EVALUATION OF A RECONSTRUCTION OF WINTER AND SUMMER TEMPERATURES IN THE LOW COUNTRIES, AD 764–1998

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Abstract. A new reconstruction of winter and summer temperatures in the Low Countries (the present-day Netherlands and Belgian Flanders), based upon documentary evidence from AD 764 to 1705 and extended by observations to 1998, is compared with relevant paleo series from the European network. The Low Countries Temperature (LCT) reconstruction is well supported by existing evidence in both seasons from about 1300 onwards, on timescales ranging from annual to centennial. The spectral analysis confirms that the dominant oscillations in the LCT have counterparts in the independent data and that most of the periodicities characteristic for the instrumental segment of the LCT are preserved in the reconstruction. Throughout this period of reliable reconstruction there was no detectable inhomogeneity of the variances in either seasons. Prior to about 1300, there are few sources that can be used to evaluate LCT. It was possible to add some support for the LCT on decadal and centennial timescales for the 12th and 13th centuries. However, there is no independent data for the first three centuries of the reconstruction. The LCT series exhibits significant season-dependent variability on bidecadal and centennial timescales. The seasonality is particularly remarkable in the 10th and 15th centuries which were – on average – warm in the summer and cold in the winter. The 20th century was by far (three standard errors) the warmest century of the last millennium in terms of winter temperatures, while the 13th century was warmest in terms of summer temperatures (by the narrow margin of one standard error). In both seasons, the coldest centennial period was centered around 1600. The present results place the reconstructed LCT series within the existing paleoclimatic network, and provide an insight into temperature variability in the Low Countries through the centuries.

1. Introduction

Empirical estimates of natural climate variability on timescales of a few decades to centuries are vital to the problem of detecting and predicting anthropogenic warming (Santer et al., 1996). The global instrumental record (100–150 years) is too short to provide reliable estimates on longer timescales. More robust empirical insight into long-term climate variability can be obtained using paleo datasets. Global networks of paleo climate reconstructions are permanently evolving. These aew based on proxy indicators such as tree rings, corals or ice-melt records (Jones et al., 1998; Mann et al., 1999). Documentary data are an important addition to natural archives in Europe. The advantage of documentary sources is that they provide proxy data on climate conditions throughout the year, while other indicators are typically restricted to the warm period of the year (Jones et al., 1998). In

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view of the fact that seasonality plays a crucial role in low-frequency temperature variability (Morgan and Ommen, 1997; Shabalova and Weber, 1999; Datsenko et al., 2001), this feature enhances the significance of documentary sources among other paleo proxies.

There is a large body of paleo data incorporating estimates of climatic parameters from documentary evidence (Easton, 1928; De Vries, 1977; van den Dool et al., 1978; Pfister, 1985; Alexandre, 1987; Wang et al., 1991; Ogilvie, 1992; Ogilvie and Farmer, 1997; Pfister et al., 1998; Koslowski and Glaser, 1999; Glaser et al., 1999). This was recently augmented by a reconstruction of winter and summer temperatures in the Low Countries going back to circa AD 800 (van Engelen et al., 2001). The reconstruction is based on a proxy dataset of documentary indicators by Buisman and van Engelen (1995, 1996, 1998), reflecting weather conditions and severe events in a period spanning more than one millennium of the history of the Low Countries. This reconstruction, hereinafter referred to as the LCT (Low Countries Temperature), represents an initial step in exploiting the bulk of information presented by the proxy dataset.

This paper examines how the reconstructed seasonal LCT series fit in with the existing paleo temperature network. Since the process of reconstructing the LCT series has been described in detail elsewhere (Buisman and van Engelen, 1995; van Engelen et al., 2001), only a brief description of the procedure is given here (Section 2). Section 3 deals with testing of the LCT series for homogeneity of variances. In Sections 4 and 5, the LCT series is compared with a number of relevant European climatic series/reconstructions in the time domain and the spectral domain respectively. Section 6 concludes the paper.

2. The LCT Series

The idea of developing quantitative temperature-related indices from documentary proxy evidence originated from the early work of Cornelis Easton (1928). It was elaborated by Pfister (1985) and Alexandre (1987) and adopted in many subsequent studies (e.g., Wang et al., 1991; Pfister et al., 1998). The methodology involves a classification of seasons, as described in documentary and historical sources, in terms of climate-related proxy indices. For each year with sufficient data, these proxy indices may represent duration and intensity of warm or cold spells, the overall thermal conditions of the season, and a spatial distribution of cold and warmth in the area of coverage (e.g., Pfister, 1985). Over the period of instrumental measurements, the series of proxy indices are calibrated with a climatic parameter of interest.

Buisman and van Engelen published a four-volume survey of the documentary sources that were used to compile the quantitative proxy indices for the LCT reconstruction (1995, 1996, 1998, 2000). The major part of the text is devoted to detailed, annotated descriptions and analyses of the weather in the past. The sources in-

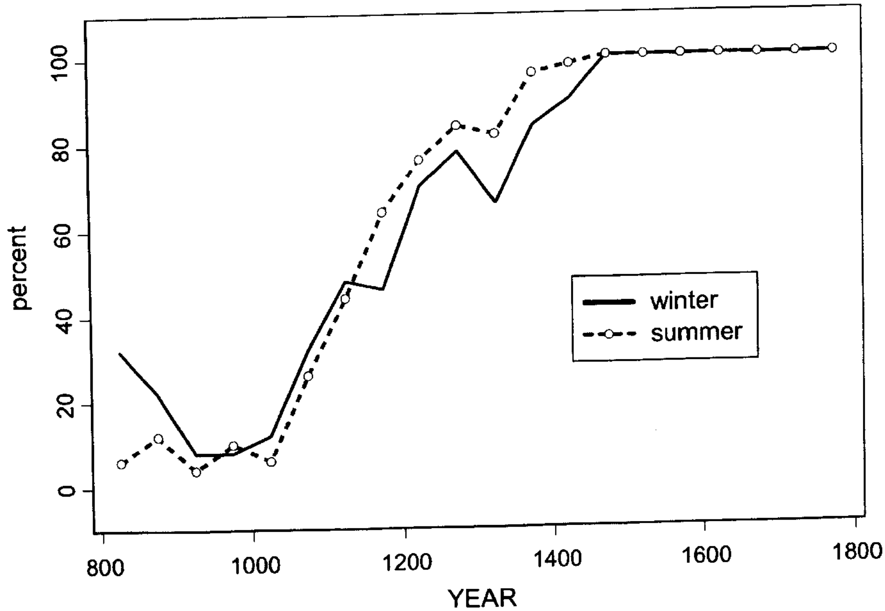


Figure 1. Percent of winters and summers per 50 year periods covered by documentary evidence.

clude direct, mostly written observational evidence, such as the instrumental series, weather diaries, letters, annals and chronicles. There is also indirect or proxy data, such as the accounts of townships, ship cargos, agriculture, water- and windmills, the accounts of river tolls etc., within which the effects of weather and climate are recorded. The proxy source provides quantitative information on the length of a frost period, the freezing of rivers, lakes and seas, the quality of harvests, the prices of various agricultural products etc. This proved to be very useful when attempting to reconstruct the weather in the Low Countries (van Engelen et al., 2001).

Given the density of available data, it was possible to develop a continuous (year by year) reconstruction reaching back to the 16th century, and a quasi-continuous (a few missing years) reconstruction going back to the 14th century (Figure 1). The further back in time one goes, the greater the number of years for which no data is available. Prior to the 13th century, only about 25% of seasons are covered by data on average. Furthermore, the existing evidence is often too scarce to allow an accurate reconstruction. Figure 2 shows the number of sources (per century) used in the reconstruction. This number increases rapidly from just a few at the beginning of the reconstruction period to its maximum of 153 in the 16th century. Figure 2 suggests that the LCT reconstruction may be considered quite accurate from the 14th century on. For many well-documented seasons of this period the reconstruction can be made in great detail. Figure 3 illustrates the geography of major sources for two subperiods. Shown are locations where the documents describing the weather in the Low Countries were found. A sharp increase in the number of sources in the later period can be ascribed to the coastal provinces of the Netherlands.

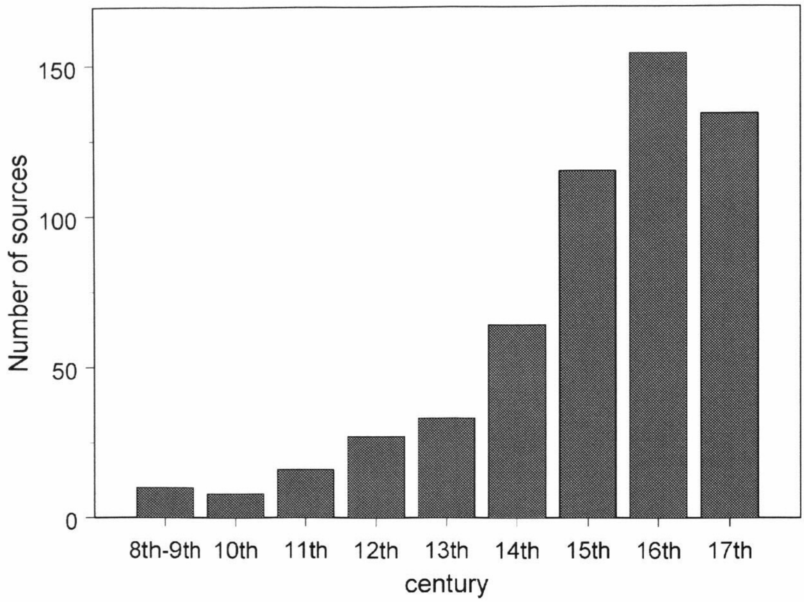


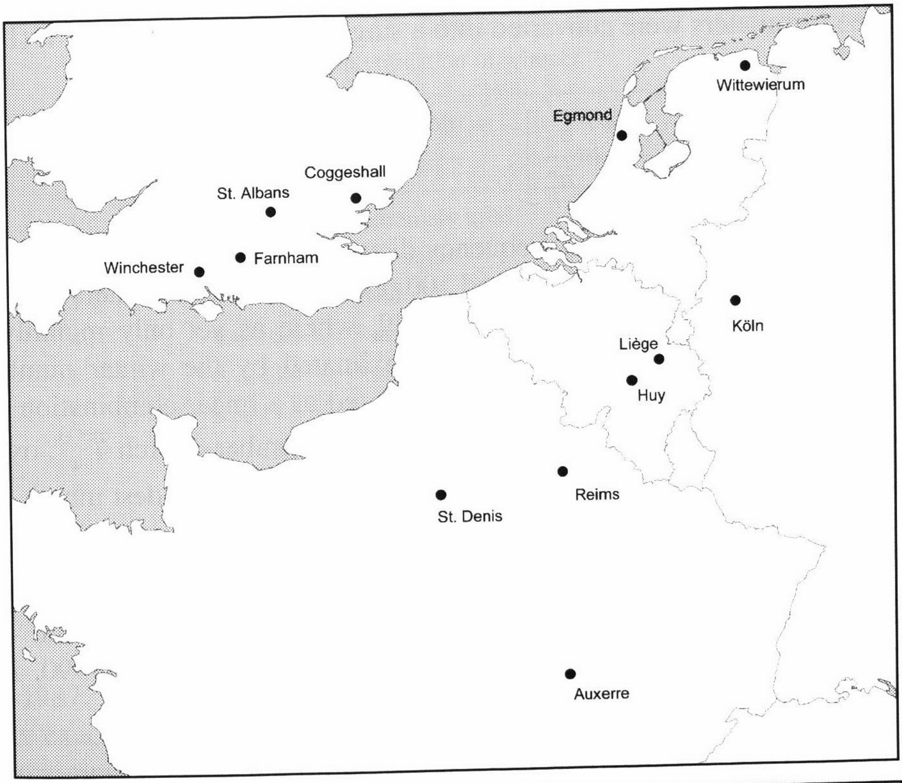
Figure 2. Number of sources per century used in the reconstruction of LCT.

The LCT reconstruction draws upon a classification of seasons in the Low Countries derived from observations at De Bilt (the Netherlands). The instrumental temperature record of De Bilt, 1706–present, was compiled at KNMI (van Engelen and Nellestijn, 1996). The early segment of the record, 1706–1734, is based on observations by Nicolaus Cruquius in Delft/Rijnsburg (van Engelen and Geurts, 1985); this is followed by the Labrijn series, 1735–1900 (Labrijn, 1945), adjusted to De Bilt. Since 1901, the daily data for De Bilt have been provided by the regular climatological service. Only monthly data are available for the period 1706–1849.

The climate of the Low Countries is mild and humid. The area is bordered by the North Sea and has an extremely flat topography, which makes the Low Countries rather windy. The dominating westerlies create a mild and uniform maritime climate with the annual mean temperature of 9.8 °C (1971–2000 average at De Bilt). Although the weather is quite changeable from day to day, uncomfortable conditions are rare. Winters are typically mild (3.3 °C) but waterways may freeze during occasional cold spells, allowing the Dutch to indulge in their traditional winter sport of skating on the numerous canals and lakes. The summers are moderately warm, with mean temperature of 16.6 °C. Precipitation is evenly spread over the seasons; the yearly sum amounts to ca. 800 mm.

2.1. CLASSIFICATION OF WINTERS

The classification of winters in the Low Countries is based on a combination of three parameters: the number of frost days n_f ($T_{min} < 0\,°C$), ice days n_i ($T_{max} < 0\,°C$) and very cold days n_c ($T_{min} < -10\,°C$). For the instrumental subperiod 1850 to present, with available daily instrumental readings of temperature at De Bilt,



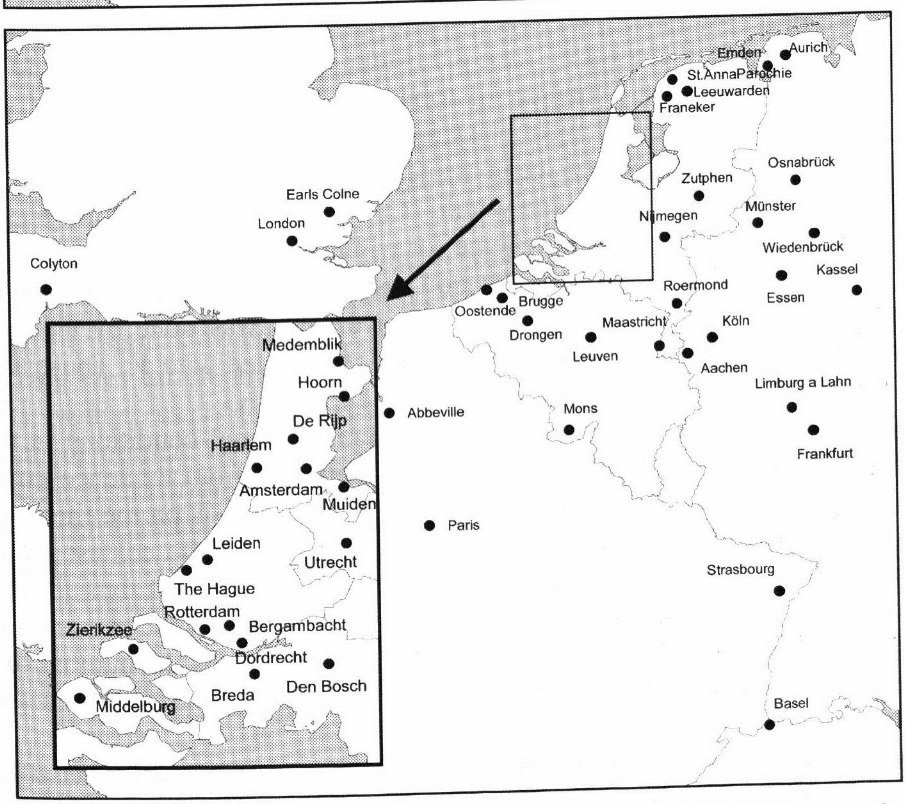


Figure 3. Geographic distribution of sources used in the reconstruction of LCT for two subperiods: 1200–1250 (top) and 1600–1650 (bottom).

these three parameters were converted into a single series of frost index V (IJnsen, 1981, 1998):

$$V = 33\frac{1}{3} \cdot \left[\frac{(n_f)^2}{(n_f^*)^2} + \frac{n_i}{n_i^*} + \frac{n_c}{n_c^*} \right], \tag{1}$$

where n_α^* are the upper 1% of n_α frequency distributions (1850–present). V varies between zero (winters without frost) and 100 (extremely severe winters).

For the instrumental subperiod 1706–1849, where as yet only monthly data were available, the frost index V was approximated by the winter number H (IJnsen, 1981). The winter number H is calculated as a linear combination of the three temperature averages: over the cold season November–March $\overline{T}_w^{(1)}$, over the climatological winter December–February $\overline{T}_w^{(2)}$, and over the coldest month $\overline{T}_w^{(3)}$:

$$H = a_0 + a_1 \cdot \overline{T}_w^{(1)} + a_2 \cdot \overline{T}_w^{(2)} + a_3 \cdot \overline{T}_w^{(3)}. \tag{2}$$

Here a_i are the empirical coefficients of values 74.88, –4.61, –3.32 and –2.31, respectively. H varies between zero and 100. Over the period 1851–1990, H and V are functionally related (IJnsen, 1981, 1998) by the equation:

$$V = exp[5.1592 \cdot tanh(0.01346 \cdot H)], \tag{3}$$

with a correlation coefficient 0.97. Using this relation, V is extended back to 1706.

In accordance with the frequency distribution of V, the 284 winters of the instrumental period 1706–1990 were classified into 9 categories C_V that relate the ranges of V with the values of mean winter temperature (DJF) at De Bilt. The categories are labeled from extremely mild ($C_V = 1$) to extremely cold ($C_V = 9$). Table I presents the classification scheme for winters.

To extend this classification to the non-instrumental data, the frost index V has to be estimated from documentary evidence. This was done by using three generalized proxy indices or aspects A_t, A_d and A_i, related with V. These aspects are quantified by discrete numbers.

The thermal aspect A_t characterizes the overall thermal conditions in winter and ranges from 1 to 5 (mild to cold). A_t is estimated from evidence covering the whole winter season November–March, with an emphasis on the three winter months December–February and an additional emphasis on the coldest month of the season. Clearly, A_t is related to the winter number H, and thus to V. The duration aspect A_d characterizes the length of the period with frost (n_f) and ranges from 0 to 2 (short/long). The intensity aspect A_i approximates the number of cold and very cold days and varies between 0 and 2 (low/high); it may be characterized by the ratio V/n_f.

The aspects are calibrated in terms of categories C_V as follows. The values of aspects have been estimated using historical documentary evidence of the period from 1850 onwards. The outcome of the scoring has been tested for the period

Table I
Classification of winters

Category (C_V)	Frost index (V)	Definition	Frequency (%)	Temperature DJF (°C)
1	<3.2	Extremely mild	1.0	6.2
2	3.3–5.7	Very mild	3.8	5.4
3	5.8–9.7	Mild	11.1	4.3
4	9.8–16.6	Fairly mild	21.0	3.3
5	16.7–28.4	Normal	26.2	2.3
6	28.5–44.3	Cold	21.0	1.2
7	44.4–73.0	Severe	11.1	–0.1
8	73.1–82.0	Very severe	3.8	–1.8
9	≥82.1	Extremely severe	1.0	–2.4

1901–1987. For 73 winters out of 87 (84%), the sum of the scores of the three aspects exactly matches the category C_V, as calculated from the daily data. For the remaining winters, the difference between the category and the sum of the aspects does not exceed one point. Such close correspondence between C_V and $A_t + A_d + A_i$ enables an extension of the developed classification into the pre-instrumental period. Using estimates of the three aspects for a particular winter of the pre-instrumental period, the category of this winter is approximated by the sum of the aspects and the temperature value is derived from the classification in Table I.

Such a fine nine-grade differentiation was possible for many well-documented winters of the pre-instrumental period. In some cases, and especially in the period prior to approximately 1200, evidence was often too scarce to support such a nine categories differentiation. Winters with insufficient evidence were classified directly (with no use of the aspects) into just three main categories (obviously very mild, about normal, obviously very cold); an estimate of temperature was then derived from the original classification by grouping the categories three by three. Figure 4 top shows the reconstructed winter (DJF) LCT series (764–1705) supplemented by observations over the instrumental period 1706–1998. The categorical data for the whole period are presented in (van Engelen et al., 2001).

2.2. CLASSIFICATION OF SUMMERS

The classification of summers is based on a single parameter – the summer number S (IJnsen, 1976, 1998). Analogously to the winter number H, S is calculated as a linear combination of the three temperature averages: over the summer season

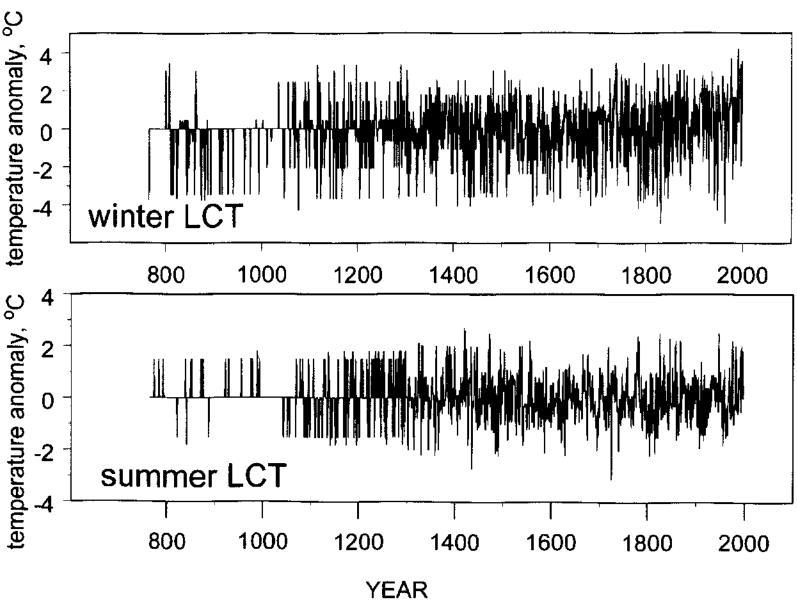


Figure 4. Reconstructed LCT anomaly series for winter (DJF) and summer (JJA).

May–September $\overline{T}_s^{(1)}$, over the climatological summer June–August $\overline{T}_s^{(2)}$, and over the warmest month $\overline{T}_s^{(3)}$:

$$S = a_0 + a_1 \cdot \overline{T}_s^{(1)} + a_2 \cdot \overline{T}_s^{(2)} + a_3 \cdot \overline{T}_s^{(3)}, \tag{4}$$

with coefficients a_i equal to –246.2, 0.1573, 0.0670 and 0.0489, respectively. Table II shows the classification scheme for summers. 284 summers of the period 1706–1990 were classified into nine categories C_S, based on the frequency distribution of S. The categories C_S, labeled from extremely cool ($C_S = 1$) to extremely warm ($C_S = 9$), relate the ranges of S with the values of mean summer temperature (JJA) at De Bilt.

In the pre-instrumental period, the category of a summer is estimated directly from documentary evidence, and a corresponding temperature value is taken from the classification. Clearly, such a fine differentiation is only feasible for a limited number of well-documented summers. Even when the evidence is abundant, a distinction between the adjacent categories involves an educated guess by a historisist. Often, particularly in the period prior to 1300, evidence is too scarce for inferring nine categories. Summers with insufficient data were classified into 3 main categories – obviously very cool, about normal, obviously very warm. A temperature estimate was then derived from the classification by grouping the original categories three by three.

The reconstructed summer (JJA) LCT series (772–1705) is shown in Figure 4, bottom; over the instrumental period, the reconstruction is continued with the observed temperature values. The categorical data for the whole period are provided in (van Engelen et al., 2001). Using the modern-day relation between the

Table II
Classification of summers

Category (C_S)	Summer number (S)	Definition	Frequency (%)	Temperature JJA (°C)
1	<13.7	Extremely cool	1.0	14.0
2	13.8–24.1	Very cool	3.8	14.6
3	24.2–34.5	Cool	11.1	15.1
4	34.6–44.8	Fairly cool	21.0	15.6
5	44.9–55.2	Normal	26.2	16.2
6	55.3–65.5	Warm	21.0	16.7
7	65.6–75.9	Fairly warm	11.1	17.3
8	76.0–86.3	Very warm	3.8	17.8
9	≥86.4	Extremely warm	1.0	18.3

annual-mean and seasonal temperatures (IJnsen, 1998), the series of annual-mean temperature was produced from the reconstructed seasonal series.

3. Homogeneity of the Variances

In this section we examine homogeneity of the variances in the LCT, for winter, $T_w(i), i = 1, \ldots, 849$, and summer, $T_s(i), i = 1, \ldots, 856$. The applied statistical tests are not sensitive to the series' gaps. In the first test the seasonal series are checked for the presence of the change points (jumps) in the variance via an analysis of the cumulative sums of squares of the series, as proposed by Inclan and Tiao (1994). The cumulative sums D_k are computed as:

$$D_k = c_k/c_N - k/N, \qquad c_k = \Sigma_{i=1,k} \Delta T^2_{w/s}(i). \tag{5}$$

Here $\Delta T_{w/s}(i), i = 1, \ldots, N$, are the winter/summer temperature deviations from the long-term means. The value of k at which the absolute value of D_k exceeds the critical boundary of the test D^* indicates a change point in the variance (a year around which a jump in variance occurs). An iterative scheme, consisting of splitting the series into two segments (before and after change point) and analysing the cumulative variance for each segment separately, gives a number of change points in the case of multiple changes.

The results of analysis of the cumulative sums D_k for the seasonal LCT series, including the test statistic M:

$$M = \sqrt{N/2} \cdot \max|D_k|, \tag{6}$$

Table III

Change points in the variances of the seasonal LCT series as detected at the 0.05 significance level in the Inclan and Tiao (1994) test. Columns 2 and 3 show the actual number N of years with data in the analyzed period and the test statistics M (Equation (6)). For the periods with M exceeding the critical value 1.358, column 4 shows the corresponding year (change point), while for the other periods column 5 gives their mean variance

Period	N	M	Year of change	Mean variance $(°C)^2$
Winter				
764–1998	849	1.99	1206	–
764–1206	108	0.86	–	5.20
1207–1998	741	1.44	1650	–
1207–1650	393	0.93	–	2.47
1651–1998	348	0.73	–	3.21
Summer				
783–1998	856	2.64	1320	–
783–1320	184	1.29	–	1.46
1321–1998	672	1.14	–	0.82

are summarized in Table III. There are two/one change points in the winter/summer LCT series, respectively.

In winter, the first change point in the variance at around 1206 approximately corresponds to the transition from the period with insufficient data (three grades scheme for most winters) to the period of detailed reconstruction (nine grades scheme). The second change point in the variance occurs roughly at the beginning of the instrumental period. This jump (increase) of variance is to be expected as the continuum of local instrumental measurements incorporates more of inter-annual variability than the proxy estimates bounded by the nine values. The ratio of the variances in two segments, 1207–1650 and 1651–1998, is 0.77. In the segment 764–1206 there is no evidence of the variance change.

In summer, the single change point in the variance occurs at the beginning of the 14th century (1320). As in the winter series, this jump corresponds to the transition from the early period of predominantly three grades reconstruction to the period of detailed nine grades reconstruction. Unlike the winter series, the summer LCT series, with its low level of variability in general, does not show any change point in the variance at the beginning of the instrumental period. The annual-mean series, as calculated from T_w and T_s, appears homogeneous over the whole period 764–1998.

Table IV
Temperature series/reconstructions used for evaluation of the LCT

Series	Period	Season	Lat. (N)	Long. (E)	Reference
CET	1659–1996	s, w	51.0	2.0	Manley, 1974, updated
C. Europe	1550–1994	s, w	46.5	8.0	Pfister, 1985, updated
IWI	1501–1995	w	~53–55	~9–14	Koslowski and Glaser, 1999
Lamb's index	1200–1440	a, s, w	England		Ogilvie and Farmer, 1997
EUR	1068–1979	a	50.0	0.0	Guiot, 1992
W.-C. Europe	750–1300	w	~45–55	~0–15	Pfister et al., 1998

The Inclan and Tiao test could fail to recognize a change point in the cases when the periods of relatively small or large variances are short. The local extrema in the variances of the LCT are analysed further with the Bartlett test (e.g., Layard, 1973), and additionally, given that estimates based on the Bartlett test may be not robust for the series with deviations from normality, with the jackknife method (Layard, 1973). In both tests, after the series are cut into K non-overlapping time periods of length N_i, we seek to reject the null hypothesis that the variances in K samples of length N_i years are equal. For various N_i ranging from 25 to 100 years, the null hypothesis of the equality of the variances is not rejected at the 0.05 significance level for both seasonal series in both tests. In the annual-mean series, both tests indicate a short period of inhomogeneity (small variances) around 1900.

4. Comparison with Existing Data

Table IV lists the paleo series from the European network used to evaluate the LCT. The series' potential for evaluation depends on a number of factors, such as the series' quality (accuracy of reconstruction), dependence on the LCT, length, and degree of spatial aggregation. With one exception (CET), the series in Table IV are reconstructions, which implies that they describe only a portion of climatic variance. The spatial separation between the series is also important. In Europe, the cross-correlation coefficient decreases by approximately one tenth with an increase of between-site distance of about 330 km (Datsenko et al., 2001). A brief description of each series is given prior to comparison.

On yearly basis, the relation between the series is estimated by the correlation coefficient. On decadal to centennial timescales, the filtered series are compared. Three filtering procedures are used: the running averaging, low-pass filtering in the spectral domain and filtering based on Singular Spectrum Analysis (SSA: Vautard et al., 1992). All three methods give similar results; the SSA method, however, provides also a statistical significance test for the derived components of variability. By

Table V
Correlations with the LCT

Series	The whole period	By centuries: 16th	17th	18th	19th	20th
CET, winter	0.71		0.82	0.66	0.62	0.76
CET, summer	0.79		0.94	0.74	0.75	0.84
C. Europe, winter	0.69	0.59	0.63	0.65	0.81	0.82
C. Europe, summer	0.61	0.57	0.69	0.44	0.68	0.73
IWI, winter	–0.75	–0.64	–0.76	–0.75	–0.76	–0.83

expanding the series in terms of the eigen vectors of the matrix of autocorrelations at lags 0 to M years, SSA decomposes the series into the so-called trend component (describing variations on timescales longer than M), a number of oscillations (with periods smaller than M), and a high-frequency noise. All SSA components which are shown below are stable with respect to variation of M. Technical details on the SSA method can be found in (Vautard et al., 1992). Some results on application of SSA to the European paleo records are reported in (Shabalova and Weber, 1999).

4.1. LCT VERSUS CET AND C. EUROPE

The instrumental record of Central England Temperature CET (1659–1998) is a composite monthly record based on various sites in the region centered at 55° N, 0° E (Manley, 1974; updated). An overview of the CET record and its detailed analysis are provided in (Jones and Hulme, 1997) and (Plaut et al., 1995; Baliunas et al., 1997; Benner, 1999) respectively. The CET and the LCT series are not completely independent, as (1) the CET record was used, though among many other data, to estimate the aspects for the winter LCT series in the period prior to 1706, and (2) a 16-yr gap (1707–1722) in the English observations was filled up with the 'adjusted' Dutch observations. In spite of the series' slight interdependence, the CET is a valuable source for evaluation because of its absolute quality, availability of seasonal resolution and proximity to the LCT.

The C. Europe temperature series is a revised version of the (Pfister, 1985) seasonal temperature index based on early-instrumental temperatures at a number of European sites for the period 1750 to present and on documentary data for the earlier period. The Pfister regional reconstruction refers to the territory of Switzerland and southern Germany.

The correlation coefficients of the LCT with the CET and C. Europe series are shown in Table V, for the entire common periods and for each century separately. The correlations are rather high in both seasons and robust over time.

On interannual to interdecadal timescales, the cross-correlations remain at the level 0.6–0.7, being strongest between the LCT and CET in winter. As an example, Figure 5 shows the 20-year running averages of the series and their smoothed versions, as obtained by SSA with $M = 100/ =$ yr. The temporal patterns of the three series are consistent on interdecadal timescales in both seasons. All six seasonal series share a pronounced cold episode in the last quarter of the 17th century. The LCT and C. Europe series consistently indicate predominantly warm winters in the first half of the 17th century and cool summers at the end of the 16th century. It will be shown in Section 5 that the spectral characteristics of the LCT, too, have counterparts in the CET record.

4.2. LCT VERSUS IWI

The Ice Winter Index (IWI hereinafter) was recently reconstructed by Koslowski and Glaser (1999) from apparently independent documentary evidence for the area of the Western Baltic. The period of reconstruction is 1501–1995. In terms of the individual years of the period 1634–1700, a comparison between the IWI and De Bilt winter temperatures (as reconstructed by van den Dool et al., 1977) has been made by Koslowski and Glaser (1999). They found only seven inconsistent winters. This indicates a good agreement between the series on interannual timescales. Correlations in Table V show that this conclusion can be extended to the whole period 1501–1995.

Figure 6 compares the IWI (cf. Figure 3 in Koslowski and Glaser, 1999) with the winter LCT on interdecadal timescales. To facilitate the comparison, the IWI (which is positive for cold winters) is inverted. The agreement is remarkable. The temporal patterns of both series show two major cold episodes extending over the periods 1650–1710 and 1770–1840, and three smaller cold events centered around 1570, 1600 and 1890; the warm phases of the series compare well, too.

4.3. LCT VERSUS LAMB'S INDEX

The revised version of Lamb's seasonal temperature indices for England is based on an improved historical dataset covering the period AD 1200 to 1439 (Ogilvie and Farmer, 1997). Ogilvie and Farmer mention 14 severe and frosty winters and 2 extremely hot summers that occurred in England during this period. With no exception, all these extreme events have counterparts in the LCT.

The decadal averages of the annual-mean temperature index for England (see Figure 6.4 in Oligvie and Farmer, 1997) and the decadal averages of the annual-mean LCT (Figure 7) show consistent temporal patterns. Only a couple of decades, most notably 1260–1269 and 1430–1439, drop out of the common pattern. In the first half of the 13th century and in the 14th century the agreement is generally good. The series share a cold start at the beginning of the 13th century, a subsequent warming trend interrupted by a cooling at around 1250, and a warm decade at the end of the 13th century. In the 1300s, both series exhibit a cooling trend at the

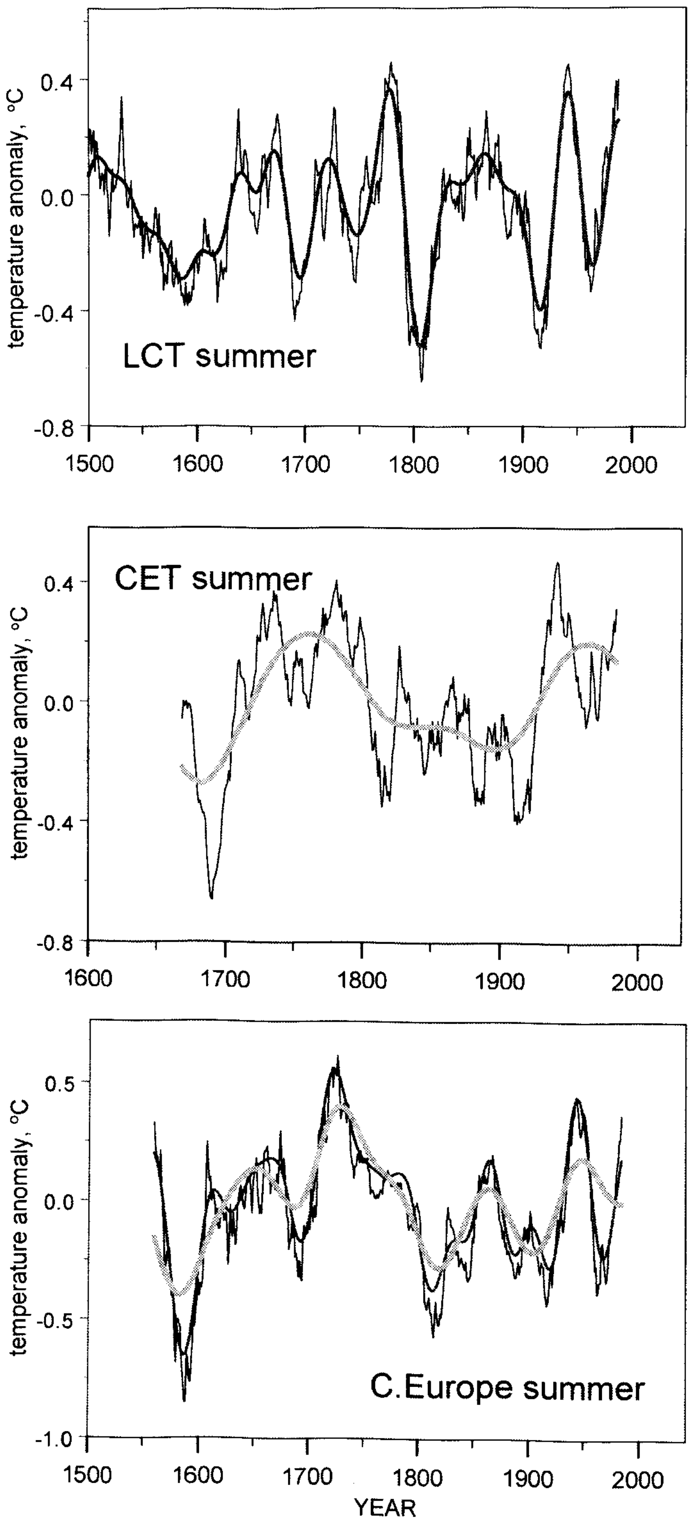


Figure 5a. Comparison of summer (JJA) temperature series LCT (top), CET (middle) and C. Europe (bottom). The thin curves are the 20 year running averages of the series; the smoothed thick curves are their SSA-based partial reconstructions.

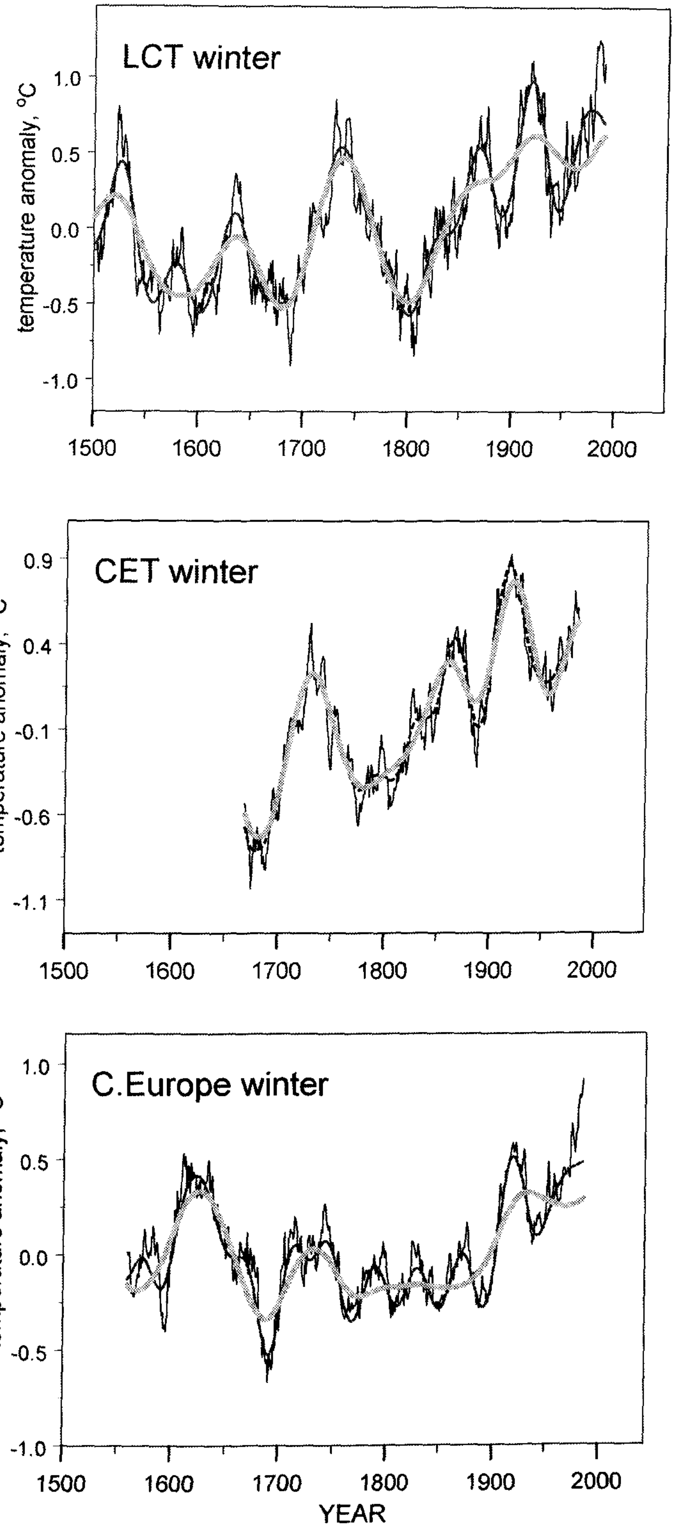


Figure 5b. Same as in Figure 5a but for the winter (DJF) temperatures.

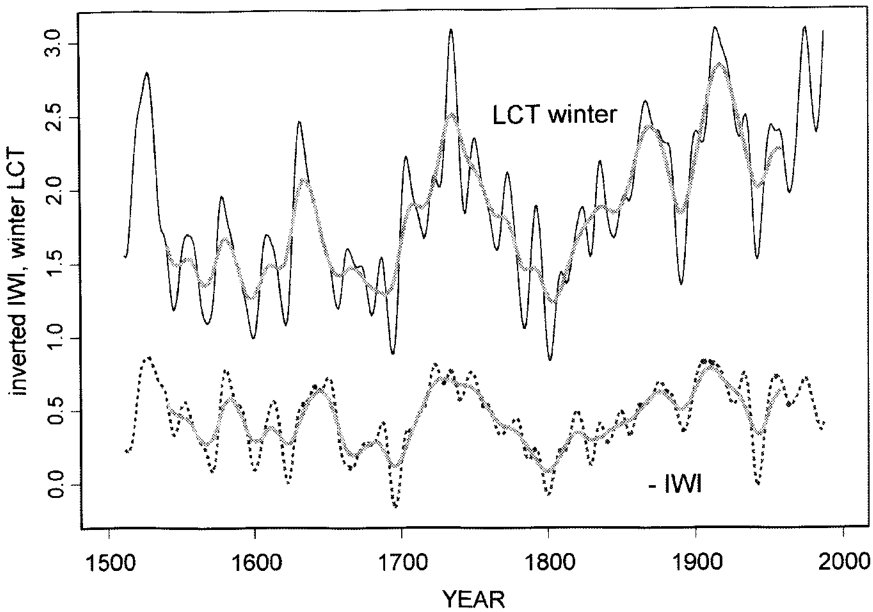


Figure 6. Winter series LCT and IWI (inverted). The thin/heavy curves are obtained by applying a Gaussian low pass filter with a 20/40 year cutoff period, respectively.

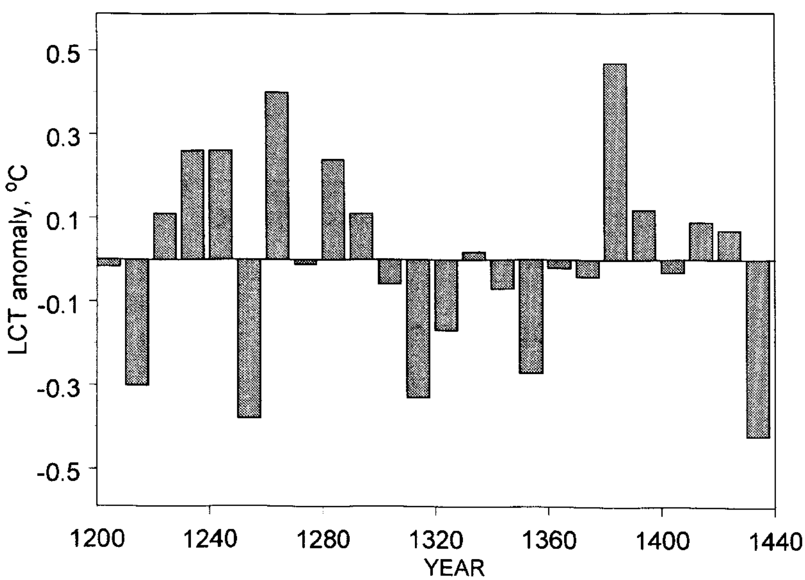


Figure 7. Decadal averages of the annual-mean LCT anomalies for the period 1200–1440.

beginning of the century, a reverse to a warmer episode around 1340–1350, and a subsequent cooling trend. The end of the 13th century is warm and the beginning of the 15th century is about normal in both series. Thus, the English source generally supports the LCT reconstruction in the 13–15th centuries.

4.4. LCT VERSUS EUR

The gridded reconstruction of the annual-mean temperature by Guiot (1992) is based on a multi-proxy dataset which appears to be independent of documentary data used to reconstruct the LCT. Guiot's reconstruction incorporates a large variety of proxy and instrumental data, including the annual-mean series C. Europe and CET, and covers the fairly long period 1068–1979. For the period 1068–1550 thus this reconstruction represents an independent source. The drawback of the reconstruction is that it describes only about 50% of the temperature variance. A single reconstructed series of Guiot's grid, from the nearest to the Netherlands grid point 50° N × 0° E, is taken for comparison; it is referred to as the EUR hereinafter.

The yearly correlation coefficient between the LCT and EUR gradually decreases from its maximum 0.58 over the latest period 1800–1979 to about 0.34 over the extended period 1300–1979. On interdecadal timescales, the series are also positively though weakly correlated; the agreement is rather poor in the period prior to 1400.

On centennial timescales, however, the LCT and EUR show a pronounced similarity of patterns of variability over the whole period of reconstruction. The components of temperature variability on timescales longer than 100 years, as derived by SSA with $M = 100$ years applied to the annually resolved series back to 1300, are shown in Figure 8. Both centennial components are statistically significant against red noise surrogates (500 Monte-Carlo simulations) at the 95% confidence level. The associated dominant timescale is about 120 years in both series. Details on the ~120 yr oscillation in the EUR are provided in (Shabalova and Weber, 1999). Figure 8 indicates that while the magnitude of centennial variability in the LCT and EUR series is different, their temporal patterns are consistent over the period of reconstruction back to 1300. The local minimums and maximums occur roughly in the same sub-periods. In the pre-1300 period, the cold 12th century is followed by the warm 13th century in both series (not shown).

4.5. LCT VERSUS W.-C. EUROPE

The winter temperature index W.-C. Europe is reconstructed by Pfister et al. (1998) for a large region comprising the Low Countries, Austria, northern Italy and parts of France and Germany over the period 750–1300. The W.-C. Europe reconstruction is based on 8850 documentary texts of which a ~15% fraction is formed by the Dutch source. The series dependence and their fragmentary character prior to the 12th century severely restricts the comparison. On the other hand, the ~85% fraction of independent sources incorporated into the W.-C. Europe reconstruction gives some justification to using it in support of the LCT reconstruction.

Each of the extremely cold and warm winters in the W.-C. Europe series (cf. Figure 10 in Pfister et al., 1998) has a counterpart in the LCT series (Figure 4 top). This is to be expected, as the extremes in the W.-C. Europe series reflect the events synchronous over the large area in the European domain. However, not only

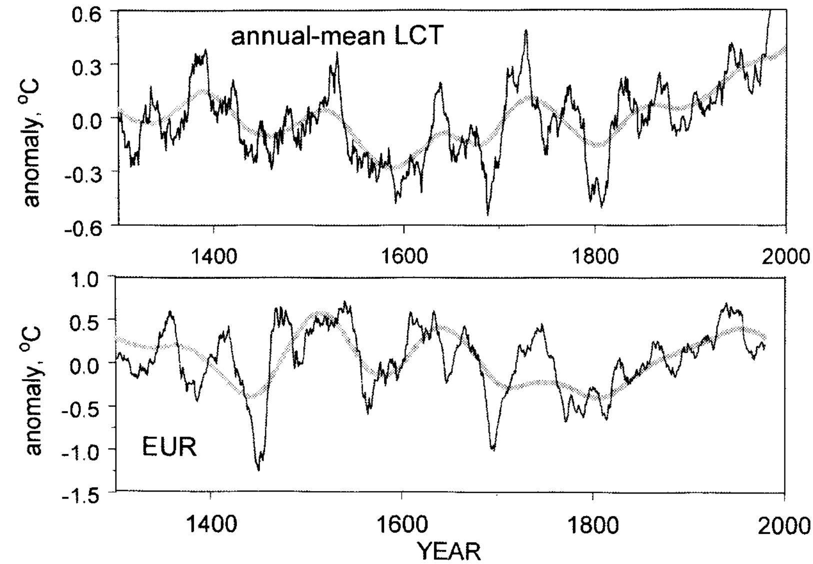


Figure 8. Centennial components of variability (timescales longer than 100 years) in the annual-mean LCT and EUR, as obtained by SSA with $M = 100$ years applied to the annually resolved series. The components describe 3/16% of the variance in the LCT/EUR series, respectively.

extremes compare well. An interesting common feature of two reconstructions is a period from the late 9th to the early 11th century, which is clearly cold in both winter series. Note (Figure 4 bottom) that the same period appears as warm in the summer LCT. A pronounced similarity between the winter LCT and W.-C. Europe on decadal timescales in the period 1100–1300, such as coinciding warm episodes around 1120, 1190–1200, 1240–1250 and cool episodes at 1160–1170 and 1210–1220, adds to the conclusion that independent sources incorporated into the W.-C. Europe reconstruction seem to support temperature variations in the winter LCT in the period prior to 1300.

4.6. SUMMARY

Over the period extending back to approximately 1300, the LCT reconstruction is well supported by the existing paleo evidence in both seasons. Over the same period, the LCT appears rather accurate, detailed, quasi-continuous and homogeneous. Further back, the LCT reconstruction becomes increasingly discontinuous and less accurate; the source of independent data for evaluation becomes nearly exhausted. Nonetheless, the annual-mean LCT series shows a consistency with the temperature index for England back to 1200 on decadal timescales, while the centennial component of variability in the LCT is consistent with that in the EUR back to the 11th century. Prior to the 11th century, the lack of independent data precludes the evaluation; the LCT reconstruction, particularly in summer, seems unique for the European mid-latitudes.

5. Spectral Analysis

In this section, we focus on the period 1321–1998 which is, in both seasons, the period of reliable homogeneous reconstruction supplemented by observations since 1706. The missing values in the winter and summer series (21 and 6 respectively) were filled in by the respective long-term means (1.85 and 16.21 °C). The oscillations are identified by application of the standard Fast Fourier Transform (FFT).

The FFT variance spectra of the LCT series over the period 1321–1998 are shown in Figure 9. A number of significant oscillations emerge on interannual timescales. In winter, the most prominent peak corresponds to the period of 3.5 yr. We note that in the instrumental segment of the winter series analysed separately, the 3.5 yr oscillation also appears prominent. The ~7.8 yr peak, being significant in the instrumental segment of the winter LCT, is absent in its pre-instrumental segment. In the summer series, the most pronounced oscillation has a period of 2.5 yr (2.2 yr in the instrumental segment). In the annual-mean LCT, there are two significant oscillations on interannual timescales, with periods ~5.2 years and ~3.5 years (5.2 yr and 3.1 yr in the instrumental segment). The same periods were identified by Benner (1999) in the annual-mean CET record.

On the low-frequency range, the summer (and annual-mean) LCT series exhibits an oscillation with an approximately bidecadal timescale, ~24 year, which is also characteristic for the instrumental segment analyzed separately. The winter (and annual-mean) LCT series shows the significant concentration of power on timescale ~120 year.

The temporal patterns of the ~120 year oscillation in T_w and T_a are almost identical; the pattern in the annual-mean temperatures is shown in Figure 8. The centennial oscillation is not a unique feature of the presently analysed reconstruction. The ~120 year cycle has been detected in the CET record (Benner, 1999), EUR series (Figure 8), as well as in the other paleo temperature proxy records in the northern hemisphere (Shabalova and Weber, 1999; Hong et al., 2000). A similar cycle is also characteristic for the solar irradiance series (Stuiver et al., 1991), which suggests the solar-climate relation on centennial timescales.

An approximately bidecadal cycle has been identified in many instrumental and proxy climate series reflecting variability on spatial scales from local (Baliunas et al., 1997), through regional (Wang et al., 1991; Cook et al., 1998) to global (Ghil and Vautard, 1991). In the LCT, the 24-yr summer mode is not robust. The oscillation is best pronounced from the mid-1600s to the 1900s, and vanishes in the first half of the 20th century. The bidecadal oscillation with the same properties was reported for the CET record by Baliunas et al. (1997).

Thus, the temperature variability in the LCT series is characterized by a number of oscillations inbedded in the predominantly white-noise background spectrum. On interannual timescales, the oscillations found in the pre-instrumental segment of the LCT do not differ much from those in the instrumental segment, except for

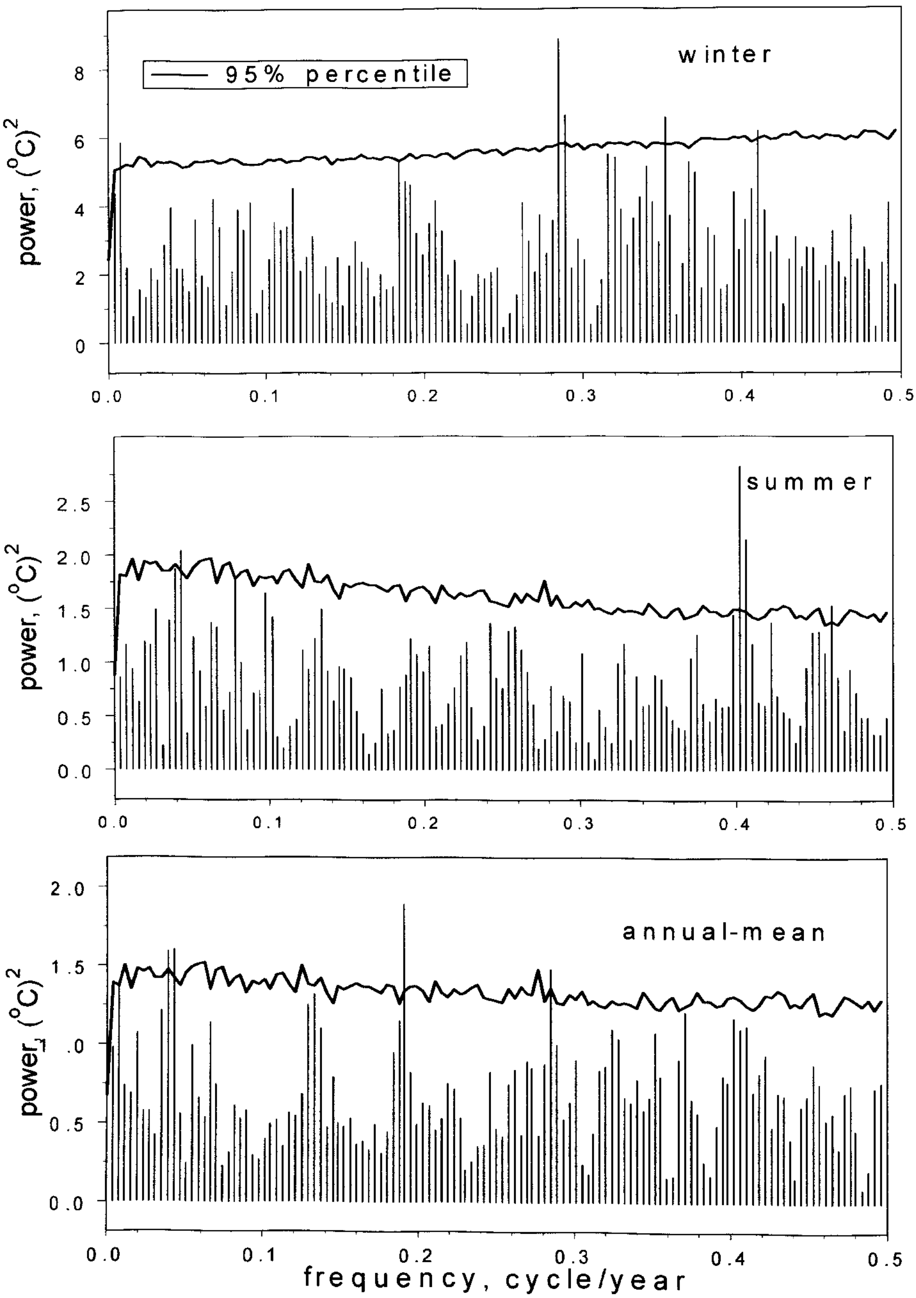


Figure 9. Fourier spectra of the LCT series from 1321 to 1998. The 95% red noise significance level is indicated.

the ~7.8 yr period in winter temperatures which is only present in the instrumental segment. The dominant interannual timescales in the LCT have counterparts in the CET record. On the low-frequency range, the LCT series display two characteristic timescales: ~24 year in summer and ~120 year in winter. These cycles are shared by a number of climatic records. The ~70 year oscillation identified earlier in the European temperatures by Schlesinger and Ramankutty (1994) seems absent in the LCT.

The seasonal dependence of the low-frequency components of temperature variability in the LCT makes it difficult to establish any continuous interval in the past which could be called undoubtedly warm or cold. The 10th and 15th centuries, for instance, are on average warm in summer while cold in winter. On the other hand, the period from the mid-1500s to 1700 is one of the coldest in both seasons, and thus can be associated with the Little Ice Age in the Low Countries. The 20th century is by far (three standard errors margin) the warmest in the winter LCT. In the summer LCT, the 13th century is the warmest one, but by the narrow margin (about one standard error). The seasonality of low-frequency temperature variability, as identified in the LCT, is in line with the earlier analyses of instrumental (Bradley and Jones, 1993; Datsenko et al., 2001) and paleo (Morgen and Ommen, 1997; Shabalova and Weber, 1999) data.

6. Conclusion

A new millennium-long reconstruction of temperature in the Low Countries, as derived from documentary evidence for winter and summer separately, is compared with a number of series from the European paleo network, including: the CET, the C. Europe temperature index by Pfister, the winter severity index IWI by Kozlowski and Glaser, the revised temperature index for England by Ogilvie and Farmer, and the EUR series by Guiot. The comparison shows that the LCT reconstruction is well supported by the existing evidence back to approximately 1300, in both seasons. It is further shown that over this period all significant oscillations in the LCT have counterparts in the independent data, and that most of the characteristic periodicities of the instrumental period are preserved in the reconstruction. This substantiates our conclusion that the LCT reconstruction for winter and summer is reliable back to ~1300, at least. Over this period, the LCT reconstruction is quasi-continuous and homogeneous.

In the earlier period, the EUR reconstruction provides a support for the centennial components of variability in the LCT back to the 11th century, while the decadal Lamb temperature index for England backs up the LCT series on decadal timescales in the 13th–15th centuries. In the 8th–11th centuries, the independent data are lacking. The W.-C. Europe reconstruction by Pfister is consistent with the winter LCT in the earliest period but it largely depends on the LCT. The LCT reconstruction for summer in the 8th–11th centuries is unique for the European mid-latitudes.

Like many other instrumental and/or paleo records, the LCT reconstruction does exhibit significant variability on bidecadal and ~120 year timescales; however, it lacks power on the multidecadal timescale. The components of low-frequency variability in the LCT are season specific. The whole century may be warm or cold depending on season: the 10th and 15th centuries, for instance, are on average warm in summer while cold in winter. The 20th century is, by the three standard errors margin, the warmest one in the winter LCT. This remarkable warmth may be related to the anthropogenic greenhouse effect. The coldest centennial period is centered around 1600 in both seasons and may correspond to the Little Ice Age in the Low Countries.

The present results place the reconstructed LCT series within the existing paleoclimatic network, and provide an insight into variability of temperature in the Low Countries through the centuries.

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