been published (low-frequency series of

Moberg et al., 2005; Viau et al., 2006) that do not incorporate tree ring data. Thus the present study may provide critical information that has been obscured by the difficulties inherent in interpreting tree ring data.

METHODS

Data were obtained for long series that had been previously calibrated and converted to temperature. No tree ring data were used. After an extensive search, all data were used that had at least 20 dates over the 2000-year period. The series used were: GRIP borehole ^{18}O temperature (Dahl-Jensen et al., 1998); Conroy Lake pollen (Gajewski, 1988); Chesapeake Bay Mg/Ca (Cronin et al., 2003); Sargasso Sea ^{18}O (Keigwin, 1996); Caribbean Sea ^{18}O (Nyberg et al., 2002); Lake Tsuolbmajavri diatoms (Korhola et al., 2000); Shihua Cave layer thickness (Tan et al., 2003); China composite (Yang et al., 2002) which does use tree ring width for two out of the eight series that are averaged to get the composite, or 1.4% of the total data input to the mean computed below; speleothem data from a South African cave (Holmgren et al., 1999); SST variations (warm season) off West Africa (deMenocal et al., 2000); SST from the southeast Atlantic (Farmer et al., 2005); SST reconstruction in the Norwegian Sea (Calvo et al., 2002); SST from two cores in the western tropical Pacific (Stott et al., 2004); mean temperature for North America based on pollen profiles (Viau et al., 2006); a phenology-based reconstruction from China (Ge et al., 2003); annual mean SST for northern Pacific site SSDP-102 (Latitude 34.9530, Longitude 128.8810) from Kim et al. (2004); and Spannagel Cave (Central Alps) stalagmite oxygen isotope data (Mangini et al., 2005). This gave a total of eighteen series with quite wide geographic coverage (including tropical) and based on multiple proxies. Many other series could not be used because they had too few dates within the 2000-year span or were not calibrated to temperature. In a few cases, data that were appropriate could not be obtained from authors. None of these types of data have the temperature calibration problems inherent in tree rings. Whatever temperature calibration issues exist with these proxies are not common across the different proxies.

Data in each series had different degrees of temporal coverage. For example, the pollen-based reconstruction of Viau et al. (2006) has data at 100-year intervals. Other sites had data at irregular intervals. This data was taken as is without interpolation.

Data in each series were smoothed with a 30-year running mean. This should help remove noise due to dating and temperature estimation error. If data occurred every 100 years, each point would be stretched by the smoothing to cover 30 years. All data were then converted to anomalies by subtracting the mean of each series from that series. This was done instead of using a standardization date such as 1970 because series date intervals did not all line up or all extend to the same ending date. With only a single date over many decades and estimation error, a short interval for determining a zero date for anomaly calculations is not valid. The mean of the eighteen anomaly series was then computed for the period 1 to 1995 AD (smoothed values for 16 to 1980 AD), since most series had complete records for this interval. When missing values were encountered, means were computed for the sites having data. Note that the values do <u>not</u> represent annual values but rather are based on running means.

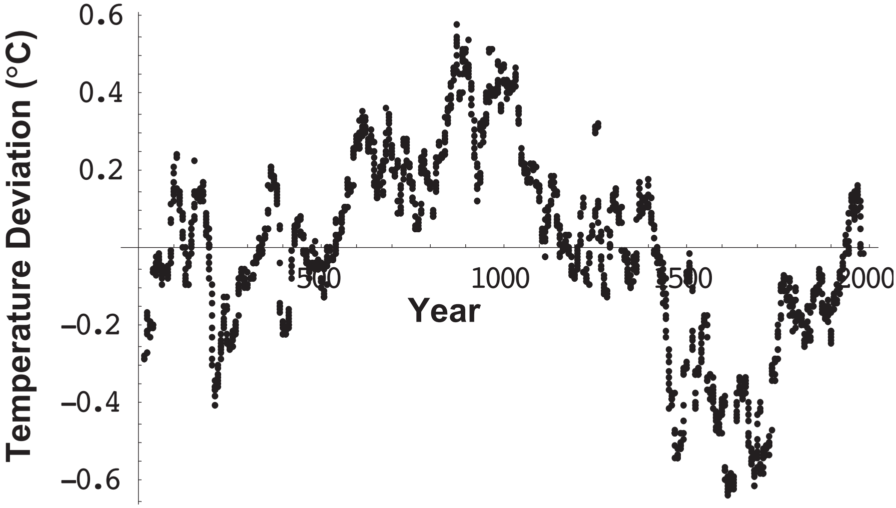

Figure 1. Mean of temperature data for 18 series.
Data archived at http://www.ncasi.org/programs/areas/climate/LoehleE&E2007.csv

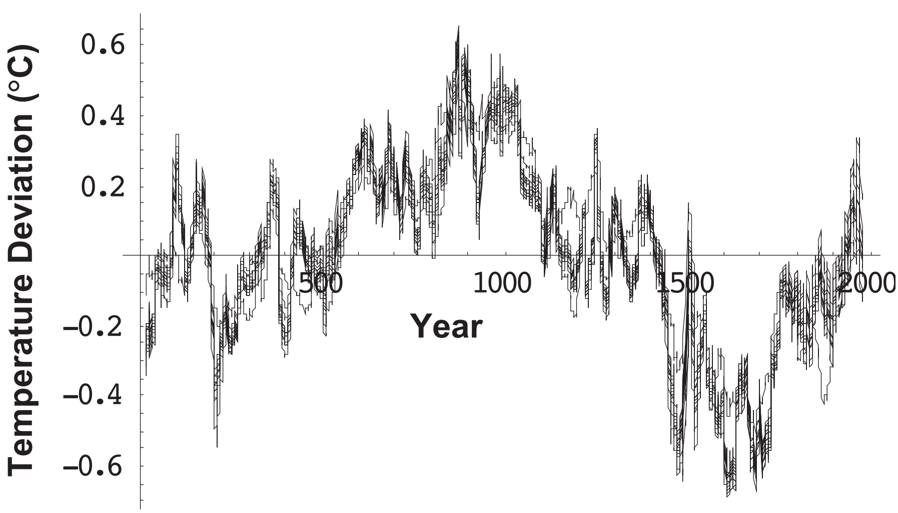

Figure 2. Sensitivity of result to individual series. Individual series were dropped and the mean recomputed, creating 18 mean series with 17 records in each, shown overlaid.

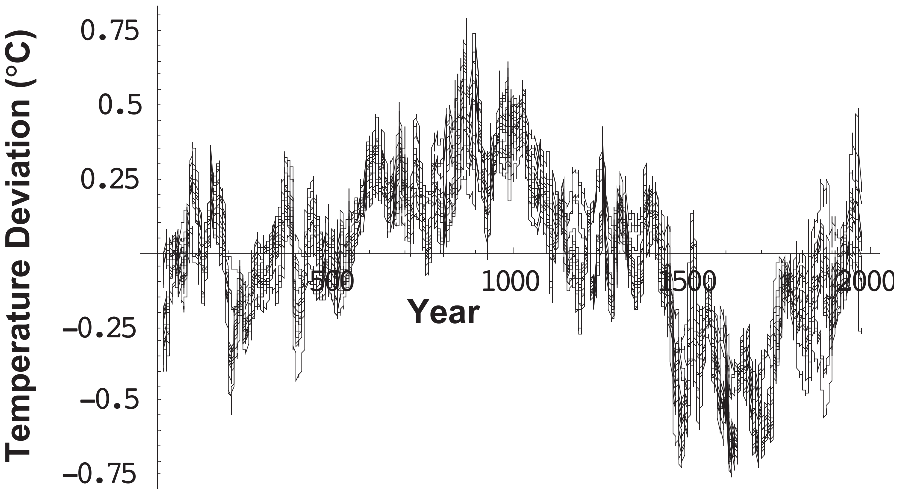

Figure 3. Random selection of 14 data sets at a time without duplicates, repeated 18 times, then overlaid, showing robustness of the pattern.

RESULTS

The time series produced by the simple mean of smoothed deviations (Fig. 1) shows quite coherent peaks. Note that the use of smoothed data (30-year running mean) means that peaks and troughs are damped compared to annual data (Loehle, 2005). Some of the input data were also integrated values or sampled at wide intervals. Thus it is not possible to compare recent annual data to this figure to ask about anomalous years or decades. The data show the Medieval Warm Period (MWP) and Little Ice Age (LIA) quite clearly. The series ends with a downtick because the last set of points are averages that include the cool decades of the 1960s and 1970s.

A test of sensitivity to individual series was performed. Individual series were dropped and the mean recomputed, with all other steps the same. These eighteen series plotted in overlay (Fig. 2) show the same pattern as the original (Fig. 1). This plot demonstrates that no single series has undue influence on the result. Random subsets of fourteen series were constructed and still show the same basic pattern (Fig. 3). Weighting the China composite or the North American pollen reconstruction more heavily also altered only details of the reconstruction. These results indicate that the reconstruction is robust to details of the series employed.

DISCUSSION

The results of this study are relevant to the question of whether the MWP and LIA were real or not. Many prior studies have shown these two historic episodes to have been real and global (see Loehle, 2006; Soon and Baliunas, 2003 and below), although this result is contested (e.g., Crowley and Lowery, 2000). The MWP and LIA show up clearly in the reconstructions of Moberg et al. (2005) and Viau et al. (2006), which are the only reconstructions of which I am aware on this timescale that do not utilize tree ring data. Broecker (2001) argues that this was a globally warm interval, a conclusion supported by deMenocal et al. (2000) and Soon and Baliunas (2003). In the present study, only three or four of the sites are from Europe, so it cannot be argued that the MWP was strictly a European phenomenon. Other studies also show the MWP (Little Climatic Optimum) in Europe (Lamb, 1965; Martinez-Cortizas et al., 1999; Shindell et al., 2001), Greenland (Dahl-Jensen et al., 1998), Africa (deMenocal et al., 2000; Holmgren et al., 2001), North America (Campbell et al., 1998; Li et al., 2000; Petersen, 1994; Shabalova and Weber, 1999), South America (Iriondo et al., 1993; Villabala, 1994), and Asia (Hong et al., 2000; Liu et al., 1998). As evidence against its existence, it has been argued that warm periods identified as the MWP in different data sets and regions of the world do not correspond in time (e.g., Bradley et al., 2003). If we consider dating error, it should not be surprising that the peak temperature dates don't line up. Assuming a valid and perfectly clear peak, dating error should spread out the peaks found in various localities (Loehle, 2005). For a standard deviation of 100 years (based on ^{14}C laboratory error), a sample of fifty series of a 500-year cycle with date and temperature estimated every 10 years for 500 years give a range of 260 years between the earliest and latest estimated peak. Geologic data can easily have a larger dating error. In addition, there is some evidence here for a double peak which would make it even less likely that samples in different regions would show the same date as the peak year. Further, regional variation and laboratory error in sample processing will cause the exact timing of local temperature peaks to differ.

It is clear that the 1995-year reconstruction shown here does not match the famous hockey stick shape (Crowley, 2000; Crowley and Lowery, 2000; Jones, 1998; Jones et al., 1999; Mann and Jones, 2003; Mann et al., 1995, 1998, 1999; Overpeck et al., 1997). I believe that this results from how time series are treated. If different series have different biases in absolute temperature and different regional responses (e.g., El Niño), and they are not shifted by their own mean values, the result will be extreme data variance, out of which no signal can be detected. Shifting time series based on some reference decade such as the 1970s (as is commonly done) implicitly assumes that a decade long interval is sufficient to properly line up series with different scales of fluctuation and different noise structures, an assumption that is not tested and which I do not believe is valid. I also believe that tree ring data will tend to show a flattened pattern because on long time scales trees are responding more to precipitation than to temperature, and for other reasons noted above. When these two mistakes are made (data alignment for anomaly calculations and the use of tree rings), and multiple series are combined to create some regional to global series, the result is simply noise, which gives a potentially false impression that there is no fluctuation or periodicity in the data. The approach to data normalization taken in this study is transparent and simple.

One persistent question is whether the MWP was "really" warmer than the end of the 20th century. Even keeping in mind that Figure 1 shows 30-year running means, it would indeed seem to show the MWP to be warmer than the late 20th century. The eighteen series used here show a mean difference of about 0.3°C between the MWP and the 20th century (range of 0 to 0.6°C difference over the periods). It must be emphasized, of course, that this result is based on limited data.

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ABSTRACT
A climatic reconstruction published in E&E (Loehle, 2007) is here corrected for various errors and data issues, with little change in the results. Standard errors and 95% confidence intervals are added. The Medieval Warming Period (MWP) was significantly warmer than the bimillennial average during most of the period 820 – 1040 AD. The Little Ice Age was significantly cooler than the average during most of 1440 – 1740 AD. The warmest tridecade of the MWP was warmer than the most recent tridecade, but not significantly so.

Keywords: anthropogenic climate impacts, historical climate trends, Medieval Warming Period, Little Ice Age, hockey stick model, time series

INTRODUCTION

Historical data provide a baseline for judging how anomalous recent climate changes are and for assessing the degree to which organisms are likely to be adversely affected by current or future warming. A recent reconstruction (Loehle, 2007) used data that largely excluded tree ring records to investigate the possible effect of proxy type on reconstruction outcome. Several errors in data handling in that report have come to light, leading to the need for this report, which corrects these errors. In addition, confidence intervals are now computed for more robust evaluation of the results.

METHODS

Loehle (2007) obtained data for long series that had been previously calibrated and converted to temperature by their respective authors. Essentially no tree ring data were used. After an extensive search, all data were used that had at least 20 dates over the 2000-year period. The series used were: GRIP borehole temperature (Dahl-Jensen et al., 1998); Conroy Lake pollen (Gajewski, 1988); Chesapeake Bay Mg/Ca (Cronin et al., 2003); Sargasso Sea ^{18}O (Keigwin, 1996); Caribbean Sea ^{18}O (Nyberg et al., 2002); Lake Tsuolbmajavri diatoms (Korhola et al., 2000); Shihua Cave layer thickness (Tan et al., 2003); China composite (Yang et al., 2002) which does use tree ring width for two out of the eight series that are averaged to get the composite, or 1.4% of the total data input to the mean computed below; speleothem data from a South African cave (Holmgren et al., 1999); SST variations (warm season) off West Africa (deMenocal et al., 2000); SST from the southeast Atlantic (Farmer et al., 2005); SST reconstruction in the Norwegian Sea (Calvo et al., 2002); SST from two cores in the western tropical Pacific (Stott et al., 2004); mean temperature for North America based on pollen profiles (Viau et al., 2006); a phenology-based reconstruction from China (Ge et al., 2003); annual mean SST for northern Pacific site SSDP-102 (Latitude 34.9530, Longitude 128.8810) from Kim et al. (2004); and Spannagel Cave (Central Alps) stalagmite oxygen isotope data (Mangini et al., 2005). This gave a total of eighteen series (Fig. 1) with quite wide geographic coverage (including tropical) and based on multiple proxies. Many other series could not be used because they had too few dates within the 2000-year span or were not calibrated to temperature. In a few cases, data that were appropriate could not be obtained from authors. Whatever temperature calibration issues exist with these proxies are not common across the different proxies. The locations of the 18 series used are shown in Figure 1.

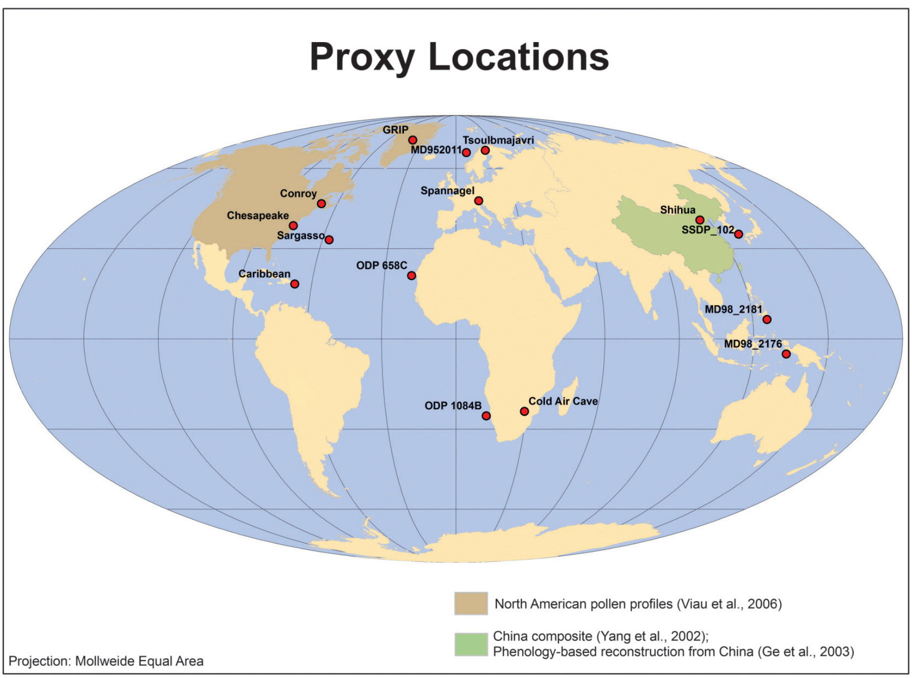

Figure 1. Map of study sites. Thanks to Mike Martin.

Four of the series (Calvo et al. 2002, deMenocal et al. 2000, Farmer et al. 2005, and Kim et al. 2004) were assumed by Loehle (2007) to be reported in ages relative to 2000, but in fact were implicitly relative to 1950. The previous study also used the proxy data column in Farmer et al. (2005) rather than the temperature column. Both these errors are corrected in the present note.

In addition, the present note treats the 18 series on a more uniform basis than in the original study. Data in each series have different degrees of temporal coverage. For example, the pollen-based reconstruction of Viau et al. (2006) has data at 100-year intervals, which is now assumed to represent 100 year intervals (rather than points, as in Loehle, 2007). Other sites had data at irregular intervals. This data is now interpolated to put all data on the same annual basis. In Loehle (2007), interpolation was not done, but some of the data had already been interpolated before they were obtained, making the data coverage inconsistent. In order to use data with non-annual coverage, some type of interpolation is necessary, especially when the different series do not line up in dating. This interpolation introduces some unknown error into the reconstruction but is incapable of falsely generating the major patterns seen in the results below. An updated version of the Holmgren data was obtained. Data on duplicate dates were averaged in a few of the series.

Data in each series (except Viau, because it already represents a known time interval) were smoothed with a 29-year running centered mean (previously called a 30 year running mean). This smoothing serves to emphasize long term climate patterns instead of short term variability. All data were then converted to anomalies by subtracting the mean of each series from that series. This was done instead of using a standardization date such as 1970 because series date intervals did not all line up or all extend to the same ending date. With only a single date over many decades and dating error, a short interval for determining a zero date for anomaly calculations is not valid. The mean of the eighteen anomaly series was then computed for the period 16 AD to 1980 AD. When missing values were encountered, means were computed for the sites having data. Note that the values do <u>not</u> represent annual values but rather are based on running means.

COMPUTATION OF CONFIDENCE INTERVALS

Standard errors and confidence intervals are somewhat complicated by the presence of cross-sectional heteroskedasticity (unequal variances) in the data. The variance about the global mean temperature of Calvo et al. (2002), for example, is almost 7 times as great as that of Viau et al. (2006). Because of this heteroskedasticity, conventional pointwise variance estimates will not have their customary χ^2 distribution, and hence the Student t distribution (see e.g. Casella and Berger 2002) will not provide accurate critical values to form confidence intervals.

It is assumed here that

$$X_{jt} = \mu_t + \varepsilon_{jt},$$

where X_{jt} is the temperature reconstruction from proxy j at time t and μ_t is global mean temperature at time t. The errors ε_{jt} are assumed to be normally distributed with mean 0 and proxy-specific variance V_j and to be independent across proxies at each point in time. As in Loehle (2007), μ_t is estimated by the simple mean

$$m_t = \frac{1}{n_t} \sum_j X_{jt},$$

where the sum is taken over the n_t proxies that are active at time t (n_t = 18 for most dates). The variance of m_t is therefore

$$Var(m_t) = \frac{1}{n_t^2} \sum_j V_j,$$

where again the sum is taken over the n_t proxies that are active at time t.

The proxy-specific variances V_j may be estimated over the time-series dimension, with a conservative adjustment for degrees of freedom, by

$$\hat{V}_j = \frac{1}{N_j} \sum_t \frac{n_t (X_{tj} - m_j)^2}{n_t - 1},$$

where the sum is now over the N_j dates for which proxy j is active. The heteroskedasticity-adjusted standard error of m_t is then

$$s_t = \frac{1}{n_t} \left(\sum_j \hat{V}_j \right)^{1/2},$$

again taking the sum only over the n_t proxies that are active at time t.

During 148 – 1425 AD all 18 proxies are active and s_t is constant at 0.136 °C. The standard errors increase gradually as proxies drop out, rising to 0.178 °C in 1935 when only 11 proxies are still active. Although the V_j are estimated with almost 2000 points in time, the 29-year running mean implies that effectively at most only about 60 of these are independent. Assuming approximately 60 degrees of freedom, the 95% confidence intervals in Figure 2 extend 2.00s_t above and below m_t.

The maintained assumption of cross-sectional independence of the errors is not unreasonable with the present data set, given the good geographical distribution of the proxies used. In studies with a substantially denser network of proxies, however, cross-sectional correlation would eventually become an important consideration.

RESULTS

The corrected point estimates of global temperature anomalies produced by taking the mean of the smoothed deviations are shown in Figure 2, together with 95% confidence

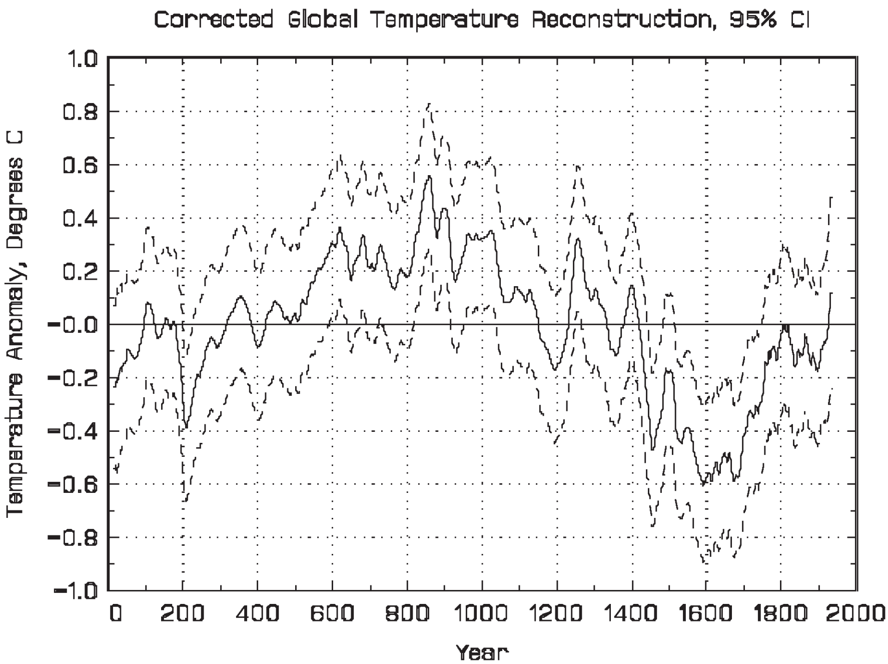

Figure 2. Corrected reconstruction with 95% confidence intervals.

Data for this graph is online at <http://www.econ.ohio-state.edu/jhm/AGW/Loehle/>

intervals. With the corrected dating, the number of series for which data is available drops from 11 to 8 in 1935, so that subsequent values of the reconstruction would be based on less than half the total number of series, and hence would have greatly decreased accuracy. Accordingly, the corrected estimates only run from 16 AD to 1935 AD, rather than to 1980 as in Loehle (2007).

The corrected estimates are very similar to the original results, showing quite coherent peaks. Note that the use of smoothed data (29-year running mean) and the existence of dating error in the series means that peaks and troughs are damped compared to annual data and are likely even damped compared to the true history (Loehle, 2005). Some of the input data were also integrated values or sampled at wide intervals. Thus it is not possible to compare recent annual data to this figure to ask about anomalous years or decades.

The corrected data continue to show the Medieval Warm Period (MWP) and Little Ice Age (LIA) quite clearly. The confidence intervals in Figure 2 indicate that the MWP was significantly warmer than the bimillennial average during most of approximately 820 – 1040 AD, at the 5% level (2-tailed). Likewise, the LIA was significantly cooler than the bimillennial average during most of approximately 1440-1740 AD.

The peak value of the MWP is 0.526 Deg C above the mean over the period (again as a 29 year mean, not annual, value). This is 0.412 Deg C above the last reported value at 1935 (which includes data through 1949) of 0.114 Deg C. The standard error of the difference is 0.224 Deg C, so that the difference is significantly non-zero at the 10% level (t = 1.84). While instrumental data are not strictly comparable, the rise in 29 year-smoothed global data from NASA GISS (http://data.giss.nasa.gov/gistemp) from 1935 to 1992 (with data from 1978 to 2006) is 0.34 Deg C. Even adding this rise to the 1935 reconstructed value, the MWP peak remains 0.07 Deg C above the end of the 20th Century values, though the difference is not significant.

The main significance of the results here is not the details of every wiggle, which are probably not reliable, but the overall picture of the 2000 year pattern showing the MWP and LIA timing and curve shapes. Future studies need to acquire more and better data to refine this picture.

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