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A thousand-year record of temperature variations for Germany and Central Europe based on documentary data

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ABSTRACT: This paper presents a temperature reconstruction of the past 1000 years for Central Europe, based on chronological records. The advantages and limitations of this hermeneutic, text-based approach are discussed and the statistic methodology is introduced. Historical documents represent direct observation of weather and atmospheric conditions with highest temporal resolution available and precise dating. A major advantage of these extensive data is that they allow the reconstruction of large numbers of variables such as winter temperature, precipitation, pressure patterns or climate extremes as well as floods or storms. Within this hermeneutic climatological research approach, even human impacts and social dimensions of climate development can be examined. In order to quantify the historical information, statistical methods are applied, based on an index approach. Copyright © 2009 John Wiley & Sons, Ltd.

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KEYWORDS: temperature reconstruction; 1000 years; historical sources; Central Europe; monthly resolution.

Introduction

There are now several time series concerning climatic changes in Europe over the past 1000 years which are based on documentary records. Some of them allow conclusions about the entire time span (Buismann, 1996; van Engelen *et al.*, 2000, 2001; Glaser, 2008), while others cover separate phases (Alexandre, 1987; Brázdil and Kotyza, 1995) or are part of regional case studies (Munzar, 1995; Pfister, 1999; Deutsch and Rost, 2005; Mudelsee *et al.*, 2006).

For certain periods, historical sources can provide climate information with up to daily resolution for all seasons and are therefore an excellent basis to understand natural variability and circulation dynamics. Notably, it is possible to date the information explicitly and, above all, the approaches allow the reconstruction of different variables such as winter temperature, precipitation or pressure patterns. Furthermore, historical sources allow a long time perspective of (modern) extremes when viewed in comparison with historical documented cases, whereas natural proxies generally do not reflect extreme events to a similar degree of accuracy (Brázdil *et al.*, 2006; Bürger *et al.*, 2006).

An existing database for Germany and Central Europe (Glaser, 2008) has here been updated with new data, making it possible to reconstruct temperature for the last millennium. For this purpose, a modified calibration method was used. Furthermore, a method to estimate the error caused by the process of indexing was developed. The resulting newly derived temperature reconstruction provides insight into natural temperature variability in Europe from a hermeneutic perspective.

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Data and methods

The majority of data originate from different sources scattered over the area where German is or was the predominant language in the historical context. Under the assumption that this region is homogeneous for monthly and seasonally resolved temperature (Rapp, 2000; Glaser, 2008), sources from different places were used as indicators for a temperature series of the whole area; for instance, a 'cold winter' in one region was assumed to have been a cold winter in the rest of Germany/Central Europe too. The temporal and spatial distribution and density of information that are included in the database are shown in Fig. 1. For the following analysis only data from Central Europe were used.

Historical data

There is a wide range of historical sources available for the area under consideration. Numerous annals, town chronicles, harvest records and diaries provide direct and indirect climate-related information (Pfister, 1999; Brázdil *et al.*, 2005; Glaser, 2008).

At least five periods can be distinguished concerning historical climate information in Central Europe:

1. The oldest sources, from the 8th century until the 11th century, are more or less sporadic, describing single events, especially catastrophic extremes such as floods, droughts and severe winters, as well as earthquakes, aurora borealis, etc. For the period around AD 1000 some of the annals as well as some chronicles cannot be located exactly. The modern name of the source does not reveal the original historical location, but rather the finding place. There are some fluctuations concerning the abundance and variety of the sources which can be related to the overall political

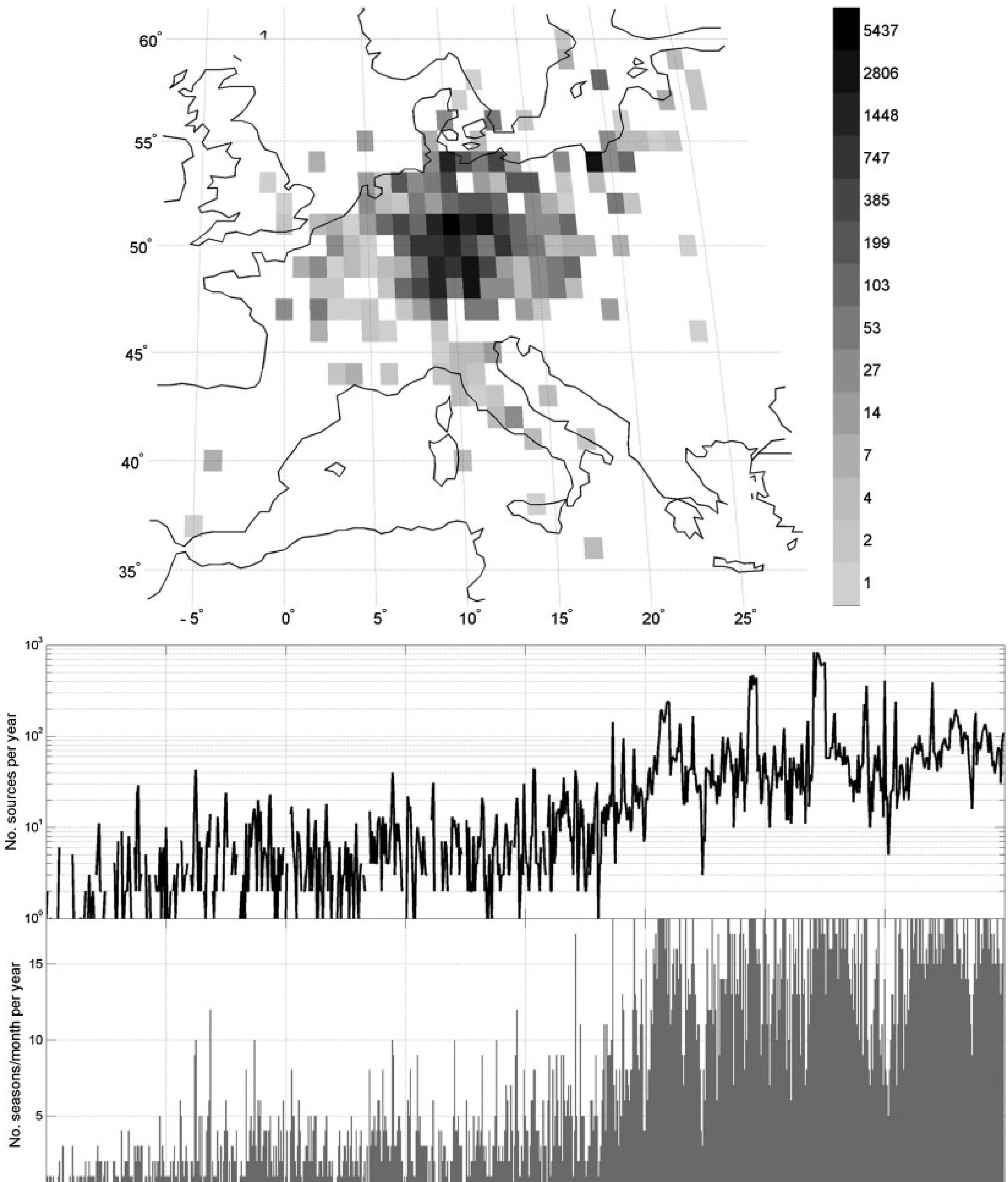

Figure 1 Spatial and temporal distribution and density of information in the database HISKLID. The grey scale on the map represents the number of information per region. The two time series show the absolute number of items of information per year and the number of covered seasons and months per year

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and cultural changes. For the period after AD 1000, with the establishment of the Ottonian dynasty (in AD 936), cultural development spread, with an increased interest in writing and documentation. At the beginning of the 11th century the variety and complexity of sources increased, with a higher reliability and differentiation than for the period before.

2. From the Late Medieval Period (around AD 1300) onwards there is more continuous information of winter and summer conditions available, as well as an increasing amount of information about spring and autumn. Again, the number of annals and chronicles rose significantly. The *Monumenta Germaniae Historica* (MGH), an edition of medieval sources, which is partly digitised and available through a virtual Library (Pertz, 1826) and the *Chronik Deutscher Städte* (CDS, Chronicles of German Cities), covering wide parts of the historic Holy Roman Empire stretching over Europe, is some sort of 'backbone' for large parts of the reconstructions. The sources – many in Latin, the others in old German regional languages – provide differentiated information about seasons, single events, extremes and phenological dates, as well as impacts on society (see Glaser, 2008).
3. Starting from AD 1500, there are such an number of sources available that it is possible to derive monthly descriptions. Printing technology had been developed by Gutenberg in AD 1458, the paper industry was growing and more people could read and write. During this period, so-called astrological calendars became quite popular – an important basis for daily weather descriptions. Textual sources and observations became much more sophisticated. Priors of monasteries and even peasants kept their diaries, describing the relation between weather situation and the status of the agriculture and harvest results as well as prices. Town chronicles describe in detail damage due to weather extremes and their costs.
4. For Central Europe, early instrumental readings are available since AD 1680; most of them are sporadic, rather experimental and far from being standardised or homogenised. Following the first attempts and examples of the Royal Society, the Royale Société de Medicine de Paris and the Academia de Cimento, for a short time from AD 1781 to 1793 the network of the *Societas Meteorologica Palatina* was established, stretching from North America into Russia, with the first set of standardised measurements. All these early instrumental readings came along with daily weather descriptions. With the Age of Enlightenment a new scientific perspective on climate was established (Schneider-Carius, 1955; Körber, 1987).
5. Since the mid 19th century, several climatological societies have been founded and some regional and national networks have been established. The First International Meteorological Congress, held in Vienna in AD 1873, resulted in a major breakthrough in the history of meteorology, including the establishment of national meteorological services with their respective networks of weather observation stations. These station records form the basis for modern instrumental climatology.

Much of the historical written data and a compilation of the weather references used for this study were published by Glaser and Militzer (Glaser and Militzer, 1993; Glaser, 2001, 2008). Significant parts (approximately 60%) of the data can be accessed via the web interface www.hisklid.de (Historische Klimadatenbank Deutschland – historical climate database Germany). The sources for the data used are included in this database. The website and database also include thermal and hygric indices and a sea ice index for the Western Baltic from AD 1500 onwards (Koslowski and Glaser, 1999). These compilations and the entire database are under permanent development so that the 1000-year long temperature series presented here is an updated version of an earlier one published by Glaser (2001).

To calibrate the temperature indices based on the documentary evidence to temperature values, instrumental data were used. Since the study area was assumed to be homogeneous for temperature, we used the updated Mean Temperature series for Germany (MTG) as derived by Rapp (2000), which was originally presented in a report of the 'Deutscher Wetterdienst' (German weather service – Schönwiese *et al.*, 1993; Rapp, 2000). This series, which was homogenised for urban warming trends, starts in AD 1761 and is composed of different data in different sub-periods. The data for AD 1761–1890, for instance, are from four stations (three before AD 1776) – one each from the Netherlands, Germany, Austria and Switzerland (Rapp, 2000).

Quantifying historical documents

From the written sources it is possible to derive temperature-related indices (e.g. Brázdil *et al.*, 2005). For this purpose, in a first step a critical source analysis was applied which is one of the leading principles of hermeneutics. Besides the critical examination and interpretation of the historical source, further criteria for the evaluation, based on climatological and thus physical characteristics of climate, can be used; with respect to climate, the reconstructed temperature fields, pressure patterns or atmospheric conditions must be consistent. To achieve this, beyond hermeneutics natural scientific facts can also be included in the evaluation of the raw information (Glaser, 2008).

One important reason why historical observations are reliable is that the economic success or even the survival of agriculture-based societies depended highly on the harvest, which again depended on the weather. The dating was very precise with the year was structured by holy days of obligation. Therefore the historical observers – peasants, astrologers, guards who watched for fires from the city towers, chroniclers and scientists – were highly aware of weather and climate. All descriptions show very impressive efforts to justify their entries while comparing them to the phenological status, bringing the information into a temporal context while comparing it to earlier events and date the observation in a calendar.

From AD 1500 onward, there are a sufficient number of sources available to allow the derivation of monthly temperature indices, which are available until AD 1750. For this, a seven-point scale was employed, ranging from -3 for 'extremely cold' to 0 for 'normal', to $+3$ for 'extremely hot'. In order to improve the objectivity of this classification, semantic profiles for each source were created in which the hierarchical meanings of the specific expressions and terms describing weather and climate that were used by single authors were ranked and assigned to the indices. The abundance of sources makes it possible to draw a very detailed picture of the conditions of certain periods that can also be used to validate the quality of sources. For instance, as modern observations show, there is a high correlation between the ratio of snowy to rainy days with winter temperatures (Flohn, 1949, 1979). Thus, weather diaries with daily entries on precipitation types allow for checking the plausibility of statements on winter temperatures. The comparison with regular weather patterns is another way to adjust and validate the gathered information (Lenke, 1960, 1968). For the period before AD 1500, only seasonal indices with an unweighted three-term classification for temperature were used even if, for some periods, data of higher resolution are available. This loss of information and thus of variability, in the actual periods, was accepted in favour of homogeneity of the time series during AD 1000–1500.

Several studies in historical climatology have shown a linear relation between temperature indices derived from documentary evidence and instrumentally observed temperature (Lamb, 1977; Bradley and Jones, 1992; Brázdil *et al.*, 2005; Dobrovolný *et al.*, 2008; Glaser, 2008). Here we present an approach to derive approximate temperature values from the indices: the frequency distributions of both the MTG measurements for the period AD 1760–1950 (expressed as anomalies from its long-term mean, and binned into seven classes to facilitate direct comparison with the historical indices) and the indices for the period AD 1500–1750 show a similar shape (Fig. 2). Neither the instrumental data nor the indices show a normal distribution if applying a statistical test (e.g. Kolmogorov–Smirnov). The deviations in skewness and kurtosis can be explained, on the one hand, as artefacts due to the reduction to seven classes, but on the other hand also as a reflection of the climate characteristics. The qualitatively broadly similar shapes of the instrumental *versus* index data distributions can be considered as an indicator for the reliability of the method of quantifying narrative sources.

The reduction to a seven-point scale leads to a loss of information compared to the instrumentally observed temperatures: the indices suppress small variations from the mean since the zero class describes variations within almost one standard deviation (STD). They also neglect a concise differentiation of the full range of extremes as they assign all events above a certain level to the same extreme class (−3 and 3). To obtain a realistic level of variance in the final temperature reconstruction in spite of this fact, we used a simple variance scaling technique to calibrate the data. For this purpose the annual mean of the monthly indices was calculated, thus gaining more than seven possible classes to keep variability that is similar to the natural variability within the calibrated series. Before calculating the annual mean, the monthly indices were weighted with the STDs of the corresponding monthly mean temperature series derived from the instrumental measurements (MTG) for AD 1761–1970 to assure an appropriate weight of each monthly index value. After normalising (by dividing by its STD) the resulting annually resolved time series for the period AD 1500–1750, it was multiplied by the STD of the annual mean (σ_a) of the instrumental data (MTG) in the period AD 1761–1970. This procedure generates a time series of the reconstructed annual temperature anomalies:

$$\Delta\vec{T}_{\text{recon}} \left[\sum_{m=1}^{12} \sigma_m \vec{i}_m\right]_{\text{norm}} \sigma_a$$

where σ_m is the STD for each month derived from the instrumental readings and $\vec{i}_m$ is the index series for each month. The data for the period AD 1000–1500 are treated similarly and will be introduced later in this paper. This simple calibration procedure relies on the assumption that both the temperature variance and mean level remained constant over a long time period. This is evidently a simplification and methodologically different from the traditional statistical calibration of climate proxy data against representative instrumental data based on data in a long period of overlap between the two datasets. In our case, however, such a period of overlap is not available and

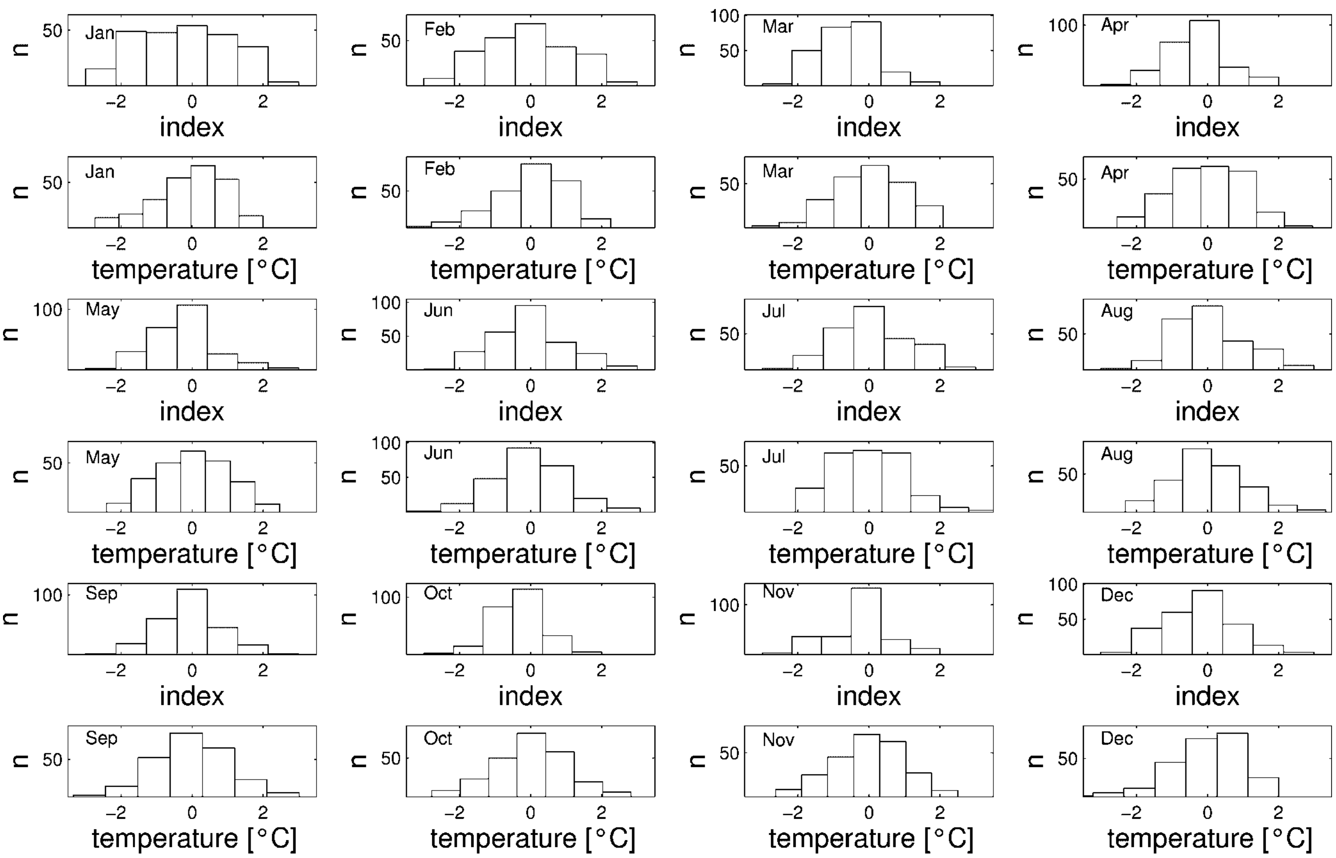

Figure 2 Distribution of indices derived from historical sources (AD 1500–1750) *versus* distribution of temperature measurements (Rapp, 2000) for each month

therefore we are restricted to using non-overlapping data in combination with the assumption of long-term constant mean and variance. In order to take account of a wide range of natural variability for the calibration, a long period (AD 1761–1970) of instrumental temperature measurements for Germany (MTG) was used.

It cannot be estimated from instrumental data alone how serious the problem regarding the assumption of constant long-term variance and mean is. Long simulations with coupled atmosphere–ocean general circulation models, forced with changing solar irradiance, can instead be used to give an indication. To obtain a rough estimate of how much the temperature variance in the region of interest can differ between 250-year periods, temperature output from a 1000-year long forced simulation with the model ECHO-G Erik2 (González-Rouco *et al.*, 2006), averaged over Central Europe, was used. The standard deviation of the moving 250-year STD series for each month in the simulation range from 0.02 to 0.07°C, and 0.04°C for the annual values. Compared to the full variances in the observed MTG data, ranging from 1.3°C for June to 2.8°C for January (0.79°C for the annual values), this long-term change in variance is very small. Therefore, the simplifying assumption that the variance for long periods remains constant seems reasonably valid for the last millennium. A similar analysis for the variability in the long-term mean in the simulation shows that the STD of moving 250-year mean temperatures for each month vary within a range from 0.11°C for July to 0.25°C for January (0.16°C for the year). This provides an approximate estimate of the degree of uncertainty in the final calibrated temperature reconstruction that is caused by our calibration approach based on no overlap between instrumental and proxy data.

There are additional uncertainties in the final temperature reconstruction that arise during the interpretation and mapping of the raw information onto the seven- or three-point index scale.

It is reasonable to assume that people living in regions of large temperature fluctuations, e.g. mountainous areas, are relatively insensitive to small temperature fluctuations. Thus, for example, an index score of +1 in the Alps would equate to a higher temperature anomaly than a score of +1 in a coastal region. The same observation applies between seasons; we cannot assume that a score of +1 in summer and +1 in winter indicate the same absolute temperature anomaly. Consequentially, indices correlate with normalised temperatures, which show coherent patterns for the study area, thus supporting the use of indices from different places. The effect of the uncertainty in the indexing procedure is estimated later in this paper.

The question then is: how many degrees Celsius does an index score of +1 indicate, as a function of the month in the year? To answer this, the linear relation between the indices and the temperatures can be used to calculate the monthly temperature anomalies as a fraction *i* (i.e. the index) of the monthly variability σ_m. Subsequently, the annual temperature anomalies are calculated as the average of these monthly anomalies:

$$\Delta \vec{T}_{\text{recon}} = \frac{a}{12} \sum_{m=1}^{12} \sigma_m \vec{i}_m$$

with the scaling factor *a* for the monthly values. Therefore, assuming the STDs of the annual anomalies are the same ($\sigma_{\text{recon}} = \sigma_a$), it is possible to estimate the scaling factor:

$$\text{STD}\left(\frac{a}{12} \sum_{m=1}^{12} \sigma_m \vec{i}_m \right) = \sigma_a \Leftrightarrow |a| = \frac{\sigma_a}{\text{STD}\left(\frac{1}{12} \sum_{m=1}^{12} \sigma_m \vec{i}_m \right)}$$

For the area and data under consideration *a* is approximately 0.85; i.e. an index score of one relates to a temperature anomaly of about one STD. The STDs of the monthly temperatures range from about 1.3°C for July to 2.8°C for January; therefore one index score relates to a distinct temperature difference.

The year-to-year signal of temperature variations is strong compared to changes in the medium-term temperature development that might have affected people's perception of temperature. To estimate these medium-term changes the 31-year moving average (following the climate normal period) of each month in the MTG series was calculated. The standard deviation of this series ranges from 0.2°C for July to 0.7°C for January, which is only 15–25% of the STD of the unsmoothed monthly temperatures. Bearing in mind a high inter-annual and monthly variability compared to low medium-term changes, it appears reasonable that people were able to clearly distinguish temperature anomalies.

As already mentioned, the calibration method used here differs from previous approaches that use a calibration period of overlapping proxy and instrumental data to estimate the relation between the proxy and the climate signal. The rationale behind the presented method is (as already noted) based on two assumptions: first, that there is a linear relation between the indices and temperature as shown in several studies (Lamb, 1977; Bradley and Jones, 1992; Brázdil *et al.*, 2005; Dobrovolný *et al.*, 2008; Glaser, 2008); second, that the temperature variability of a long period (here more than 200 years) stays constant.

The question then is how single observations of historical observers can lead to a long-term signal. There is enough evidence that historical observers were able to recognise deviations on a monthly or seasonal scale because the observations were related to manifold indicators of agricultural practise and environmental conditions. Since the observations cover a broad range of climate variability, these deviations reflect distinct temperature differences. Long-term trends result from accumulations of unidirectional temperature anomalies in several months. Even in instrumental records single months do not show a pronounced long-term signal (Fig. 3) but a high inter-annual variability. The long-term signal (as shown in Fig. 4) results if many months in a longer period show anomalies with the same sign. The ability of the hermeneutic approach to provide climate information in all seasons and months is a major advantage over many other proxies which are sensitive only to particular seasons of the year. Of particular importance is information on winter temperatures, as the amplitude of variability is higher than in other seasons. Therefore winter temperatures have a greater impact on the overall temperature signal. As Fig. 3 shows, there is a remarkably strong inter-annual variability for each month as well as a high range of variability, especially for the winter months (the figure, though, does not allow direct comparison of the size of variability in different months as normalised data are plotted). As shown in Fig. 6, the variance of the historical observations using the described method leads to a long-term signal.

For the period before AD 1500, when monthly index data are not available, the calibration was performed using a further simplified approach, based on determining a decadal index for each season (Lamb, 1977; Glaser, 2008). To achieve this, a running 11-year sum of indices for each season was calculated. Then, using the same method as for the monthly indices, the time series of each season was calibrated so that it matched the STD of the 11-year moving average of the same season in the instrumental period. The 11-year annual mean was then calculated, thus deriving a time series of the 11-year running annual temperature anomalies.

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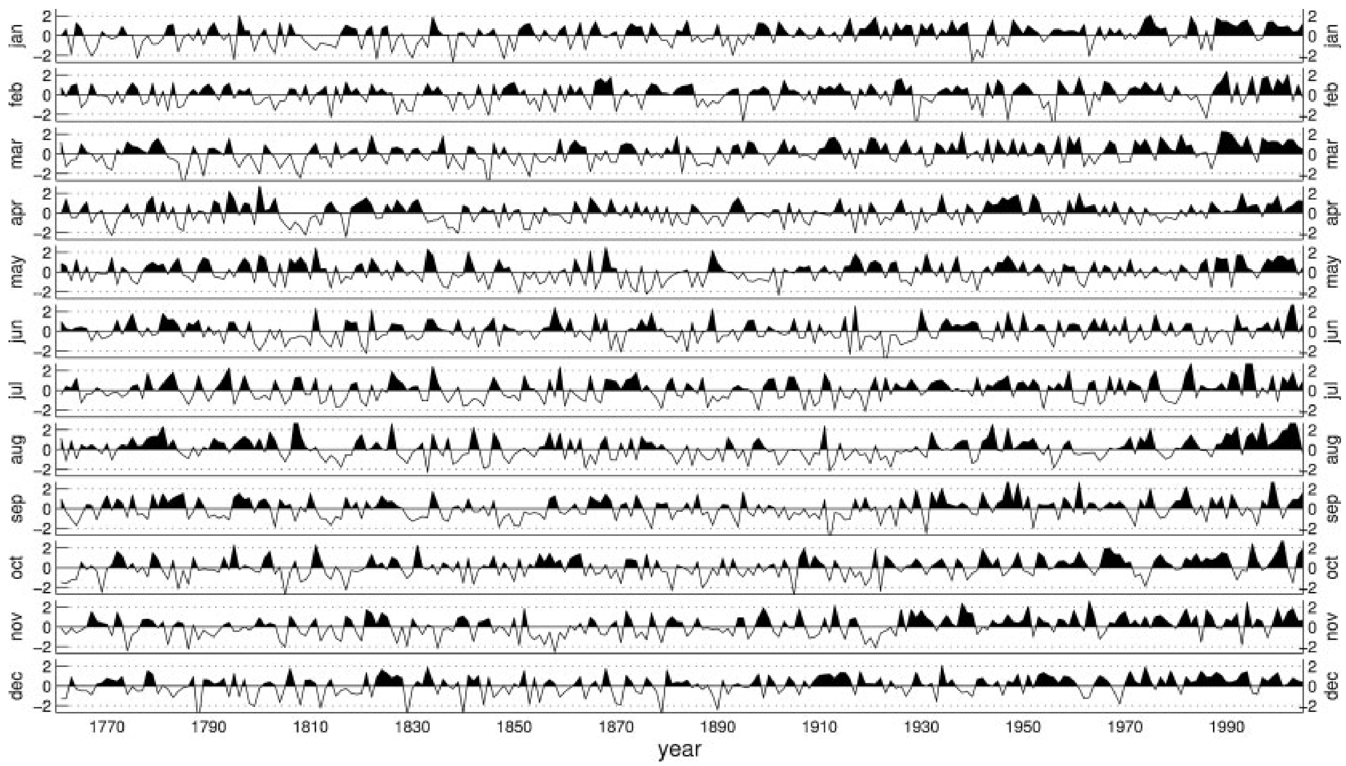

Figure 3 Normalised monthly temperature series for Germany (updated after Rapp, 2000). The reference period is AD 1770–1970

To check the loss of information when using the indexing method (compared to a continuous temperature scale), 3-point and 7-point indices were calculated from the instrumental records (MTG) and subsequently calibrated to temperature using the method described above (Fig. 4). This technique was also tested on simulated temperature data for Central Europe derived from the model ECHO-G Erik 2 (González-Rouco *et al*., 2006). Figure 4 shows in principle a strong capability of indices to describe long-term variations. Even with reduction to a 3-point scale and subsequent calibration back to temperature, thereby losing information, it is possible to keep the low-frequency signal as shown by the 11-year mean temperatures.

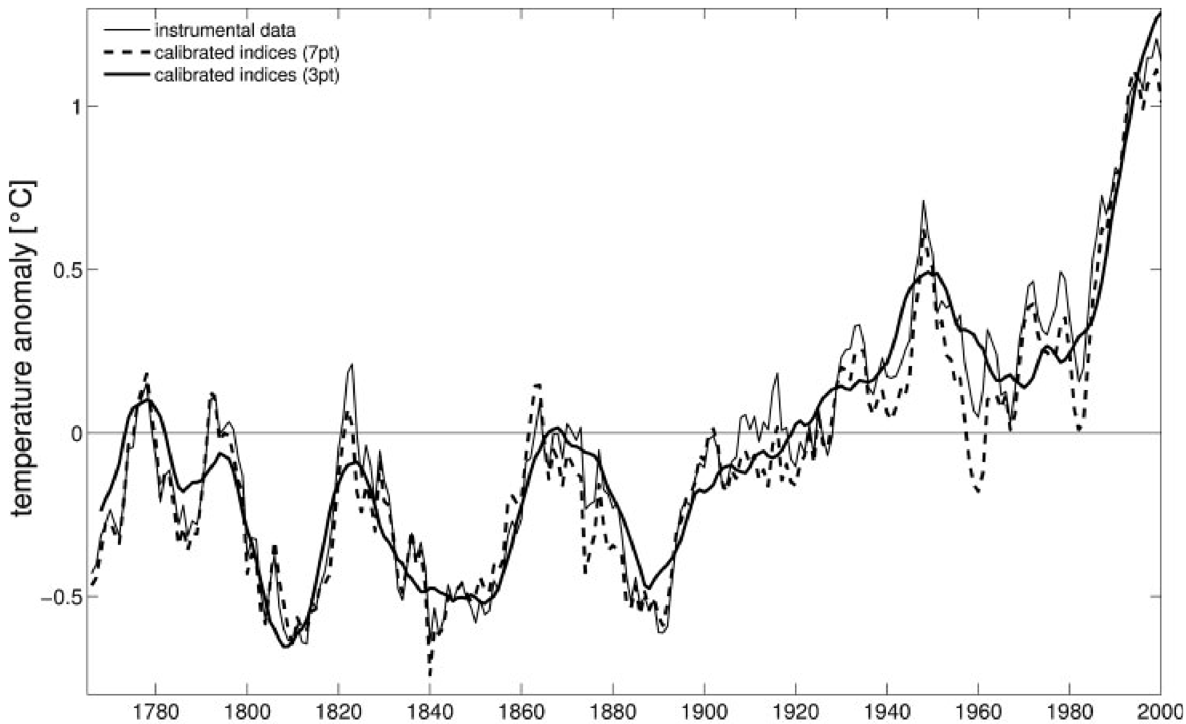

Figure 4 Comparison of instrumental temperature data for Germany (updated after Rapp, 2000) with calibrated indices that were derived from the instrumental data after degradation onto a 7-point and 3-point index scale. All series are 11-year moving averages

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Error estimation

In order to assess important sources of uncertainties in the calibrated series, a Monte Carlo (MC) method was used. For this purpose, possible errors were added during the calibration process, which was then repeated 1000 times. Possible errors that were investigated here emanate from:

1. the uncertainties related to the indices (indexing error);
2. the uncertainties due to the reduction to seven/three classes (index class width); and
3. the medium-term variability of the monthly/seasonal mean temperatures.

The individual errors were estimated as follows. Because of two subjective judgements on which the indices are based, there is an uncertainty related to the values: firstly, the subjectivity related to the observation and documentation of the perceived temperatures; and secondly the subjectivity of creating an index based on this documentation. To estimate this indexing error, every index value was randomly altered by one index step or left unchanged with an even probability for each case (i.e. 33% each) before calibration.

The error of the index class width can be thought of as the uncertainty related to the reduction of temperature to seven or three classes. It is estimated as the product of the scaling factor *a* and the STD of the month/season ($a_{\text{month/season}} \cdot \sigma_{\text{month/season}}$). This error is assumed to be uniformly distributed in the range of the class width on the monthly/seasonal values.

In order to estimate the error related to the possible adaptation of people's perception, an arbitrary choice had to be made: we used the climate normal period to estimate medium-term changes in monthly/seasonal mean temperatures. Thus, the monthly/seasonal temperature series of MTG were smoothed with a 31-year moving average. The STDs of these smoothed series were then set as the STDs of random errors with a normal distribution.

In order to calculate the overall error, in a first step the original indices were randomly altered by one index step and subsequently calibrated to monthly/seasonal temperatures as described above (indexing error). The remaining two errors (index class width and medium-term variability) were then randomly varied and added to the monthly/seasonal temperatures. This procedure was repeated 1000 times, thus gaining 1000 possible temperature series. Then, to construct a combined uncertainty range for the calibrated index-based reconstruction, the double STD of these series was used as an 'error bar', as this arguably roughly corresponds to a 95% confidence interval. This is about 0.71°C for the annual values (hence about 0.2°C for the 11-year means) for the period with monthly resolved data (AD 1500–1750) and 0.49°C for the 11-year moving average in the seasonally resolved period (AD 1000–1500). The indexing error accounts for 60% of the overall error when using monthly resolved data and for 70% when using seasonal resolved data. For the instrumental readings the error for the monthly mean temperatures is ±1°C; therefore the annual error is approximately 0.3°C and the error in 11-year averages is about 0.09°C.

Verification of the indexing method

The error estimation discussed above concerns various errors that are methodologically inherent to the construction of indices. It does provide any information about the prediction skill of the derived calibrated indices. Therefore, to address this issue also, the calibrated reconstruction is validated against instrumental data. Even though it was not possible to meaningfully calibrate the reconstruction against overlapping instrumental data, there are in fact some early instrumental observational series that can be used for validation over the period AD 1710–1750 where indices derived from historical sources are available independently from the instrumental records. The average annual instrumental temperature anomalies for the stations *Berlin-Tempelhof* and *de Bilt* (TempBdB; for details see Brumme, 1981) were calculated and compared with the calibrated indices. These two stations are the only ones from a relevant geographical region available for this period and they were also included in the MTG series which was used above for the calibration. The correlation between the average temperature for those stations and the German temperature reconstruction based on documentary data is very good ($r = 0.88$), thus allowing use of the average of only two stations for verification purposes. TempBdB was also used to close a gap in the reconstruction during the period AD 1750–1760, for which neither the documentary data nor the MTG series are available. Figure 5 compares the calibrated temperature series with TempBdB.

To test the performance of the reconstruction the correlation coefficient *r*, the root mean squared error (RMSE) and the coefficient of efficiency (CE) were calculated for the verification period (AD 1710–1750). A value of $r = 0.73$ indicates the strength of the linear relationship; just above 50% of the instrumental temperature variance is 'explained' by the proxy data. 2*RMSE could be taken as error for the reconstruction (approximate 95% prediction interval). For the verification period RMSE is 0.5°C; therefore the error for the annual values after AD 1500 can be assumed to be approximately 1°C. Although this is larger than the estimated error from the MC approach (0.71°C), the latter one is used: the verification period is too short to estimate the error for the seasonal resolved data, i.e. for the time before 1500, where the data are smoothed with the 11-year moving average. The CE can be described as an 'expression of the true squared *r* of a regression equation when applied to new data' (Wilson *et al.*, 2006). More precisely, CE compares the sum of the squared residuals obtained for the reconstruction (i.e. the differences between estimated and instrumental data in the validation period) and the sum of squared residuals obtained when the mean value of the instrumental data are used. It ranges from negative infinity to 1.0, which indicates perfect estimation. A value of zero implies that the residuals are the same as with just the mean of the instrumental data, and hence positive CE values indicate some prediction skill of the calibrated reconstruction. For AD 1710–1750 the CE is −0.15, which thus would indicate poor prediction skill. This, however, does not necessarily imply a problem with the reconstruction but might equally well reflect problems with the raw data used for BdB. These early instrumental observations are not homogenised, and there may be both a systematic bias and year-to-year errors in the BdB series. Further comprehensive error estimation, taking a regional evaluation into account, is required and under development. This issue can be addressed once the index series has been extended until AD 1800. Work on this task is ongoing.

Results

Results are obtained both concerning methodological aspects and those referring to temperature development since AD

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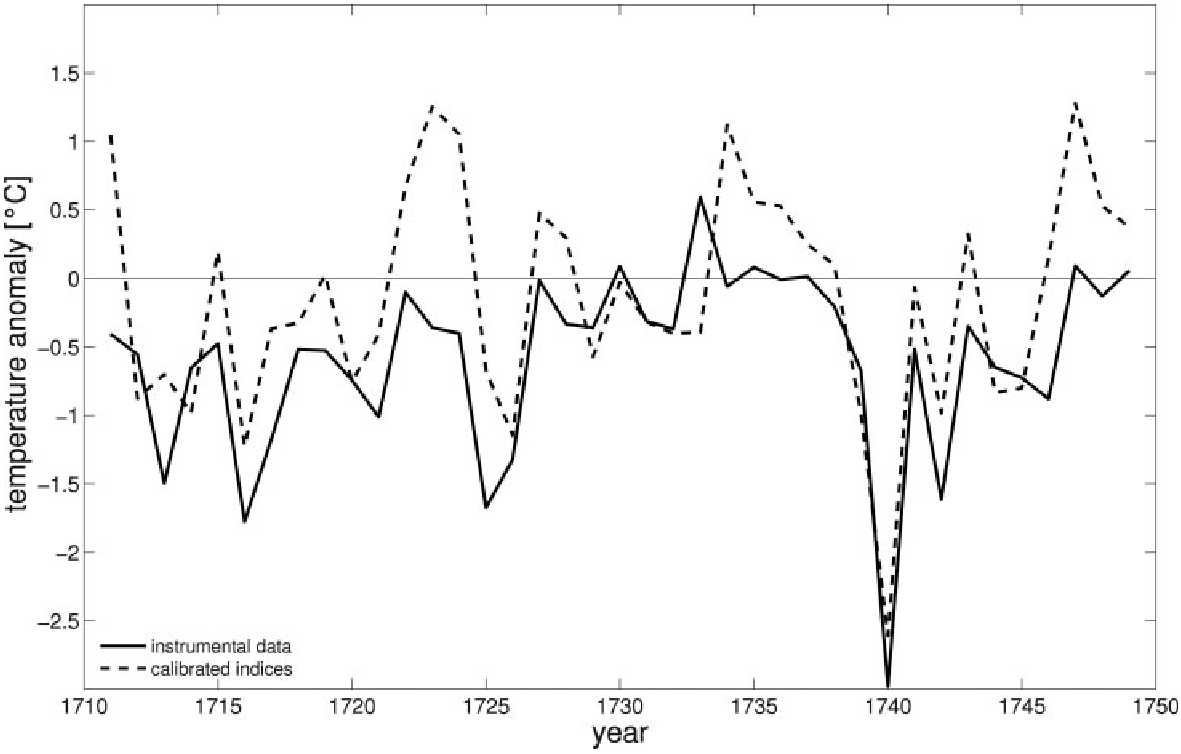

Figure 5 Comparison of the annual means of calibrated indices with the average of the instrumental records from de Bilt and Berlin/Tempelhof (TempBdB) for the verification period AD 1710–1750

1000. It was shown above that the indexing method has a strong potential for temperature reconstructions: on the one hand, the seven- (and even three-) point scale is sufficient to represent the natural variability on decadal scales and longer, as shown in Fig. 3. On the other hand, there is also an influence of the subjective process used for defining indices. In spite of the reduction of information, the method still allows analyses of climate variability as shown in Fig 4. The long-term signal in annual mean temperatures (at least in the instrumental period; Fig. 2) is the result of an accumulation of unidirectional temperature anomalies in several months. In the following, the long-term development of reconstructed temperature changes is described and discussed.

Temperature development since AD 1000

In Fig. 6, the 11-year moving average of annual temperature anomalies (reference period AD 1760–1970) for Germany/Central Europe for the last 1000 years with the error resulting from the indexing process is shown. The change of temperatures during the last 1000 years exhibits significant characteristics concerning the annual mean temperature, which spans a range of ±1.5°C for the 11-year averages. Apart from the long-term trends, there are also decadal fluctuations. The data bear evidence of several dramatic temperature drops as well as prominent warming periods – often in quick succession. This holds both for the part based on documentary evidence (AD 1000–1750) and the part based on instrumental observations (AD 1751–2007).

The following medium term trends can be identified:

1. A pronounced warm period from AD 1200 to 1350 which could be termed the Late Medieval Warm Optimum. This period was characterised by rapid changes between temperature drops and warming episodes. This pattern can be recognised above all during the 14th century, when it occurred several times in the course of a few decades. The especially contrastive situation of hot summers with cold or even severe winters during this period is remarkable (Glaser, 2008). This period in Central Europe was apparently more often dominated by high-pressure conditions than in subsequent periods (Glaser, 2008). In contrast, it appears that the contemporary greenhouse climate and its significant warming during the winter months correlate with increasing zonal circulation patterns (Jacobeit *et al.*, 2001; Sturm *et al.*, 2001; Luterbacher *et al.*, 2002) for Europe. From this difference follows the conclusion that the Medieval Warm Optimum does not represent a historical predecessor or an analogue of the modern greenhouse climate regarding the level of the annual mean temperatures and the circulation pattern.
2. A transition period with a difference between the warmest period around AD 1350 and the coldest period around AD 1550 of about 1°C. The scenario of the historical temperature drop is characterised by a shortening of the vegetation period of about 14 days (Glaser, 2001). This led to procrastination regarding the beginning of the season of spring as well as earlier winter conditions. The effect was a severe aggravation of agro-economical conditions, resulting in an increasing number of bad harvests, frost damage and crop failures (Behringer, 2007; Buszello, 2007).
3. A cold phase during AD 1550–1850, which coincides with the often referred to 'Little Ice Age'. This period is a further example for a prominent deviation from the 'normal' temperature towards a colder climatic situation, with differences in 11-year mean temperatures of up to 2.5°C in comparison to today. The absolute temperature minimum (coinciding with the Maunder Minimum of weak sunspot

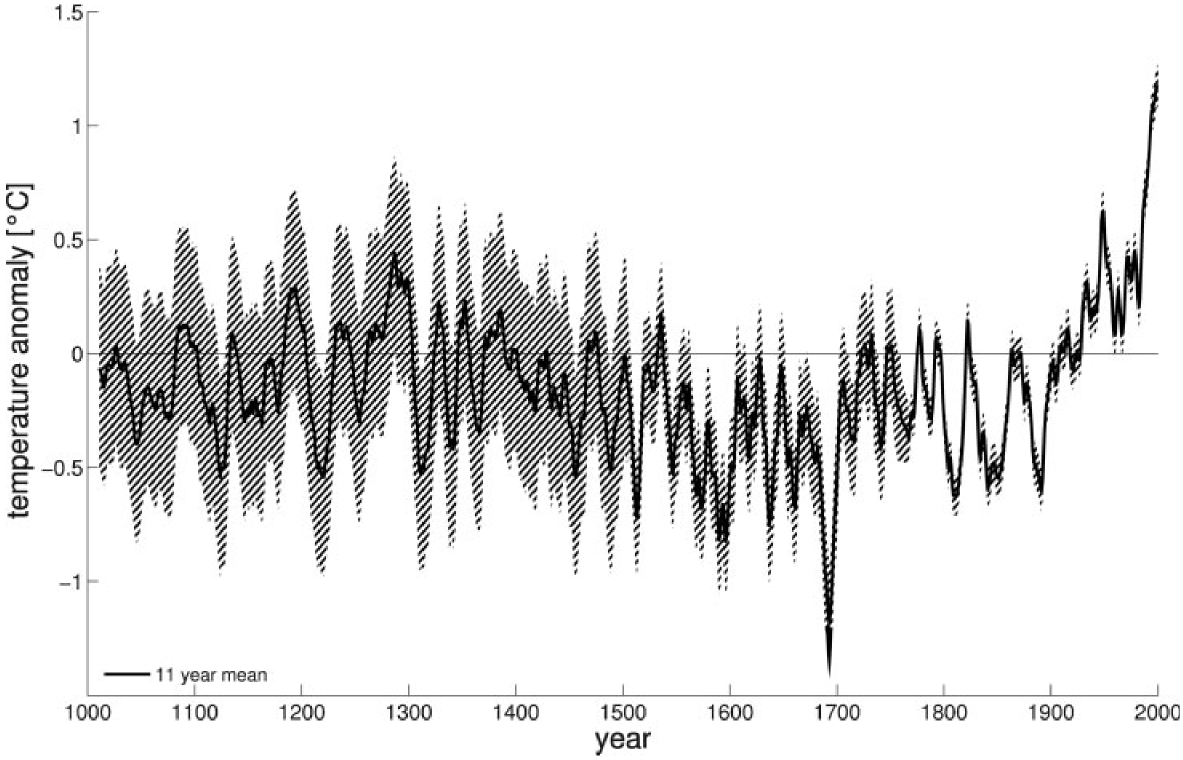

Figure 6 Thousand-year record of 11-year moving average temperature anomalies derived from historical sources (AD 1000–1750) and instrumental data (AD 1751–2007). The hatched area shows the estimated error (±1 STD, adapted for 11-year averages) using a Monte Carlo (MC) approach. This error is ±0.49°C during AD 1000–1500, and 0.24°C during AD 1500–1750. The comparable error in the instrumental data is 0.09°C

cycle) occurred during the period AD 1675–1700. The aggravation of the agro-economical situation mentioned for the transition period (point 2) increased even more (Pfister, 1999; Glaser, 2001). However, during this time span there is a period of about 100 years from just before AD 1700 to 1800 when a significant warming of about 1°C took place, which is comparable to the extent of the temperature increase during the 20th century, albeit at a considerably lower absolute temperature level. The development of the temperature between AD 1800 and 1900 shows three pronounced, successive oscillations of temperature decreases with subsequent rewarmings amounting to about 1°C. The respective temperature minima can be dated shortly after AD 1800, around AD 1850 and at the end of the 19th century. Taking into account the decelerated reaction of the glaciers (Holzhauser and Zumbühl, 1999), the temperature minima match clearly with the dates of the major extensions of the alpine glaciers.

4. The modern climate warming starting from around AD 1900, with a further significant increase in temperature from the AD 1970s where the increase of 11-year means of temperature to the present, was approx. 2°C.

Discussion

A comparison of the temperature reconstruction of the last millennium for Germany/Central Europe based on the hermeneutic approach with those derived from various proxies as well as a forced simulation with an atmosphere–ocean general circulation model (GCM) shows strong similarities in long-term temperature evolution (Fig. 7). A simple correlation analysis, based on 101-year averages, (Table 1) shows initially a strong agreement between the temperature time series based on documentary data derived here and the multi-proxy reconstructions for the Northern Hemisphere (NH) by Mann and Jones (2003; $r = 0.71$) and Moberg *et al.* (2005; $r = 0.72$), the documentary data-based temperature reconstruction for the Low Countries (essentially the Netherlands) by van Engelen *et al.* (2001; $r = 0.82$) and the Germany/Central Europe average for the forced GCM simulation obtained with the model ECHO-G Erik 2 (González-Rouco *et al.*, 2006; $r = 0.58$). Higher correlation coefficients are hardly to be expected if one considers that regional series for Central Europe are being compared with Northern Hemisphere data series (apart from the Low Countries series). Nevertheless, the high correlation values show that at least the greater pattern of climate development in the series is in broad agreement. Such a result speaks for the quality of the underlying approaches. Of special interest is the comparison of the results with those from van Engelen *et al.* (2001) derived for the adjacent Netherlands using a comparable hermeneutic approach with independently derived data. The winter temperature reconstruction (Fig. 8) shows high correlation ($r = 0.75$ for the 31-year moving average). Climatologically, one would perhaps expect higher correlations between the two nearby regions. The data, however, show some contradictions; the periods AD 1300–1350 and AD 1450–1480 seemed to be cooler in the Netherlands, while during AD 1510–1540 the winter seemed to be significantly warmer in the Netherlands. Such shifts appear also during the instrumental period, e.g. AD 1830–1860. The summer temperatures (Fig. 9) show for large parts similarities but also some contradictions, e.g. AD 1080–1120 and AD 1550–1580 and also during the modern instrumental period AD 1850–1880. The contradictions and shifts may perhaps be explained as the result of different circulation patterns, but problems related to the raw information and the interpretation to index data cannot be excluded.

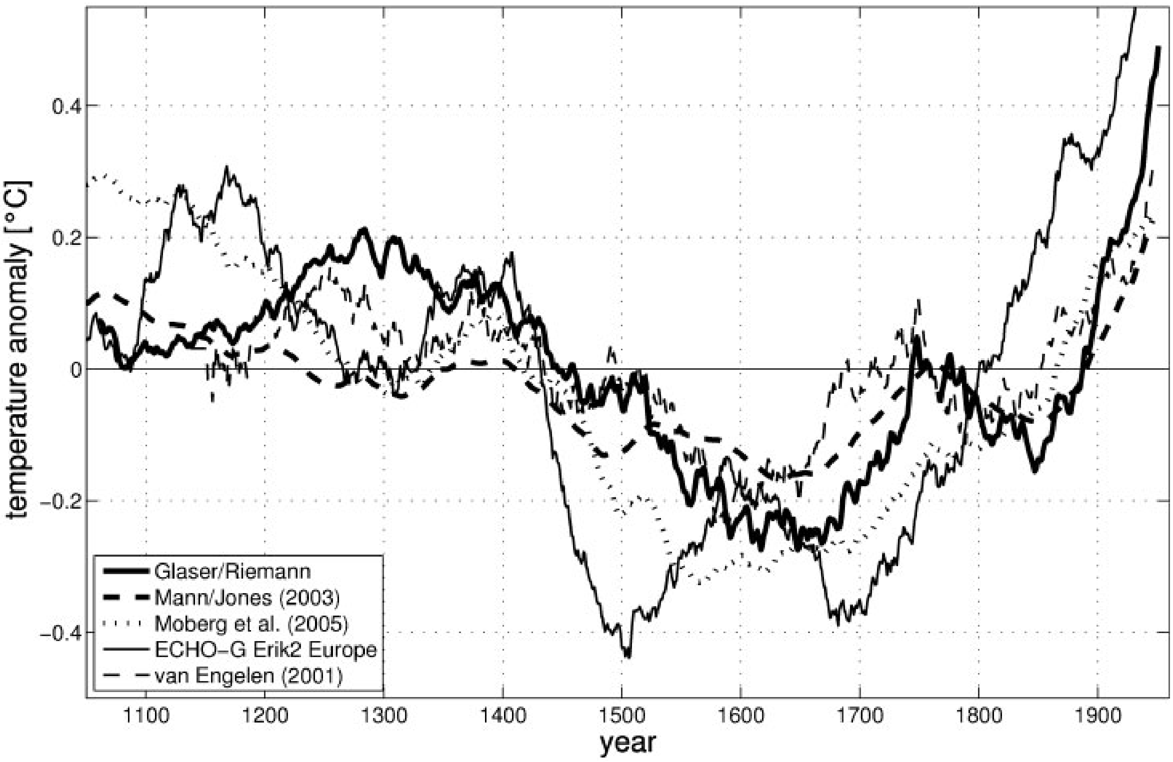

Figure 7 Comparison of the temperature series for Germany with other annual mean temperature reconstructions and simulations (101-year moving average). See text for identification of the various series

Comparisons with reconstructions derived from natural proxies show in general fewer similarities. This might be due to the fact that these series originate in adjacent areas with different climatic settings. The comparison with a tree ring series (Büntgen *et al.*, 2005) located in the Lötschental (Alpine region) as a summer temperature signal shows qualitative similarities but also contradictions. One reason apart from the different climatic situation might be that the tree ring parameters represent temperatures in summertime for the period May to August and not the meteorological summer season. Reconstructions for the same area based on speleothems (Mangini *et al.*, 2005) as a winter temperature signal show qualitatively the same similarities and contradictions (Fig. 8).

In comparison to other reconstructions, the Medieval Warm Optimum appears to be delayed for the region under consideration here. The often-quoted remarks about the medieval warm period – the so-called Medieval Warm Optimum – refer first of all to the events that took place in northern Europe, in particular in Norway, and in Iceland and Greenland. The suggested temperature increase of at least 1–2°C can be related to the colonisation and expansion history of the Vikings (Lamb, 1977). The blossoming of the Vikings disappeared with the cooling of the climate, which occurred earlier in northern Europe than in the centre of the continent. There is also a chapter in the latest IPCC Report (2007) in which the climate evidence over the last two millennia is presented. Medieval warming was heterogeneous in terms of its precise timing and regional expression (Crowley and Lowery, 2000; Esper *et al.*, 2002; Jones and Mann, 2004; D'Arrigo *et al.*, 2006).

The particular advantage in hermeneutic research, compared to other approaches to reconstruct past climate, is that the statements are based on direct and proximate observations of the weather and weather conditions, which have a higher resolution and can usually be explicitly dated. For Central Europe, the abundance and structure of written documents are so rich that it is beyond dispute that they comprise one of the most reliable items of 'proxy' information available (Mann, 2002). Especially noteworthy is also the possibility of the designation of high-resolution dating as a further 'proxy'. Furthermore, the hermeneutic approach offers the possibility of reconstructing several variables which, partly owing to limitations of the rest of the climate archives, are not reproducible. For example, these can be precipitation, pressure conditions or also climate extremes such as storms or floods (de Kraker, 2006). In addition, the climate impacts and the reactions of society, the *human impacts* and *human dimensions* can be determined and so contribute to a better understanding of the human–environment relationship.

Table 1 Correlations between 101-year smoothed reconstructions (Glaser and Riemann, this paper; Mann and Jones, 2003; Moberg *et al.*, 2005; van Engelen *et al.*, 2001) and a GCM simulation ECHO-G-Erik2 (González-Rouco *et al.*, 2006) before 1900 (Pearson correlation at 95% level)

	Glaser and Riemann	Mann and Jones (2003)	Moberg *et al.* (2005)	ECHO-G-Erik2 Europe	van Engelen *et al.* (2001)
Glaser, Riemann	1.00	0.72	0.73	0.58	0.82
Mann, Jones	0.72	1.00	0.86	0.69	0.73
Moberg *et al.*	0.73	0.86	1.00	0.78	0.74
ECHO-G-Erik2	0.58	0.69	0.78	1.00	0.54
van Engelen *et al.*	0.82	0.73	0.74	0.54	1.00

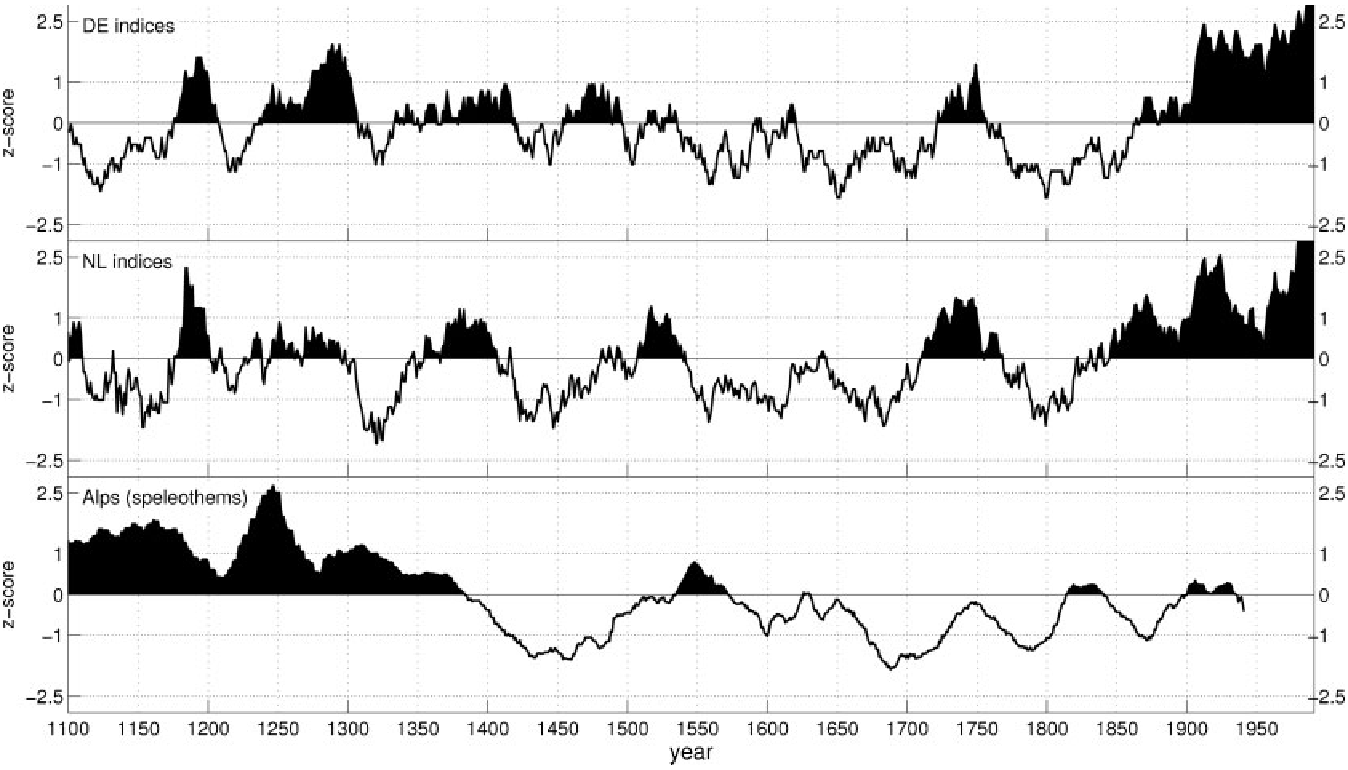

Figure 8 Winter temperature reconstructions for Germany, the Netherlands (Van Engelen *et al*., 2001, 2003), based on documentary data, and the Alps (Mangini *et al*., 2005), based on speleothems (*z*-score of 31-year moving average)

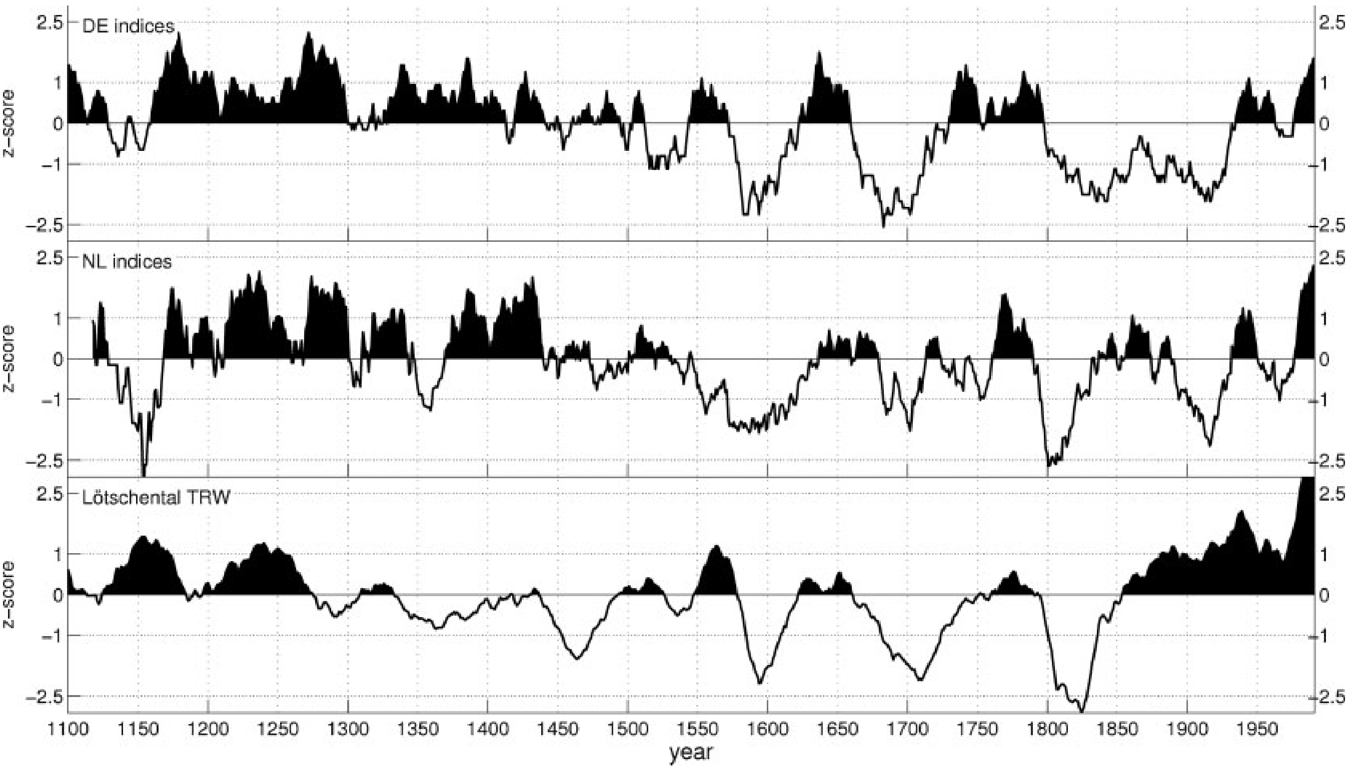

Figure 9 Summer temperature reconstructions for Germany, the Netherlands (Van Engelen *et al*., 2001, 2003), based on documentary data, and the Alps (Büntgen *et al*., 2005), based on tree ring parameters (*z*-score of 31-year moving average)

Conclusion

The hermeneutic approach, coupled with the indexing method, is suitable for deriving temperature series from documentary data for Germany/Central Europe. The study shows that the presented method allows a reconstruction of long-term climate variability, with the major advantages that the hermeneutic approach covers all seasons and provides exact dating. Therefore, the data allow cross-validation with other independently derived proxies. Thus the methodological spectrum in palaeoclimatology can be enriched and more medium-scale results can be presented.

The results show good correlations with those derived from other multi-proxy approaches, another documentary-data based reconstruction and a forced climate simulation. Nevertheless there are some differences concerning the temperature development in the first 250 years, which is often called the Medieval Warm Optimum. Further discussion of these differences will inspire the debate on climate regionalisation and the temperature development for this period.

Besides, the hermeneutic approach offers many more possibilities using the information on climatic impacts and climatic vulnerability and the interaction with society. The high-resolution climate and weather information of the documentary approach is unique.

If one considers that with the latest publication of the IPCC (IPCC, 2007) further temperature increase has gained plausibility and that, above all, the regional effects of climate change are increasingly of importance, the stated advantages of the hermeneutic approach as compared to global and hemispheric models seem yet more important. Especially in the last few years, analyses with respect to various weather extremes have been conducted in which floods and climatic impacts were of special interest (Glaser and Stangl, 2003; Thorndycraft *et al.*, 2003). These European research activities can be related to work by Chinese and Japanese colleagues, who carry out research on typhoons, among other topics or, for example, to reconstructions of El Niño events (Diaz and Pulwarty, 1994) as well as work in the Caribbean (Walsh and Reading, 1991), or the Indian Ocean (Walsh *et al.*, 1999). The hermeneutic approach coupled with the indexing method opens further perspectives for regional climate reconstructions.

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