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The extra-tropical NH temperature in the last two millennia: reconstructions of low-frequency variability

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Abstract

We present two new multi-proxy reconstructions of the extra-tropical Northern Hemisphere (30–90° N) mean temperature: a two-millennia long reconstruction reaching back to AD 1 based on 32 proxies and a 500-yr long reconstruction reaching back to AD 1500 based on 91 proxies. The proxies are of different types and of different resolutions (annual, annual-to-decadal, and decadal) but all have previously been shown to relate to local or regional temperature. We use a reconstruction method, LOC, that recently has been shown to confidently reproduce low-frequency variability. Confidence intervals are obtained by an ensemble pseudo-proxy method that both estimates the variance and the bias of the reconstructions. The two-millennia long reconstruction shows a well defined Medieval Warm Period with a peak warming ca. AD 950–1050 reaching 0.7 °C relative to the reference period AD 1880–1960. The 500-yr long reconstruction confirms previous results obtained with the LOC method applied to a smaller proxy compilation; in particular it shows the Little Ice Age cumulating in AD 1580–1720 with a temperature minimum of –1.1 °C below the reference period. The reconstructed local temperatures, the magnitude of which are subject to wide confidence intervals, show a rather geographically homogeneous LIA while more geographical inhomogeneities are found for the Medieval Warm Period. Reconstructions based on different number of proxies show only small differences suggesting that LOC reconstructs 50-yr smoothed extra-tropical NH mean temperatures well and that low-frequency noise in the proxies is a relatively small problem.

1 Introduction

The late Holocene (the last few thousand years) is in many ways comparable to the present period and its climate constitutes the background to which the current climate and the projected future climate should be compared. The amplitude of the natural variability and the response of the climate system to external forcings in late Holocene can help us understand the consequences and the impacts of coming changes in the

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forcings whether they are of natural, e.g. solar and volcanic, or anthropogenic origin. Unfortunately, instrumental records rarely reach further back than to the middle of the 19th century and for earlier periods it is necessary to deduce climate information from climate proxies, i.e. historical archives or natural recorders of climate such as ice-cores, speleothems, tree-rings, lake and marine sediments etc.

A number of temperature reconstructions based on compilations of proxies of different types have been presented in the literature beginning with Groveman and Landsberg (1979) and with increasing frequency after the much publicized reconstructions by Mann et al. (1998) and Mann et al. (1999). Many of the reconstructions show relatively weak variability with only little evidence for previous temperature anomalies comparable to those of the 20th century. Most local, regional, hemispheric, and global temperature reconstructions reveal that a generally warmer climate regime persisted sometime between ca. AD 800–1300 and a generally colder climate regime persisted sometime between ca. AD 1300–1900. The earlier warm period is usually referred to as the Medieval Warm Period (MWP) or Medieval Climate Anomaly whereas the later colder period often is referred to as the Little Ice Age (LIA). Unfortunately, there still exist no universally accepted chronological definitions for the start and end of either period. The spatio-temporal homogeneity of the MWP on a global or hemispheric scale is still debated (Bradley et al., 2003; Broecker, 2001; Esper and Frank, 2009; Diaz et al., 2011) whereas a homogeneously cold LIA recently seems to be a less contested issue (Juckes et al., 2007; Matthews and Briffa, 2005; National Research Council, 2006; Wanner et al., 2008).

In many studies much focus has been placed on comparing the amplitude of the warming during the MWP with that of the recent decades in order to assess whether the recent warming is unprecedented either in magnitude or rate during the past one or two millennia. Less focus has been placed on the LIA despite the fact that the amplitude of its coldest period (presumably the 17th century) is perhaps the biggest uncertainty in the climate of the millennium and that a better understanding of the amplitude of this cooling is very important for improving our understanding of the climate sensitivity.

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Recently, there has been increasing evidence that many reconstructions are based on statistical methods that seriously underestimate low-frequency variability and trends (von Storch et al., 2004; Bürger and Cubasch, 2006; Zorita et al., 2007; Smerdon and Kaplan, 2007; Christiansen et al., 2009). In particular, Christiansen et al. (2009) systematically investigated this underestimation in 7 different reconstruction methods using an ensemble pseudo-proxy method. Christiansen (2011a) attributed this underestimation partly to sub-optimal use of linear regression models and suggested a method, LOC, that was designed to overcome this problem. The LOC method is based on forward modelling of proxies based on the local temperatures. The local reconstructed temperatures are then averaged to obtain a large-scale (e.g. the Northern Hemispheric) mean temperature. That the LOC method reconstructs low-frequency variability well was confirmed in pseudo-proxy experiments (Christiansen, 2011a).

We have previously in Christiansen and Ljungqvist (2011a) presented a LOC based multi-proxy reconstruction of the extra-tropical Northern Hemisphere (NH) mean temperature in the last millennium. This reconstruction showed larger low-frequency variability than previous reconstructions with a minimum anomaly in the LIA about 1.1 °C lower than the temperature in the calibration period, AD 1880–1960 (50-yr smoothed). Although its variability was stronger, the LOC reconstruction shared the gradual cooling of the first 800 yr of the millennium with most previous reconstructions.

In this paper we extend the LOC reconstruction back to AD 1 to which end we have compiled a set of 32 proxies. The 32 proxies are a subset of a larger compilation of 91 proxies all reaching at least back to AD 1500 and which all previously have been shown to respond to temperature. We use this large proxy set to present an improved LOC reconstruction of the period since AD 1500. Christiansen and Ljungqvist (2011a) used 40 proxies and we expect that the larger number of proxies in the present paper will narrow the confidence interval. The proxies are described in Sect. 2 and a brief summary of the LOC method together with details about the data processing are given in Sect. 3. The reconstructions are presented in the three subsections of Sect. 4; the two-millennia long reconstruction is discussed in Sect. 4.1, the 500-yr long

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reconstruction in Sect. 4.2, and the geographical dispersion of the local reconstructions in the LIA and the MWP is discussed in Sect. 4.3. Some discussion of the robustness of LOC reconstructions to different degrees of spatial averaging is given in Sect. 5. We close with our conclusions in Sect. 6.

2 Proxies

We have compiled a set of 91 temperature proxy records from the extra-tropical NH, all of which reach back to at least AD 1500 and of which 32 reach back to AD 1 (or for the case of Mongolia and Dulan to the first centuries of the first millennium). The proxies are selected according to two criteria: they should have a documented relation to temperature and should have been published in the peer reviewed literature. Table 1 lists the proxies and gives, among other information, their geographical positions, their temporal resolutions, and their original references. Of the 91 proxies 65, 10, and 16 are of annual, annual-to-decadal, and decadal resolution, respectively. Blue Lake (number 7 in Table 1) and Lake C2 (49) are log-transformed.

The geographical distribution of the proxies is shown in the left panel of Fig. 1. Note, that a few pairs of proxies share the same geographical position but are based on different archives. The 91 proxies considered in the 500-yr long reconstruction have a reasonable geographical coverage although some inhomogeneities are observed. In particular, the oceans and the internal parts of the continents, North America, North-east Asia, and most of the interior of Asia, are sparsely covered while some clustering is found in China, Europe, Greenland and to a lesser extent in Western North America. However, the instrumental temperature record shows that the regions with good data coverage very well can capture both the trend and amplitude of temperature changes in the extra-tropical NH as a whole (Brohan et al., 2006). The subset used for the two-millennia long reconstruction (blue symbols in Fig. 1) shows larger inhomogeneities; in particular North America and Central Europe have a sparser coverage. Only proxies with significant correlations to the local temperature enter the LOC reconstruction

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as explained in more details in the next section. The right panel of Fig. 1 shows the geographical distribution of the 55 proxies (24 reaching back to at least AD 300) that correlate significantly at the 1 % level with the local temperatures in the period from AD 1880 to the last year of each proxy. The correlations are given in column Corr2 in Table 1. This reduced proxy set shows basically the same geographical inhomogeneities as described above for the full set of proxies.

All the proxies are shown as function of time for the period since AD 1500 in Fig. 2. The proxies reaching back to at least AD 300 are also shown for the full period in Fig. 3. Where the proxies have consecutive annual values these are connected. The annual resolved proxies are all complete except for Grotte di Ernesto (34, missing years 1681–1691, 1840–1857), Iceberg Lake (40, missing years 1642, 1825, 1834, 1867, 1899, 1957, 1982), and Burgundy (9, missing year 1978). These years have been filled in with linear interpolation. A few of the proxies display outliers, the most conspicuous being Teletskoe Lake (78) which shows a peak near AD 1600. We have confirmed that the outliers have only marginal influence on the NH mean reconstructions.

Some of the proxy records we use here were among the 40 proxies used in the 1000 yr long extra-tropical NH temperature reconstruction by Christiansen and Ljungqvist (2011a) but many new records are also introduced. We have also utilized other versions of some records, either because they reach longer back in time or because newer versions of the records have become available. We have thus used the Avam-Taimyr regional tree-ring width chronology (Briffa et al., 2008) instead of the Taimyr tree-ring width chronology (Naurzbaev et al., 2002). The Avam-Taimyr record is a combination of the tree-ring width chronologies from Taimyr (Naurzbaev et al., 2002) and Bol'shoi Avam (Sidorova et al., 2007). The new Chesapeake Bay sea sediment record (Cronin et al., 2010) is used instead of the older one (Cronin et al., 2003).

We have tried to obtain a complete set of high-resolution temperature proxy records covering the last two millennia and fulfilling our data requirements stated above. Unfortunately, the Sierra Nevada tree-ring width chronology by Scuderi (1993) could not be obtained despite repeated attempts. Furthermore, several potentially useful historical

documentary data sets from Europe cannot be used in this study since they do not have a sufficient overlap with the gridded instrumental data in HadCRUT3v (Brohan et al., 2006). Hence, the Central Europe temperature reconstruction by Dobrovolný et al. (2010), the Germany/Central Europe temperature reconstruction by Glaser and Riemann (2009), and the Stockholm winter/spring temperature reconstruction by Leijonhufvud et al. (2010) cannot be used here. However, the size of the proxy compilation used in this study is still larger than those used in all comparable studies with the exceptions of Mann et al. (2008) and Mann et al. (2009).

3 Reconstruction method

The LOC reconstruction method is introduced and motivated in Christiansen (2011a) and additional details and discussions can be found in Christiansen (2011b), Tingley and Li (2011), and Christiansen and Ljungqvist (2011a). Here we only give a brief description. The method requires calibration periods with simultaneous values of proxies and local temperatures. We assume that both proxies and temperatures are centered to zero in the calibration period. The LOC reconstruction method relates proxies to local temperatures and consists of three steps: (1) the proxies are screened and only proxies with a statistically significant relation to the local temperature in the calibration period are preserved. (2) Each of the proxies that passed the test is related linearly to the local temperature; $P = \lambda T + \xi$, where the noise ξ and the local temperature T are considered independent. It is important here that the proxy is chosen as the dependent variable. The regression coefficient λ is determined from the data in the calibration period. The local temperature is then reconstructed by $T = P/\lambda$. (3) The reconstructed local temperatures are averaged to form the reconstructed large-scale (here extra-tropical NH) mean temperature.

LOC avoids the underestimation of the low-frequency variability by using a forward model where the proxy is the dependent variable and by avoiding an explicit model for the spatial covariance structure of the temperature field. The forward model is the

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physical sound choice as we expect proxies to respond to local temperature and not the other way around. If the local temperature was chosen as the dependent variable the reconstructions would be biased towards zero. It is tempting to use a specific covariance model to infer temperatures in regions without proxies and then include these in the NH mean. However, the covariance structure calculated from the calibration period may not be relevant for the reconstruction period which can lead to underestimation of variability. An extreme example is found in sea-level reconstructions (Christiansen et al., 2010).

Note that the calibration periods can be different for the different proxies. This feature was not used in previous LOC reconstructions (Christiansen, 2011a; Christiansen and Ljungqvist, 2011a) but will be exploited in the present work. Likewise, the local reconstructions may not necessarily cover the same periods and the NH mean will then be calculated from a different number of local reconstructions in different periods. This is only important for the two-millennia long reconstruction before AD 300 as Dulan (21) and Mongolia (56) only reach back to AD 155 and AD 262, respectively.

In this paper we use gridded instrumental temperatures from HadCRUT3v (Brohan et al., 2006). This data-set is defined on a $5^\circ \times 5^\circ$ latitude-longitude grid and covers the period AD 1850–2010. The data coverage varies strongly with time as can be seen from Fig. 4, which shows the average number of months with data in the different decades. Because data scarcity is strong in the 19th century, in particular over land outside Europe, we do not use instrumental temperatures from the earliest period and all our calibration periods begin in AD 1880 or AD 1900. As in Christiansen (2011a) and Christiansen and Ljungqvist (2011a), missing monthly data are filled with inverse distance interpolation. The annual means are then obtained to give the annually resolved temperature field which is then interpolated to the positions of the proxies. See Christiansen and Ljungqvist (2011a) for a discussion of the impacts of the interpolation methods. We do not detrend the local temperatures before using them for calibration. This is the usual choice in reconstruction studies and only has a small effect on the LOC method (Christiansen, 2011a). To match the proxies, the local temperatures have

been low-pass filtered with a cut-off at 5 or 10 yr if the corresponding proxy is of annual-to-decadal or decadal resolution. Here and in the rest of the paper low-pass filtering is performed with a simple running average filter.

It is well known that most temperature proxy records primarily respond to a specific season (Jones and Bradley, 1992). Since we calibrate each proxy record to its local annual mean temperature, we may reject some proxy records that have a strong response to its optimal season. The correlation between different seasons is, however, usually high on decadal and longer time-scales.

Confidence intervals are calculated by an ensemble pseudo-proxy method as in Christiansen and Ljungqvist (2011a). This calculation is based on a 500-yr long forced experiment (Stendel et al., 2006) with the ECHAM4-OPYC3 climate model. The positions and the number of the pseudo-proxies mimic those the real proxies. The pseudo-proxies are constructed by adding realistic noise to local temperatures where the realistic noise is constructed to have the same autocorrelation spectra as the residuals between the real proxies and the corresponding local temperatures. See Christiansen et al. (2009) and Christiansen (2011a) for more details about the ensemble pseudo-proxy method. The ensemble pseudo-proxy method estimates both the variance and the bias of the error. In this respect it is superior to, e.g. the Bayesian approach (Tingley et al., 2011), which only provides the variance (see the discussion in Tingley and Li, 2011, and Christiansen, 2011b). This point is in particular important for the reconstruction problem where the bias has been shown to be a serious problem (von Storch et al., 2004; Bürger and Cubasch, 2006; Zorita et al., 2007; Smerdon and Kaplan, 2007; Christiansen et al., 2009).

4 Reconstructions

We first consider the extra-tropical NH mean reconstructions. The two-millennia long reconstruction is discussed in Sect. 4.1 and the 500-yr long reconstruction in Sect. 4.2. For both periods we first present the reconstruction based on the calibration period

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AD 1880–1960 and then discuss the differences when compared to reconstructions based on other calibration periods. The reconstructions calibrated in AD 1880–1960 are provided with confidence intervals estimated with the ensemble pseudo-proxy method. In Sect. 4.3 we consider the geographical distribution of the local reconstruction in selected periods.

4.1 The NH two-millennia long reconstruction

We first consider the two-millennia long reconstruction based on 32 proxies that reach back to at least AD 300 (shaded rows in Table 1). With the calibration period AD 1880–1960 16 proxies have positive correlations with the local temperature and are significantly related to this temperature at the $p = 0.01$ level as estimated with a t -test. The correlations are shown in Table 1 and significant values are boldfaced. The correlations between the 16 proxies and their local temperatures fall in the interval 0.32–0.92 with mean/median of 0.52/0.41. Assuming that the proxies and local temperatures are without serial correlations (which is obviously not true, see Christiansen and Ljungqvist (2011a) for a discussion of the effects of using a more strict test) choosing $p = 0.01$ corresponds to a cut-off correlation of 0.29. From these 16 proxies the local temperatures are reconstructed and inspection of the 50-yr smoothed versions shows that they all fall within reasonable limits with anomalies of no more than $\pm 4^\circ\text{C}$. The extra-tropical NH mean temperature obtained as the simple mean of these local reconstructed temperatures is shown in Fig. 5.

The coldest period in this reconstruction is ca. AD 1580–1720 where the temperature anomaly reaches -1.1°C relative to AD 1880–1960. This is in agreement with the millennia long LOC reconstruction of Christiansen and Ljungqvist (2011a) based on 40 proxies of which 23 passed the t -test. The two reconstructions are in fact quite alike regarding the second millennium both in shape and amplitude. However, the reconstructions are not totally independent as a subset of the proxies is used in both studies as discussed in Sect. 2. The cold period AD 1500–1900, the LIA, is also a prominent feature of previous reconstructions but the LOC reconstructions give colder temperatures

than other reconstructions. A very distinct warm peak occurs in the reconstruction in the second half of the 10th century with temperatures up to 0.7 °C warmer than the calibration period AD 1880–1960 equalling the temperatures of the mid-20th century. This warm event represents the climax of the MWP. Note that the extra-tropical NH mean temperature from HadCRUT3v in AD 1880–1960 is 0.23 °C colder than in the often used standard climate period AD 1961–1990.

Confidence intervals of the 50-yr smoothed values are superimposed on the reconstruction in Fig. 5. These confidence intervals are calculated by an ensemble pseudo-proxy approach as described in Sect. 3 mimicking the conditions of the real-world reconstruction. We see that the LOC reconstruction only has small bias and that the 95 % confidence interval has a width of 0.6 °C. This makes anomalies in AD 1500–1900 (LIA) and AD 950–1050 (MWP) significantly different from zero while the temperatures before AD 900 do not show any significant deviations from the mean temperature in the calibration period AD 1880–1960.

We have repeated the reconstruction with different calibration periods. As mentioned previously the LOC method allows different calibration periods for the different proxies. Using a calibration period beginning in AD 1880 and lasting to the end of each proxy (see Table 1) 24 proxies pass the *t*-test at the 1 % level. This set of proxies includes the 16 proxies that passed the test with the calibration period AD 1880–1960 and eight new proxies. From the correlations listed in Table 1 we see that the larger number of proxies are due mainly to an increase in the correlations with the new (mainly longer) calibration periods and not due to a decrease of the cut-off frequency related to these longer calibration periods. For a few of the proxies the correlations change drastically with the change in the calibration period (e.g. China Stack, 14) making them less reliable. The correlations now fall in the interval 0.28–0.90 with a mean/median of 0.46/0.41.

From these proxies the local temperatures are reconstructed and adjusted to zero mean in the reference period AD 1880–1960 (this step is necessary because of the different calibration periods). Figure 6 (blue curve) shows the NH mean based on these 24 local reconstructions. A similar reconstruction with the calibration period

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beginning in AD 1900 is also included (red curve). With this choice of calibration periods 21 proxies pass the test and the correlations now fall in the interval 0.26–0.89 with a mean/median of 0.48/0.45. We find only small differences between the three NH mean reconstructions. This is in agreement with Christiansen and Ljungqvist (2011a) that showed that the LOC reconstruction method is fairly robust with respect to changes in, e.g. the calibration period.

4.2 The NH 500-yr long reconstruction

All 91 proxies in Table 1 have been considered in a reconstruction of the period since AD 1500. Using a calibration period AD 1880–1960 we find that 47 proxies pass the *t*-test at the 1 % level. The correlations between these accepted proxies and their local temperatures fall in the interval 0.29–0.92 with a mean/median of 0.49/0.42. The resulting extra-tropical NH mean reconstruction is shown in Fig. 7 (black curve). Again we find a cold 17th century with temperatures around –1 °C below the AD 1880–1960 level in agreement with the millennia long reconstruction of Christiansen and Ljungqvist (2011a). Good agreement is also found when comparing to the reconstruction reaching back to AD 1 from the previous section (also shown in Fig. 7, blue curve).

The confidence intervals calculated with the ensemble pseudo-proxy approach again show only a small bias. The width of the 95 % confidence interval is now 0.4 °C, making the whole period AD 1500–1900 significantly colder than the calibration period. The confidence interval is more narrow than that of the two-millennia long reconstruction as should be expected because of the larger number of proxies. Compared to this reconstruction based on 32 proxies (16 accepted) we find that the amplitude of the high-frequency variability in the reconstruction based on 91 proxies (47 accepted) has decreased as expected due to the larger number of proxies (Christiansen, 2011a). This decrease is around 15 % when the high-frequency variability is measured as the variance of the 50-yr high-passed reconstructions.

We have again repeated the reconstruction with different calibration periods lasting to the end of each proxy and beginning in AD 1880 or AD 1900. For these calibration

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intervals 55 and 47 proxies pass the t -test and the correlations fall in the intervals 0.24–0.90 and 0.26–0.89 with means/medians of 0.46/0.41 and 0.48/0.45. The resulting NH mean reconstructions strongly resemble the reconstruction based on the calibration period AD 1880–1960 (Fig. 8) with differences falling inside the 95 % confidence interval shown in Fig. 7. The largest differences are found in the level of the cold minimum in the first half of the 19th century. In comparison, very small differences are found in the cold minimum in the 17th century.

4.3 The geographical distribution

As we have seen, the LOC method gives local reconstructions at the positions of the proxies (but not elsewhere in contrast to field reconstruction methods). LOC is designed to produce a good large-scale (e.g. NH) low-frequency mean and relies on both temporal and spatial averaging to reduce the high-frequency noise (see also Sect. 5). However, LOC only determines the amplitude of the local temperature anomalies. The sign is determined by the proxies themselves. Negative values of a local reconstruction in a given period are a consequence of the proxy having a smaller value in this period than in the calibration (reference) period.

We have estimated the confidence intervals of 100-yr means of the local reconstructions with the ensemble pseudo-proxy approach described previously. Compared to the confidence intervals of the extra-tropical NH mean we do not profit from spatial averaging but, on the other hand, we do not have the complication of the unknown spatial covariance. The widths of these confidence intervals on the local reconstructions vary a lot as they depend, among other factors, on the correlation between the proxy and the local temperature and on the autocorrelation structure of the proxy. As LOC takes the proxy as the dependent variable the confidence intervals of the local reconstructions decrease substantially when the correlation between the proxy and the local temperature grows (Christiansen, 2011b). With strong serial correlations in the proxy the correlation between local temperature and the proxy is badly constrained due to the reduced number of degrees of freedom. The latter factor makes the confidence

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intervals of the annually-to-decadally and decadally resolved proxies particularly wide. We find that when all proxies that pass the t -test at the 1 % level are considered the width of the 95 % confidence intervals varies from less than 0.5 °C to more than 2 °C.

With these considerations and limitations in mind we discuss some of the spatial features found in century long temporal means. We consider three periods: the two cold peaks of the LIA, AD 1600–1699 and AD 1800–1899 and the peak of the MWP, AD 950–1049. The geographical distributions of the mean anomalies are shown in Fig. 9, where the anomalies in the LIA are taken from the 500-yr long reconstruction and the anomalies in the MWP are from the two-millennia long reconstruction. This figure also includes histograms of the local temperature anomalies.

For the periods AD 1600–1699 and AD 1800–1899 the local anomalies have means of -0.91 and -0.76 °C. The geographical distributions of temperature anomalies in the two periods are almost identical and are relatively homogeneous with cold anomalies almost everywhere. Of the 47 local reconstructions 8 in AD 1600–1699 and 3 in AD 1800–1899 show warm anomalies. In some regions nearby local reconstructions disagree. This is particularly conspicuous in Greenland with Crete (17) and Southern Greenland (72) showing warming and Dye-3 (22), GISP2 (30), and GISP2 AR/N2 (31) showing cooling in AD 1600–1699.

The geographical distribution of temperature anomalies in the MWP shows larger inhomogeneities than observed in the LIA. In the period AD 950–1049 the mean is 0.49 °C but only 9 out of 16 local reconstructions show warm anomalies although the cold anomalies are weak. As comparison, the two-millennia long reconstruction has only one proxy with warm anomaly in each of the periods AD 1600–1699 and AD 1800–1899. Note, that all local reconstructions on Greenland agree on warm anomalies in the MWP.

As mentioned, the warm local temperature anomalies in the periods AD 1600–1699 and AD 1800–1899 are both weak and few whereas the cold anomalies in AD 950–1049 are more abundant. However, the strengths of the spatial variances in the three periods cannot be directly compared from the local temperature anomalies relative to

the calibration period. This is because the temperature anomalies are centered to zero in the calibration period and the spatial variance will therefore be zero in the this period and suppressed in overlapping or nearby periods. Centering the two-millennia long reconstruction to zero in the whole period we find the spatial standard deviations 1.01, 0.69, and 0.64 °C in AD 950–1049, 1600–1699 and 1800–1899, respectively. The standard deviations of all 100-yr means are shown in Fig. 10 as a function of the central year in the period. Values higher than those found for AD 950–1049 are only found in the 9th century, while the values for AD 1600–1699 and AD 1800–1899 are not unusual. However, applying a F-variance test shows that the standard deviation of AD 950–1049 is only significantly different from other periods when the standard deviation of these periods is less than 0.65 °C. Therefore, this analysis gives only weak indications that the MWP was unusually spatially variable. This is in accordance with results from Esper and Frank (2009) and Ljungqvist et al. (2011) (see also Sect. 6).

5 Robustness and spatial averaging

In this section we very briefly comment of the robustness of the low-frequency behavior of LOC and consider a possible limitation of pseudo-proxy experiments.

Christiansen and Ljungqvist (2011a) showed that their real-world reconstruction based on 40 proxies was robust to changes in, e.g. the calibration interval, the screening method, and the procedure for calculating the spatial average. We find similar results in the present study. However, for brevity we have only presented the results for different calibration intervals, see Figs. 6 and 8 and the discussions in the previous section.

Based on an ensemble pseudo-proxy method Christiansen (2011a) confirmed that LOC reconstructs low-frequency variability well and both Christiansen and Ljungqvist (2011a) and the present paper provided confidence intervals based on a similar pseudo-proxy method. However, pseudo-proxies are generated by degrading the local temperature by adding noise and therefore include assumptions about the temporal

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structure of the noise (Moberg, 2011; Christiansen and Ljungqvist, 2011b). In the present paper as well as in Christiansen (2011a) and Christiansen and Ljungqvist (2011a) the noise was calculated so it had the same autocorrelation spectra as the residuals between the real proxies and the corresponding local temperatures (see Christiansen et al., 2009). As these autocorrelation spectra are calculated from time-series of limited length (~80 yr) we cannot rule out that real-world proxies include low-frequency noise components that are not represented in the pseudo-proxies and which can disturb the effect of temporal averaging. It is therefore interesting to study how stable the LOC based real-world reconstructions are to the degree of spatial averaging, i.e. to the number of included proxies. The large number of proxies in the present study gives us a chance to do this.

Figures. 7 and 8 show reconstructions of the LIA based on different numbers of proxies (from 16 to 55 after screening). We note that they all agree on a minimum anomaly around AD 1600 close to -1.1 °C lower than the temperature in the calibration period AD 1880–1960 (50-yr smoothed). Christiansen and Ljungqvist (2011a) presented a LOC reconstruction of the extra-tropical NH mean temperature in last millennium based on 23 proxies (selected by screening 40 proxies). Also in this study the cold anomaly was found to be -1.1 °C. The different reconstructions disagree more about the temperature minima in the 19th century, but the 50-yr smoothed reconstructions generally fall inside the 95 % confidence interval calculated by the ensemble pseudo-proxy method. Furthermore, there does not seem to be a systematic reduction in the reconstructed temperature with an increasing number of proxies; in fact the coldest reconstruction is the one based on the largest number of proxies (red curve in Fig. 8, calibration period AD 1860 – last year). These results suggest that the effect of low-frequency noise is small and that LOC reconstructs 50-yr smoothed values well.

6 Conclusions

We have compiled a set of 91 temperature sensitive proxies located in the extra-tropical NH and reaching back to at least AD 1500. All the proxies have all been published in the peer reviewed literature. Of these proxies, 32 extend as far back as to the beginning of the first millennium. From these comprehensive proxy compilations we performed new reconstructions of the extra-tropical NH mean temperature. Note, however, that only little more than half of the proxies (the exact fraction depends on the calibration interval etc) correlates well enough with the local annual mean temperature to be included in the actual reconstructions.

The reconstructions are carried out with the LOC method (Christiansen, 2011a) which was designed to preserve low-frequency variability at the price of exaggerating the high-frequency variability. Confidence intervals have been calculated with an ensemble pseudo-proxy approach which mimics the conditions of our real-world reconstructions including the spatial and temporal averaging. These calculations indicate that the extra-tropical NH mean reconstructions have only a small bias. The corresponding 95 % confidence intervals have widths of 0.6 (two-millennia long reconstruction) and 0.4 °C (500-yr long reconstruction) for 50-yr smoothed values, thereby showing that the residual noise-variance is relatively small compared to the reconstructed low-frequency signal.

Our main conclusions are

- Our reconstructions indicate – in agreement with the results of Moberg et al. (2005), and Ljungqvist (2010) – that the first millennium AD was generally significantly warmer than the second millennium AD. The 17th century was the coldest century during the last two millennia and most of the LIA seems to have been colder than during the Dark Age Cold Period ca. AD 300–800. In general our LOC reconstructions show larger low-frequency variability than previous reconstructions.

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- Our two-millennia long reconstruction has a well-defined peak in the period AD 950–1050 with a maximum temperature anomaly of 0.7 °C. The timing of the peak of the MWP in our reconstruction is in agreement with the reconstructions of Esper et al. (2002) and Ljungqvist (2010). The reconstruction of Mann et al. (2008) shows a longer peak warming, covering the whole period AD 950–1100, and the reconstruction of Moberg et al. (2005) shows a somewhat later as well as longer peak MWP warming than in the present paper. The level of warmth during the peak of the MWP in the second half of the 10th century, equalling or slightly exceeding the mid-20th century warming, is in agreement with the results from other more recent large-scale multi-proxy temperature reconstructions by Moberg et al. (2005), Mann et al. (2008, 2009), and Ljungqvist (2010).

- Temperatures in the 17th century reach values as cold as -1.1°C below the AD 1880–1960 level in agreement with a previous LOC reconstruction by Christiansen and Ljungqvist (2011a) based on fewer proxies. We find that this result is very robust to the calibration period and the number of proxies included. This level of cooling is considerably colder than obtained with other reconstruction methods (see Christiansen and Ljungqvist (2011a) for a comparison). In the 19th century temperature anomalies reach values of ca. -1.0°C , but this value is somewhat more sensitive to the calibration period. The two temperature minima are separated by a local maximum in the 18th century. This temporal variation of the temperature throughout the LIA is in line with most previous work. Most regional to global multi-proxy temperature reconstructions studies agree that the 17th century was the coldest century during the LIA (Ljungqvist, 2010; Mann et al., 2008, 2009; Moberg et al., 2005; National Research Council, 2006), although high-latitude summer temperatures seem to have reached a minimum in the 19th century (Grudd, 2008; Kaufman et al., 2009; Ran et al., 2011; Vinther et al., 2010). The maximum cooling in the 17th century is also supported by General Circulation Models and Energy Balance Models (Ammann et al., 2007; Friend, 2011; González-Rouco et al., 2006; Jungclauss et al., 2010; Servonnat

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et al., 2010) using state-of-the-art estimates of past radiative forcing. The 18th century is generally found to be warmer than both the 17th and the 19th centuries with, regionally, temperatures as high as in the mid-20th century.

- We find that the LIA is spatially homogeneous with cold anomalies everywhere and almost the same patterns in the 17th and the 19th centuries. The homogeneity of the LIA is in agreement with previous work (Juckes et al., 2007; Matthews and Briffa, 2005; National Research Council, 2006; Wanner et al., 2008, 2011). The MWP seems much more inhomogeneous as have also been suggested in several previous studies including Bradley et al. (2003), Hughes and Diaz (1994), and Mann et al. (2009). However, we find that the statistical significance is low due to the limited number of proxies in agreement with Esper and Frank (2009) who suggested that the use of relatively few noisy and poorly replicated proxies can give a false impression of heterogeneity. Ljungqvist et al. (2011) show that, on centennial time-scales, the MWP is no less homogeneous than the LIA if all available proxy evidence, including low-resolution records, are taken into consideration in order to give a better spatial data coverage.
- The large number of proxies allow us to compare LOC reconstruction based on different number of proxies and thereby test the influence of the spatial averaging. Reconstructions based on 16 to 55 proxies (after screening) show only small differences in 50-yr smoothed temperatures that generally fall inside the 95 % confidence interval calculated by the ensemble pseudo-proxy method. This suggests that low-frequency noise is a minor problem and that LOC reconstructs 50-yr smoothed extra-tropical NH mean temperatures well.

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Table 1. List of the 91 proxies considered. The proxies used in the two-millennia long reconstruction are shaded. The column “Season” refers to the season in which the proxy has been shown to be most sensitive to temperature. Different versions of the proxies marked with a star are used for the two-millennia long and the 500-yr long reconstructions. Correlations are from the period AD 1880–1960 (Corr 1) and AD 1880–Last year (Corr 2) and are boldfaced when significant at the 1 % level according to a *t*-test that considers all years as independent.

#	Site	Longitude	Latitude	Proxy type	Sample resolution	Season	First year	Last year	Corr 1	Corr 2	Reference
1	Agassiz Ice Cap	−73.10	80.70	Ice-core $\delta^{18}\text{O}$	Annual	Annual	0	1972	0.17	0.19	Vinther et al. (2008)
2	Alps	7.50	45.00	Tree-ring density	Annual	Jun to Sep	1500	2004	0.67	0.54	Büntgen et al. (2006)
3	Austfonna	24.01	79.83	Ice-core $\delta^{18}\text{O}$	Annual	Annual	1500	1998	0.21	0.21	Isaksson et al. (2005)
4	Avam-Taimyr	97.00	71.00	Tree-ring width	Annual	Jun to Aug	1	2003	0.39	0.28	Briffa et al. (2008)
5	Belukha	86.58	49.81	Ice-core $\delta^{18}\text{O}$	Annual	Mar to Nov	1500	2000	0.00	0.09	Eichler et al. (2009)
6	Big Round Lake	−68.50	69.83	Varved lake sediment	Annual	Jul to Sep	1500	2003	0.38	0.34	Thomas and Briner (2009)
7	Blue Lake	−150.46	68.08	Varved lake sediment	Annual	Jun to Aug	1500	1999	−0.28	−0.06	Bird et al. (2009)
8	Bomi-Linzhi	98.00	30.00	Tree-ring width	Annual	Aug	1500	2002	0.38	0.48	Zhu et al. (2011)
9	Burgundy	6.00	47.00	Documentary	Annual	Apr to Aug	1500	2003	0.32	0.50	Chuine et al. (2004)
10	Camp Century	−61.13	77.17	Ice-core $\delta^{18}\text{O}$	Annual	Annual	1242	1967	0.03	0.03	Danegaard et al. (1969)
11	Central Europe	8.00	46.00	Tree-ring width	Annual	Jun to Sep	1	2003	0.15	0.46	Büntgen et al. (2011)
12	Central NWT (regional)	−110.00	63.00	Tree-ring density	Annual	Summer	1500	2003	0.07	0.05	D'Arrigo et al. (2006)
13	Chesapeake Bay	−76.40	39.00	Sea sediments	Annual-to-decadal	Warm season	1	1996	0.05	0.13	Cronin et al. (2010)
14	China Stack (regional)	105.00	35.00	Multi-proxy	Decadal	Annual	1	1990	0.72	0.31	Yang et al. (2002)
15	Colombia Icefield	−117.15	52.15	Tree-ring density	Annual	May to Aug	1500	1998	0.22	0.27	Luckman and Wilson (2005)
16	Colombia Icefield	−117.15	52.15	Tree-ring $\delta^{13}\text{C}$	Decadal	Winter	1500	1985	−0.07	−0.07	Edwards et al. (2008)
17	Crete	−37.32	71.12	Ice-core $\delta^{18}\text{O}$	Annual	Nov to Apr	1500	1973	0.41	0.39	Vinther et al. (2010)
18	Czech Lands	15.00	49.00	Documentary	Annual	Mar to Jun	1501	2008	0.47	0.66	Mönnig et al. (2011)
19	Devon Ice Cap	−82.50	75.33	Ice-core $\delta^{18}\text{O}$	Annual-to-decadal	Annual	1	1973	0.66	0.62	Fisher et al. (1983)
20	Donard Lake	−61.35	66.66	Varved lake sediment	Annual	Jun to Aug	1500	1992	−0.32	−0.17	Moore et al. (2001)
21	Dulan	98.00	36.00	Tree-ring width	Decadal	Annual	155	1995	0.41	0.44	Zhang et al. (2003)
22	Dye-3	−43.49	65.11	Ice-core $\delta^{18}\text{O}$	Annual	Nov to Apr	1	1978	0.33	0.35	Vinther et al. (2010)
23	ESIB (regional)	150.00	68.00	Tree-ring width	Annual	Summer	1500	1994	0.30	0.15	Briffa et al. (2001)
24	East China	112.00	32.00	Documentary	Decadal	Annual	1500	1995	0.83	0.81	Wang et al. (2001)
25	East China (regional)	112.50	32.50	Documentary	Decadal	Oct to Apr	1505	1995	0.92	0.90	Ge et al. (2003)
26	Eastern Carpathians	25.10	47.20	Tree-ring width	Annual	Summer	1500	2005	−0.09	0.16	Popa and Kern (2009)
27	Finnish Lapland	25.00	69.00	Tree-ring width	Annual	Summer	1	2005	0.41	0.41	Helama et al. (2010)
28	Forfjordalen	15.72	68.78	Tree-ring width	Annual	Jul to Aug	1500	1989	0.37	0.31	Kirchhefer (2001)
29	French Alps	7.00	45.50	Tree-ring width	Annual	Jun to Aug	1500	2008	0.38	0.47	Corona et al. (2011)
30	GISP2	−38.50	72.60	Ice-core $\delta^{18}\text{O}$	Decadal	Annual	−8	1987	0.32	0.33	Groote and Stuiver (1997)
31	GISP2 Ar/N ₂	−38.50	72.60	Ice-core $\delta\text{Ar}/\text{N}_2$	Decadal	Annual	1500	1993	0.71	0.53	Kobashi et al. (2010)

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Table 1. Continued.

#	Site	Longitude	Latitude	Proxy type	Sample resolution	Season	First year	Last year	Corr1	Corr2	Reference
32	GRIP	−37.38	72.35	Ice-core $\delta^{18}\text{O}$	Annual	Nov to Apr	1	1979	0.07	0.02	Vinther et al. (2010)
33	Gotland	19.00	57.00	Tree-ring width	Annual	Summer	1500	1987	0.18	0.09	Esper et al. (2002)
34	Grotte di Ernesto	11.66	45.98	Speleothem microlayer	Annual	Annual	1500	1987	−0.00	0.08	Frisia et al. (2003)
35	Gulf of Alaska	−145.00	60.00	Tree-ring density	Annual	Jan to Aug	1500	2002	0.20	0.27	D'Arrigo et al. (2006)
36	Gulf of Taranto	17.89	39.76	Sea sediments	Annual-to-decadal	Fall	1	1975	0.74	0.59	Taricco et al. (2009)
37	Hallet Lake	−146.20	61.50	Lake sediments	Annual-to-decadal	Jun to Aug	1	2005	0.25	0.33	McKay et al. (2008)
38	Haukadalavatn	−21.37	65.03	Lake sediments	Annual-to-decadal	Apr to May	1	2003	−0.18	−0.17	Geirsdóttir et al. (2009)
39	Hesheng	110.00	30.00	Speleothem $\delta^{18}\text{O}$	Annual-to-decadal	Annual	1500	1999	0.14	0.27	Hu et al. (2008)
40	Iceberg Lake	−142.95	60.78	Varved lake sediment	Annual	May and Jun	1500	1998	0.06	0.09	Los0 (2009)
41	Idaho	−114.25	44.42	Tree-ring width	Annual	Jul	1500	1992	0.08	0.04	Biondi et al. (1999)
42	Indigirka	148.15	70.53	Tree-ring width	Annual	Jun to Jul	1	1993	0.39	0.33	Moberg et al. (2006)
43	Jämtland	13.30	63.10	Tree-ring width	Annual	Jun to Aug	1500	2000	0.46	0.39	Linderholm and Gunnarsson (2005)
44	Jasper	−118.17	52.75	Tree-ring width	Annual	Apr to Aug	1500	1987	0.32	0.28	Luckman et al. (1997)
45	Karakorum	74.99	36.37	Tree-ring $\delta^{13}\text{C}$	Annual	Jun and Jul	1500	1993	−0.15	−0.15	Treydte et al. (2009)
46	Karakorum TRW	74.99	36.37	Tree-ring width	Annual	Annual	1500	1993	−0.15	−0.15	Esper et al. (2002)
47	Koralgrottan	14.16	64.89	Speleothem $\delta^{18}\text{O}$	Decadal	Annual	1	2005	−0.30	0.36	Sundqvist et al. (2010)
48	Laania	27.30	68.50	Tree-ring height inc.	Annual	Jun to Aug	1500	2007	0.21	0.17	Lindholm et al. (2011)
49	Lake C2	−77.54	82.47	Varved lake sediment	Annual	Jun to Aug	1	1987	0.21	0.22	Lamoureux and Bradley (1996)
50	Lake Silvaplana	9.80	46.45	Lake sediments	Annual-to-decadal	Jul	1500	1995	0.69	0.44	Larocque-Tobler et al. (2010)
51	Lake of the Clouds	−71.25	44.25	Pollen	Decadal	Jun to Aug	1500	1965	0.60	0.53	Gajewski (1988)
52	Lomonosovfonna	17.42	78.85	Ice-core $\delta^{18}\text{O}$	Annual	Annual	1500	1997	0.29	0.26	Isaksson et al. (2005)
53	Low Countries	5.18	52.10	Documentary	Annual	Annual	1500	2000	0.65	0.76	van Engelen et al. (2001)
54	Lower Murray Lake	−69.32	81.21	Varved lake sediment	Annual	Jun to Aug	1	1969	0.28	0.30	Cook et al. (2009)
55	Mangazeya	82.30	66.68	Tree-ring density	Annual	Summer	1500	1990	0.35	0.16	Esper et al. (2002)
56	Mongolia	98.93	48.30	Tree-ring density	Annual	Apr to Oct	262	1999	0.00	0.31	D'Arrigo et al. (2001)
57	NSIB (regional)	100.00	72.00	Tree-ring width	Annual	Summer	1500	1991	0.39	0.32	Briffa et al. (2001)
58	NW North Alaska (reg)	−167.00	67.00	Tree-ring density	Annual	Summer	1500	2000	0.17	0.17	D'Arrigo et al. (2006)
59	North China	113.00	40.00	Documentary	Annual	Annual	1500	1995	0.42	0.40	Wang et al. (2001)
60	North Icelandic Shelf	−19.30	66.30	Sea sediments	Annual-to-decadal	Summer	1	2001	−0.34	−0.11	Sicre et al. (2011)
61	North-Central China	111.50	37.00	Tree-ring width	Annual	Summer	1500	2002	0.40	0.18	Yi et al. (2011)
62	NorthGRIP	−42.32	75.10	Ice-core $\delta^{18}\text{O}$	Annual	Annual	1	1995	0.20	0.15	NGRIP members (2004)

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Table 1. Continued.

#	Site	Longitude	Latitude	Proxy type	Sample resolution	Season	First year	Last year	Corr1	Corr2	Reference
63	Northern Iceland	-19.30	66.30	Sea sediments	Annual-to-decadal	Summer	1500	2000	0.18	0.14	Ran et al. (2011)
64	Polar Urals	65.75	66.63	Tree-ring density	Annual	May to Sep	1500	1990	0.43	0.33	Esper et al. (2002)
65	Quebec	-70.00	53.00	Tree-ring density	Annual	Summer	1500	1947	NaN	-0.09	Esper et al. (2002)
66	Renland	-26.70	71.30	Ice-core $\delta^{18}O$	Annual-to-decadal	Annual	1	1980	0.69	0.59	Vinther et al. (2008)
67	Russian Plain	45.00	55.00	Multi-proxy	Decadal	Annual	5	1995	0.32	0.86	Kimlenko and Slepstov (2003)
68	Sovernaja	106.00	61.00	Lake sediments	Decadal	Jun to Aug	1500	1979	0.03	0.09	Bolshyanov and Makeev (1995)
69	Seward Peninsula	-163.00	65.00	Tree-ring density	Annual	Summer	1500	2002	0.13	-0.05	D'Arrigo et al. (2005)
70	Shihua Cave	116.23	39.54	Speleothem microlayer	Annual	May to Aug	1	1985	-0.06	0.02	Tan et al. (2003)
71	Southern Colorado Pl	-111.40	35.20	Tree-ring width	Annual	Maximum summer temp	1	1996	0.41	0.36	Salzer and Kipfmüller (2005)
72	Southern Greenland (regional)	-43.00	65.00	Ice-core $\delta^{18}O$	Annual	Winter	1500	1970	0.46	0.42	Vinther et al. (2003)
73	Southern Sierra Neva	-118.90	36.90	Tree-ring width	Annual	Jun to Aug	1500	1988	0.21	0.22	Graumlich (1993)
74	Spanish Pyrenees	1.00	42.50	Tree-ring density	Annual	May to Sep	1500	2005	0.57	0.66	Büntgen et al. (2008)
75	Sugan Lake	93.90	38.85	Lake sediments	Decadal	Winter	15	1995	-0.83	0.73	Qiang et al. (2005)
76	Svalbard	17.00	78.00	Ice melt layer	Annual	Jun to Aug	1500	1985	0.00	0.05	Tarassov (1992)
77	Tarvagatory	99.00	48.00	Tree-ring density	Annual	Summer	1500	1994	0.03	0.24	Jacoby et al. (1996)
78	Teletskoe Lake	87.61	51.76	Varved lake sediment	Annual	Annual	1	2002	0.10	0.49	Kalugin et al. (2009)
79	Tibetan Plateau	92.00	33.00	Ice-core $\delta^{18}O$	Decadal	Annual	5	1995	0.76	0.67	Thompson et al. (2006)
80	Tien Shien	72.00	40.00	Tree-ring width	Annual	Annual	1500	1995	-0.04	-0.03	Esper et al. (2003)
81	Tokyo	139.72	35.67	Documentary	Annual	Winter	1500	1975	0.65	0.72	Gray (1974)
82	Tornetråsk	19.80	68.31	Tree-ring density	Annual	Apr to Aug	1500	2004	0.63	0.58	Grudd (2008)
83	Tornetråsk TRW *	19.43	68.13	Tree-ring width	Annual	Jun to Aug	1	1993	0.54	0.50	Grudd et al. (2002)
84	Ummh an Tartar	-4.98	58.15	Speleothem microlayer	Annual	Annual	1500	1993	0.36	0.30	Proctor et al. (2002)
85	Usvyatskii Mokh	32.00	56.00	Pollen	Decadal	Annual	1500	1995	0.41	0.62	Kimlenko et al. (2001)
86	Vering Plateau	7.54	66.97	Sea sediments	Decadal	Summer	1	1995	0.22	0.31	Andersson et al. (2010)
87	WNA (regional)	-116.00	38.00	Tree-ring width	Annual	Summer	1500	1983	0.46	0.41	Briffa et al. (2001)
88	Yakutia	147.00	69.50	Tree-ring width	Annual	Summer	1500	1994	0.18	0.12	Hughes et al. (1999)
89	Yamal	68.17	66.92	Tree-ring width	Annual	Jun to Jul	1	1996	0.34	0.32	Briffa (2000)
90	Yangtze River Delta	121.00	32.00	Documentary	Decadal	Annual	1500	1997	0.55	0.58	Zhang et al. (2006)
91	Yukon	-139.00	67.00	Tree-ring density	Annual	Summer	1500	2002	0.21	-0.08	D'Arrigo et al. (2006)

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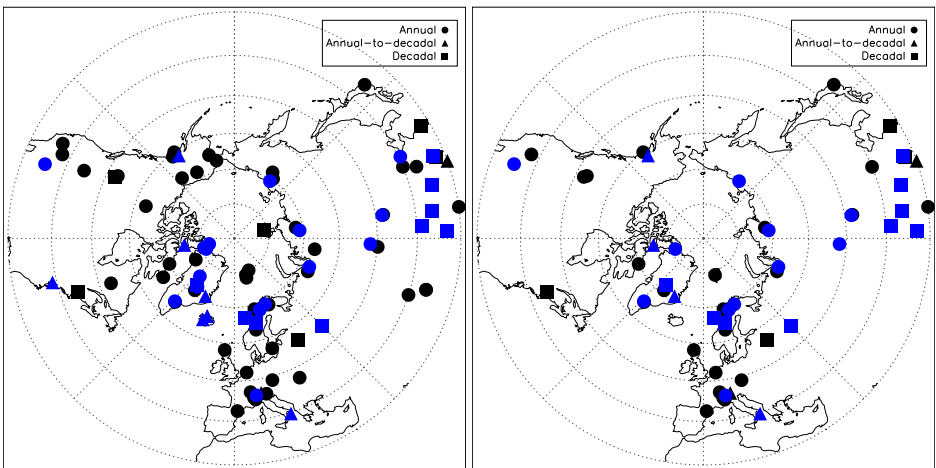


Fig. 1. The geographical locations of all the 91 proxies in Table 1 (left) and of those that correlate significantly with their local temperatures (from HadCRUT3v) in the period beginning in 1880 and lasting to the final year of each individual proxy (right). The resolution (annual, annual-to-decadal, decadal) is indicated with the symbols. Proxies that reach back to at least AD 300 are indicated in blue.

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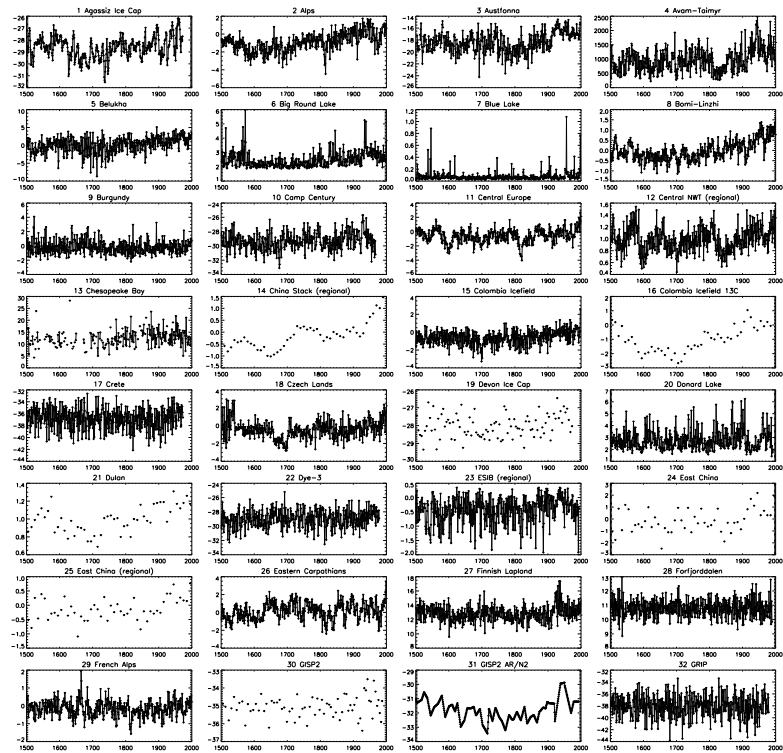


Fig. 2. The 91 proxies in Table 1 as function of time since AD 1500.

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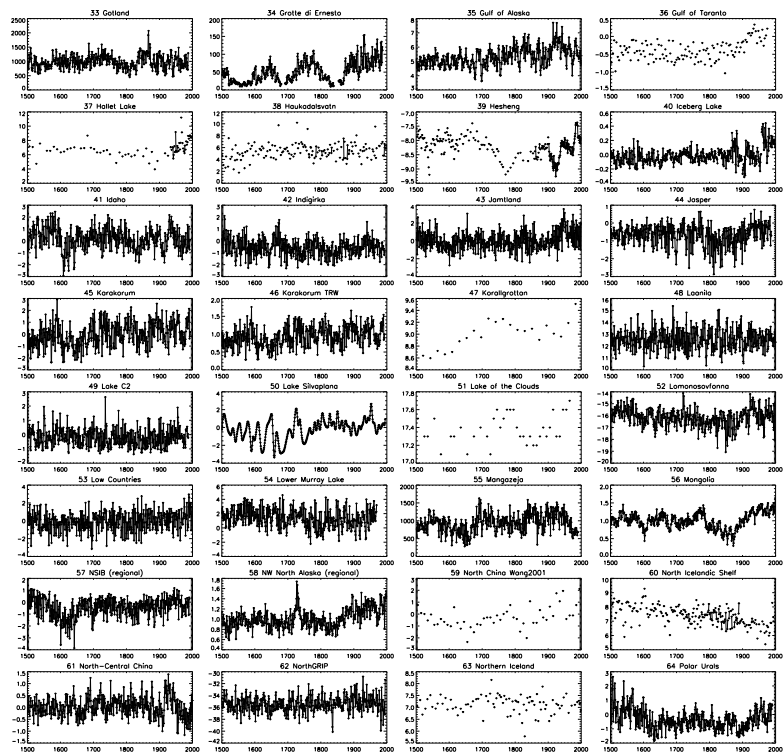


Fig. 2. Continued.

4026

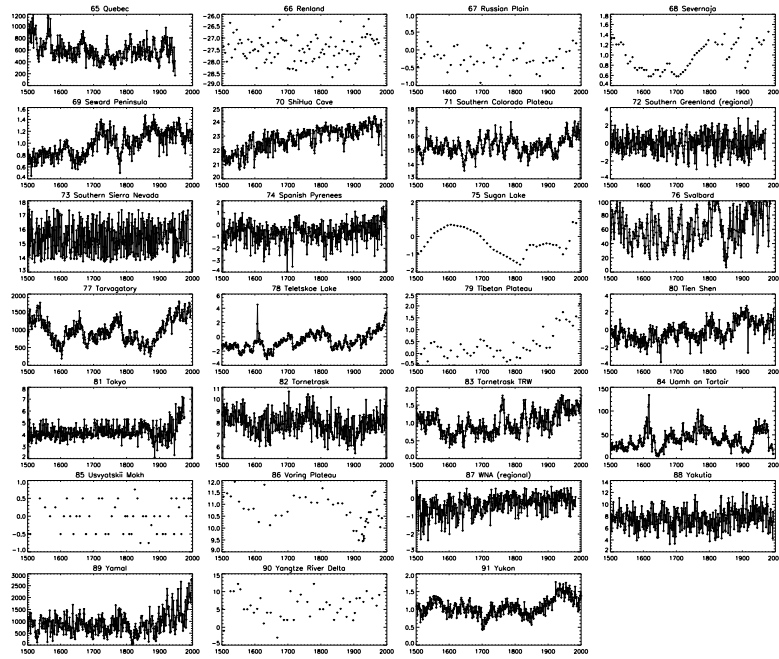


Fig. 2. Continued.

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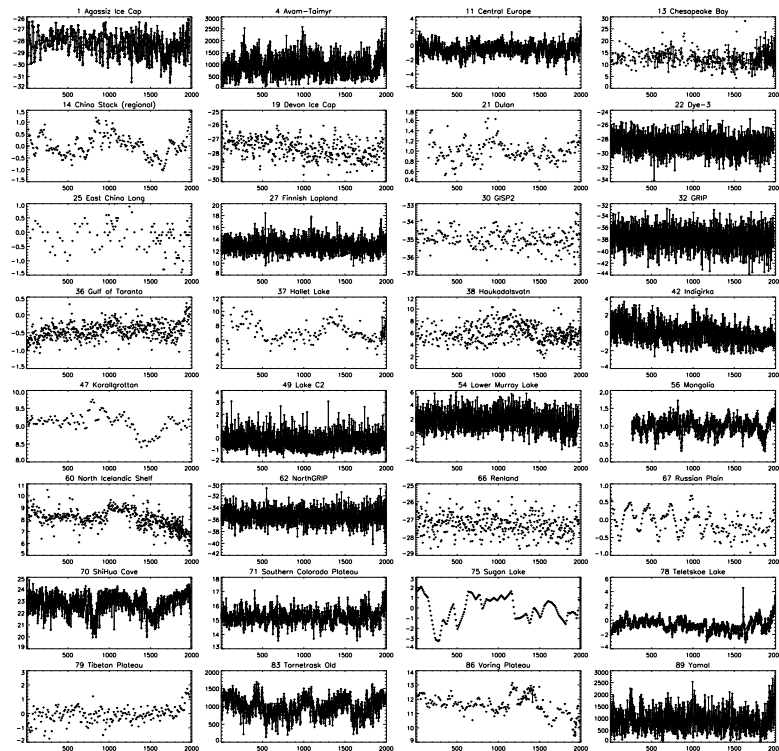


Fig. 3. The 32 proxies gray-shaded in Table 1 reaching back to at least AD 300 as function of time.

4028

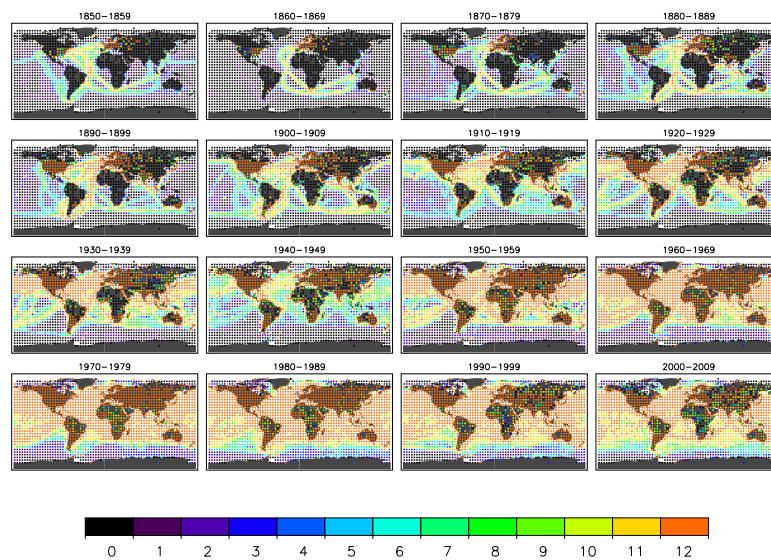


Fig. 4. Average number of months per year with data in HadCRUT3v in different decades.

4029

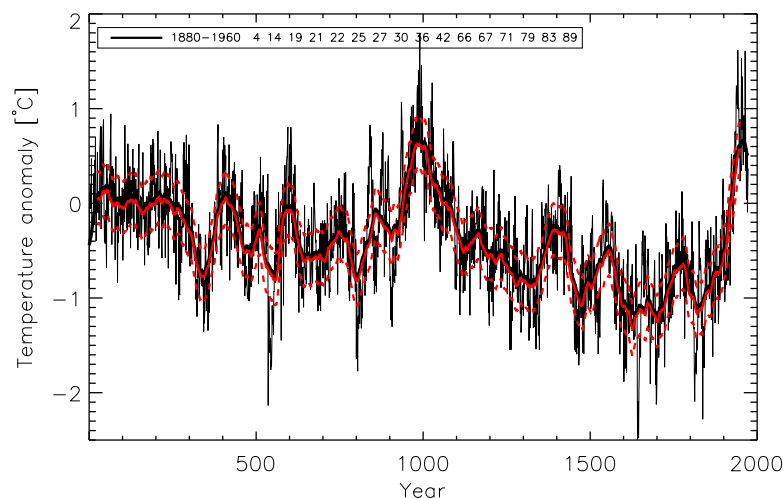


Fig. 5. Reconstruction of the extra-tropical NH mean temperature ($^{\circ}\text{C}$) based on the proxies reaching back to AD 1 in Table 1 (shaded gray). Calibration period AD 1880–1960. Only proxies with positive correlations and a p -value less than 0.01 are used. The included proxies are given in the legend. Thin curves are annual values, thick curves are 50-yr smoothed. Red curves show bias and confidence intervals for the 50-yr smoothed values. From ensemble pseudo-proxy studies mimicking the reconstructions we have calculated the distribution of 50-yr smoothed differences between reconstructions and target. The biases and the upper and lower 2.5 % quantiles are calculated from these distributions. In the figure the biases (full red curves) have been added to the real-world reconstructions. Likewise, the upper and lower quantiles have been added to the real-world reconstructions (dashed red curves).

4030

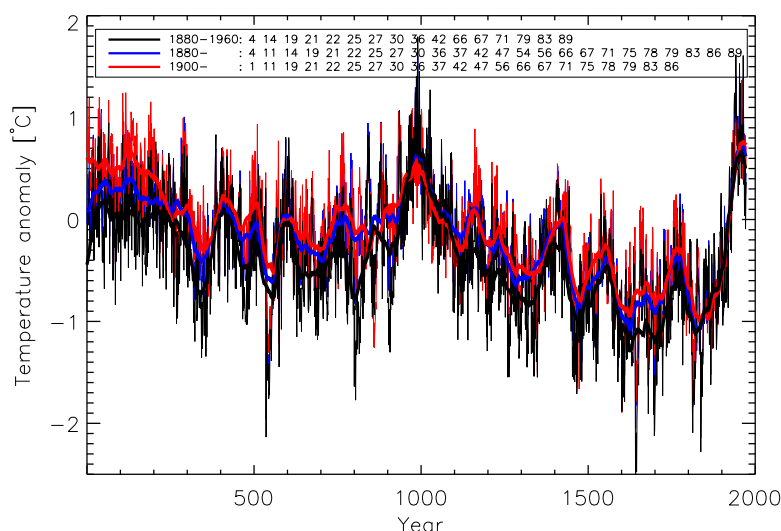


Fig. 6. Reconstruction of the extra-tropical NH mean temperature ($^{\circ}\text{C}$) based on the proxies reaching back to AD 1 in Table 1. Different calibration periods: AD 1880–1960 as in Fig. 5, 1880 to the final year of each individual proxy, and 1900 to the final year of each individual proxy. See Table 1 for the last year of the individual proxies. Only proxies with positive correlations and a p -value less than 0.01 are used. The included proxies are given in the legend. Thin curves are annual values, thick curves are 50-yr smoothed. All reconstructions centered to zero mean in AD 1880–1960.

4031

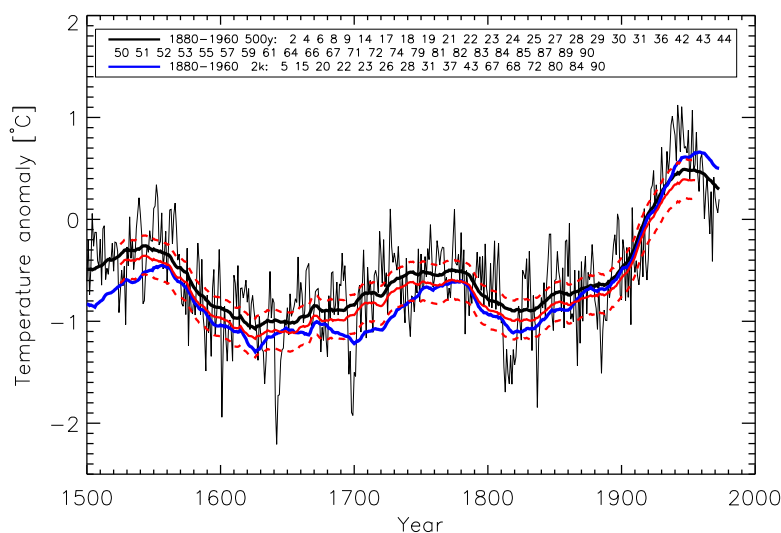


Fig. 7. Reconstruction of the extra-tropical NH mean temperature ($^{\circ}\text{C}$) based on all the proxies in Table 1. Calibration period AD 1880–1960. Only proxies with positive correlations and a p -value less than 0.01 are used. The included proxies are given in the legend. Thin curves are annual values, thick curves are 50-yr smoothed. The two-millennia long reconstruction from Fig. 5 is shown in blue. Red curves show bias and confidence intervals for the 50-yr smoothed values (see caption to Fig. 5).

4032

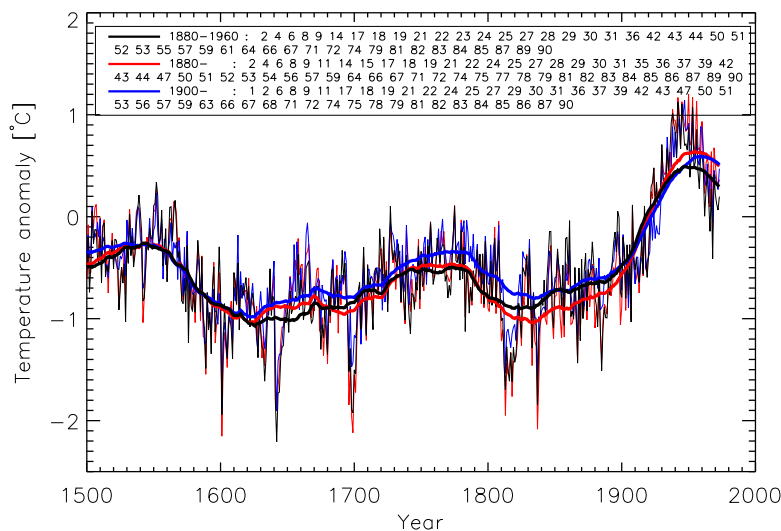


Fig. 8. Reconstruction of the extra-tropical NH mean temperature ($^{\circ}\text{C}$) based on all the proxies in Table 1. Different calibration periods: AD 1880–1960 as in Fig. 7, 1880 to the final year of each individual proxy, and 1900 to the final year of each individual proxy. See Table 1 for the last year of the individual proxies. Only proxies with positive correlations and a p -value less than 0.01 are used. The included proxies are given in the legend. Reconstructions are centered to zero mean in AD 1880–1960. Thin curves are annual values, thick curves are 50-yr smoothed. Green and yellow curves show the observed temperature mean over grid-cells with proxies and the extra-tropical ($> 30^{\circ}\text{N}$) mean, respectively.

4033

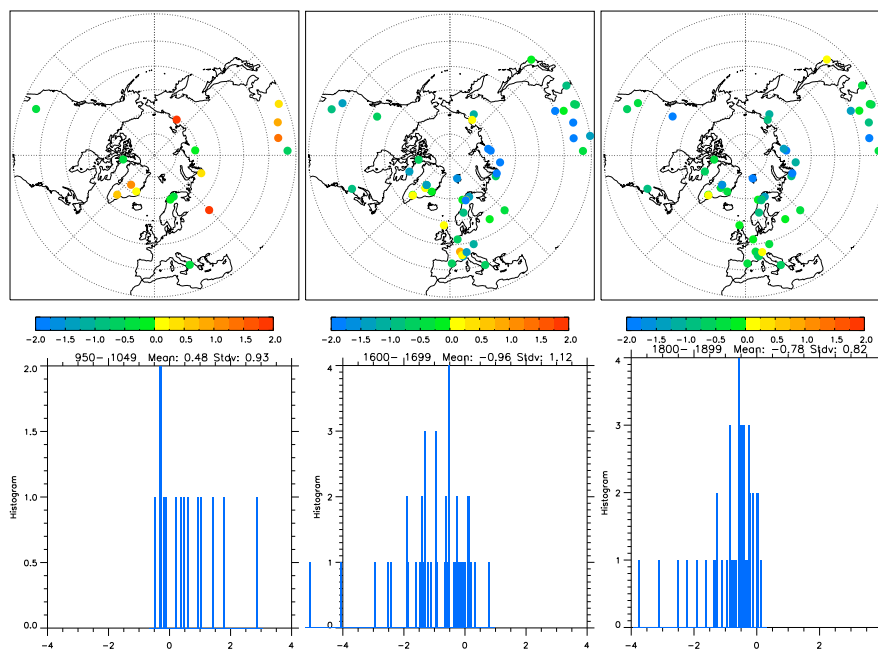


Fig. 9. Top: the geographical distributions of temperature anomalies in the period AD 950–1049 (left, two-millennia long reconstruction), AD 1600–1699 (middle, 500-yr long reconstruction), and AD 1800–1899 (right, 500-yr long reconstruction). For clarity temperatures have been cut off at -2 and 2°C . Bottom: the corresponding histograms. Calibration period is AD 1880–1960.

4034

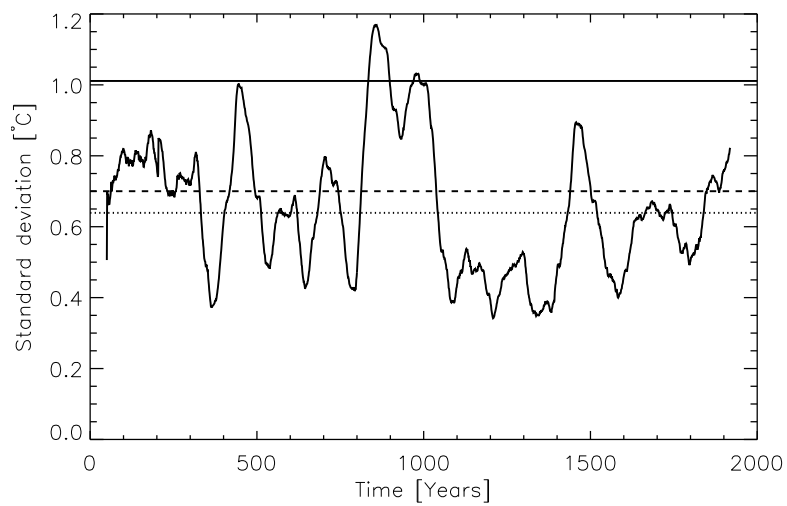


Fig. 10. The spatial standard deviation of 100-yr means of the local reconstructions (two-millennia long reconstruction, calibration period AD 1880–1960). The horizontal axis indicates the central years of the 100-yr periods. Horizontal lines indicate the standard deviation of the periods, AD 950–1049 (solid line), 1600–1699 (dotted line), and 1800–1899 (dashed line).