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European climate of the past 500 years: new challenges for historical climatology

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Abstract Temperature reconstructions from Europe for the past 500 years based on documentary and instrumental data are analysed. First, the basic documentary data sources, including information about climate and weather-related extremes, are described. Then, the standard palaeoclimatological reconstruction method adopted here is discussed with a particular application to temperature reconstructions from documentary-based proxy data. The focus is on two new reconstructions; January–April mean temperatures for Stockholm (1502–2008), based on a combination of data for the sailing season in the Stockholm harbour and instrumental temperature measurements, and monthly Central European temperature (CEuT) series (1500–2007) based on documentary-derived temperature indices of the Czech Republic, Germany and Switzerland combined with instrumental records from the same countries. The two series, both of which are individually discussed in greater detail

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in subsequent papers in this special edition, are here compared and analysed using running correlations and wavelet analysis. While the Stockholm series shows a pronounced low-frequency component, the CEuT series indicates much weaker low-frequency variations. Both series are analysed with respect to three different long-period reconstructions of the North Atlantic Oscillation (NAO) and are compared with other European temperature reconstructions based on tree-rings, wine-harvest data and various climate multiproxies. Correlation coefficients between individual proxy-based series show weaker correlations compared to the instrumental data. There are also indications of temporally varying temperature cross-correlations between different areas of Europe. The two temperature reconstructions have also been compared to geographically corresponding temperature output from simulations with global and regional climate models for the past few centuries. The findings are twofold: on the one hand, the analysis reinforces the hypothesis that the index-data based CEuT reconstruction may not appropriately reflect the centennial scale variations. On the other hand, it is possible that climate models may underestimate regional decadal variability. By way of a conclusion, the results are discussed from a broader point of view and attention is drawn to some new challenges for future investigations in the historical climatology in Europe.

1 Introduction

Europe might be rightly considered as the cradle of instrumental meteorological observations. This can be attributed to the development of the first instruments by Galileo Galilei (1564–1642) and his students and successors in Italy; a development that was then stimulated by the establishment of networks of cooperation between European meteorologists and, for example, *Rete Medicea*, the first European network of meteorological stations, had begun its activities comprising ten stations in 1653–1654 (Camuffo 2002). In the second half of the seventeenth century, further meteorological observations began in several other places, some of them still in use today. It was on the basis of such undertakings that the temperature series for Central England could be constructed from as early as 1659 (Manley 1974; Parker et al. 1992; Jones and Hulme 1997; Jones 1999), with a corresponding precipitation series for Kew, England from 1697 (Wales-Smith 1971). Also notable are a Paris precipitation series from the 1680s (Slonosky 2002) and long temperature and pressure series for Paris and London (Legrand and LeGoff 1992; Pfister and Bareiss 1994; Slonosky et al. 2001). Many other European meteorological stations started observations during the eighteenth century (Jones 2001; Camuffo and Jones 2002; Auer et al. 2007; Böhm et al. 2009; Camuffo et al. 2009).

Such notable endeavours notwithstanding, meteorological information is by no means absent for earlier periods. Investigations into pre-instrumental climate patterns need however to take advantage of the proxy information contained in natural and man-made archives. Man-made proxies consist largely of documentary evidence, which is increasingly used as a basis for research in historical climatology (e.g. Brázdil 2000, 2003, 2009; Glaser 2001, 2008; Pfister 2001; Brázdil et al. 2005b; de Kraker 2006; Jones 2008; Pfister et al. 2008; Telelis 2008; Barriendos 2009; Glaser and Riemann 2009; Kiss 2009; Macdonald et al. 2009; Camuffo et al. 2009)—a research field recently defined as being situated at the interface between climatology and (environmental) history and dealing mainly with documentary evidence using methods from both climatology and history. One of its objectives includes the reconstruction of temporal and spatial patterns of weather and climate as well as the study of climate-related natural disasters for the centuries before the establishment of national meteorological networks (Pfister et al. 2001, 2008; Brázdil et al. 2005b).

After the publication of the overview paper by Brázdil et al. (2005b), several new temperature reconstructions have been published based partly or entirely on documentary data. While many of the previous reconstructions suffered from statistically incomplete calibration and verification procedures within the instrumental period (Pfister 1984, 1992; Brázdil 1996; Pfister and Brázdil 1999; Bullón 2008), some new reconstructions benefit from a more rigorous application of such approaches to overlapping periods of documentary and instrumental data (Leijonhufvud et al. 2008, 2009; Dobrovolny et al. 2009a, b).

Substantial progress in this direction has been achieved by the European Union 6th Framework Program Integrated Project "Millennium"—European climate of the last Millennium (http://ralph.swan.ac.uk/millennium/). In the context of this project, documentary and instrumental data were used together with natural proxies and climate modelling efforts to improve understanding of climate variability in Europe over the last 1,000 years. The science devoted to studies of documentary and early instrumental data was defined as a separate sub-group within the Millennium project, a decision that opened the way to the current special issue of *Climatic Change* which takes as its theme aspects of the European climate during the past 500 years as revealed by the documentary and long-period instrumental records, but with additional information obtained from modelling studies and the comparisons between them. The individual papers in this special issue discuss new climate reconstructions and selected aspects of the European climate. The present overview paper highlights and discusses the significance of aspects the progress in historical climatology, with attention being largely confined to temperature reconstructions. To make the discussion in this paper meaningful for readers who are not familiar with the other papers in the special issue (or even historical climatology in its general sense), we include here a general introduction as well as a summary of some main features of selected papers in the special issue. Additionally, we undertake some analyses that are not performed in the other papers. As a consequence, this paper significantly extends the state of the art of historical climatology in Europe as previously portrayed in the overview paper by Brázdil et al. (2005b), which evaluated situation up to early 2000s.

The immediately following section contains a discussion of known types and properties of documentary evidence that includes information about weather and climate in Europe over the past 500 years. The third section deals with the creation of documentary-based climate series, whereas Section 4 focuses upon a new approach of developing temperature reconstructions based on documentary data—inspired by standard working methodologies from the palaeoclimate sciences dealing with natural proxy data. The fifth section focuses on the examples of the new Stockholm and Central European temperature reconstructions being developed and discussed in detail in two other papers in the special issue (Leijonhufvud et al. 2009; Dobrovolný et al. 2009b), their statistical properties, inter-comparisons between the different, but mostly independently-derived, reconstructions, and relations with different North Atlantic Oscillation Index (NAOI) reconstructions. The final section discusses the overall nature of the various findings in a broader concept and identifies new research challenges for historical climatology.

2 Types and properties of documentary evidence

The most important sources of documentary data worthy of note as sources of evidence of climate variations for the past 500 years in Europe include those identified, for example, by Pfister (1984, 1999), Pfister et al. (1999, 2008), Glaser (2001, 2008), Brázdil et al. (2005b), García-Herrera et al. (2005), de Kraker (2006) and Macdonald et al. (2009). When dealing with documentary evidence it is important to distinguish between two types of data—direct and indirect—both of which are needed for the successful reconstruction of monthly and seasonal climate, albeit in different ways. Direct data are narratives describing the course of weather and climate per se, often including accounts of the societal impacts of extreme events and their perception by individuals, local communities and authorities. Indirect data, on the other hand, refer to physically based phenomena associated with weather and climate such as plant and animal life cycle events or ice and snow seasonality features. The assumed relationship between such effects is not always apparent from the record and needs therefore to be statistically investigated when it occurs within the instrumental period (e.g. Pfister 1984, 1992, 1999; Leijonhufvud et al. 2008, 2009).

Another important distinction within the field of documentary evidence relates to the manner in which the sources were generated. An historical climate-relevant source is, in a general sense, a unit of information such as a manuscript, a piece of printed matter (book, newspaper etc.), a picture or an artefact (e.g. flood mark) from which climatic information can be inferred. With respect to source generation however, Pfister et al. (2008) draws an important distinction between individual and institutional sources, because those categories have very different properties. Sources produced by individuals are unique and idiosyncratic in the sense that they are shaped by the social background, the motivations and preferences of their authors. This source category comprises therefore a notable variety of evidence. Moreover, their temporal scope is limited to the life time of the observer and the merging of one such source with another to produce a long series presents a number of challenges. Series of institutional data produced by governments or other bodies such as the church are different in providing the possibility of long series of reasonably consistent records embracing periods of time far longer than that of a single human being. A review is provided below of the main types of information sources utilized in historical climatology. As a similar undertaking was presented in Brázdil et al. (2005b), we have here omitted references to work cited there and thus only give references to new and other work not cited in the previous overview.

(a) Individual sources

1. *Annals, chronicles, memorial books and memoirs* may contain descriptions of weather and related phenomena with inevitably varying degrees of detail together with reports on a range of non-climatological events such as wars, diseases, miracles etc. Chroniclers usually supplemented their descriptions with reflections on the observed departures of plant-phenological phases or other

features of seasonality such as snow or ice from those in "ordinary years". The rhythm of the agricultural year was a widely-understood frame of reference in agrarian societies (Pfister 1999) and departures from its normal pattern could be readily discerned and provided important experiential material for chroniclers (Mauelshagen 2008). It is, however, recognised that the quality and accuracy of any such record depends on the intellectual background of the writer and particularly whether he or she was an eye-witness to the events described.

2. *Daily weather observations* were recorded by their authors more or less regularly in ephemerides, calendars and personal diaries. As well as descriptions of the weather, they also include information about weather-related extremes and their societal consequences (Gimmi et al. 2007; Brázdil et al. 2008a; Raicich 2008).
3. *Private correspondence* may contain information about weather and related extremes if the situation concerned the author of the letter in some way or excited their interest.
4. *Illustrated broadsheets* (i.e. one-sided prints) were often printed and distributed on the occasion of disastrous or remarkable weather-related events such as floods or windstorms. These circulars (the forerunners of today's newspapers) were issued mostly by private individuals to satisfy a public demand but on occasion might be the result of official activity (Harms and Schilling 2008).
5. *Newspapers and journals* usually contained descriptions of unusual weather or weather-related extremes including information about their contemporarily understood causes and consequences for the community. They may also publish early instrumental measurements and might therefore be of particular value because the original records are sometimes lost (Brázdil et al. 2005c).
6. *Pictorial evidence* (paintings, etchings, photographs) represents climate-related phenomena (e.g. glacier snout position), weather-related disasters and specific landscapes. For example, pictorial representations of historic glaciers may allow reconstructions of the former extension and volume of the ice, sometimes with a time resolution of years. However, caution needs to be exercised in dealing with paintings prior to the early eighteenth century, which might sometimes reflect the author's imagination rather than a true representation of events. Consequently, most pictorial evidence can be regarded as true-to-detail (Nussbaumer et al. 2007).
7. *Stall-keepers' and market songs* often describe and recall extreme events such as a flash flood after a thunderstorm or torrential rain. Such occurrences excited popular interest as a result of their spectacular and dramatic nature, occasionally high death toll and the severe damage on a local or regional scale. Although they may describe the event, its occurrence and impacts, critical evaluation of the risk of distortion of reality contained in such archives (*licentia poetica*) is essential (Brázdil et al. 2005a).
8. *Early scientific papers and communications* often contain information about weather and related extremes, their occurrence, causes and impacts.
9. *Epigraphic sources* usually consist of marks or comments chiselled into stone or marked on houses, bridges, gates, or ancient trees. They often show the level of extremely high (or low) water and river levels (Munzar et al. 2006; Macdonald 2007) or recall some unusual occurrence such as someone's death by lightning or flash flood.

10. *Early instrumental meteorological observations* started in some places long before the establishment of national meteorological services in the nineteenth century. They typically contain data about air pressure and temperature, precipitation, wind direction, cloudiness and the occurrence of meteorological phenomena. Technical details on instrumentation and exposure essential for their homogenisation can sometimes be given in detail, but often the information is nevertheless insufficient for unambiguous homogenisation and combination with the modern instrumental records (Pfister 1978; Brázdil et al. 2002, 2005c; Moberg et al. 2003; Winkler 2009; Böhm et al. 2009; Camuffo et al. 2009).

(b) Institutional sources

Sources produced by institutions (e.g. hospitals, bishoprics, municipalities, military or civil authorities etc.) constitute the second category of documentary evidence. Institutional bodies were typically not directly interested in describing climate and they often kept records in order to document their activities in case of auditing or enquiry. The administrative routines involve some standardisation in the way records were kept, which is a prerequisite for an acceptable degree of homogeneity. More importantly, institutions unlike individuals often worked in the same way for centuries and in doing so they generated very long records (Pfister et al. 2008). The following categories can be distinguished:

1. *Books of account* are usually related to recurrent activities such as the control or the accounting of receipts and expenditures (in money or in kind). By-products of accounting activities, in particular remarks related to the date of receipts (e.g. the start of the vine or grain harvest) or expenditures (e.g. expenses for day laborers engaged in a specific agricultural activity) or maintenance operations (e.g. ice cutting on waterways, snow clearing), yield long time series of valuable physically based proxies (Chuine et al. 2004; Meier et al. 2007; Rutishauser et al. 2007; Brázdil et al. 2008b; Leijonhufvud et al. 2009; Mariani et al. 2009). Slightly different are the written accounts on the organization of rogations and systems of prayer in the Catholic world. These provide evidence of climatic stress giving rise to processions and other religious rituals conducted to alleviate droughts or spells of extreme weather (Barriendos 2005; Dominguez-Castro et al. 2008).
2. *Reports on weather damage related to claims for tax or similar alleviations* appeared when crops were heavily damaged as a result of inclement weather immediately before the harvest such as hail, flood, torrential rain and windstorm. In such situations taxpayers might apply for a proportional rebate which might be conceded after inspection and the production of yet more documentary evidence. Such reports may be preserved at different levels of the state administration system from that of the village to regional or state level (Brázdil et al. 2006).
3. *Official letters* written as part of a regular reporting system. These may include letters sent by estate administrators to the owners, in which they described serious weather events that influenced the productive operation of the estate (Brázdil et al. 2003). For example, governors of the Venetian colonies in the Adriatic and Eastern Mediterranean had to report on a regular basis to the authorities; importantly these reports were prepared in a consistent and standard format thereby ensuring a notable degree of homogeneity (Grove and Conterio 1994).

4. *Ship logbooks* are the most important institutional source yielding direct observations on wind direction, wind force and weather for the world's oceans and seas wherever trade and imperial interests took the ships of the age (Wheeler 2006, 2009; Wheeler and Garcia-Herrera 2009; Wheeler et al. 2009). Before the mid-nineteenth century the observations were almost entirely non-instrumental in character, but their keeping was a near-universal requirement of the military or merchant undertaking to which the ship belonged. The documents provided the only official record of the voyage but, importantly, were prepared according to a common vocabulary within each language and to common standards of observation and recording.

Researchers attempting to work with any of the documentary data here described should become familiar with the limitations related to this type of evidence. In order to overcome them, the historian's traditional requirements for the critical evaluation of sources need to be followed. The critique of sources attempts to find out why they were produced, when and by whom. With regard to individual sources, the key issue is to distinguish between observations contemporary to the event and those copied from other sources. In particular, caution is needed when working with uncritical compilations (e.g. Weikinn 1958–2002; Réthly 1962–1999), which contain different reports that are in some cases far from exact or even credible. Non-contemporary observations are often wrongly dated and this may lead to the spurious multiplication of extreme events (for a critique of such sources see e.g. Bell and Ogilvie 1978; Brázdil et al. 2005b; Pfister et al. 2008). Therefore, at least one contemporary observation is needed for a valid climatic reconstruction of a month or a season. Non-contemporary observations should only be used if they agree with an existing contemporary observation (Pfister 1984). With regard to contemporary individual sources the personal motivation and social background of the chronicler needs to be considered as part of the overall analysis of the text. When dealing with institutional proxy data, changes in the administrative, social and ecological framework generating the proxy needs to be investigated to make sure that it provides a similar signal throughout the existence of the institution (Pfister et al. 2008). Sophisticated statistical analysis can be undertaken only for the nineteenth and twentieth century, when abundant instrumental data and metadata are available (Meier et al. 2007) but for other times and sources different approaches are required (i.e. changes in the institutional framework have to be taken into account as well as purely statistical considerations).

3 Production of documentary-based climatic series

It follows from the previous sections that historical climatology faces a notable variety of documentary data that differ not only in terms of the phenomena that they describe but differ also in their temporal scales of resolution that vary from hours, through days and months to seasons. Overall however the quality and density of the documentary evidence increases forwards in time until the beginning of the instrumental period. After primary extraction and processing of these data in whatever form they are presented, the interpreted evidence can be used to create one of two types of climatic series both of which can be used for further climate reconstructions:

1. (Bio)physically-based proxies

The description of extreme events in individual sources is often supported by (bio)physically based proxies which permit the comparison of such descriptions over long time intervals. Long continuous series of (bio)physical proxies are obtained from institutional sources including books of account (Pfister et al. 2008). Dates of different agricultural activities such as the beginnings of grain or wine harvests, which have been kept over several centuries, belong to this group also (e.g. Chuine et al. 2004; Meier et al. 2007; Brázdil et al. 2008b). Another example is the proxy evidence of winter temperatures related to dates of the opening of northern harbours after winter freezing (Jevrejeva 2001; Tarand and Nordli 2001; Leijonhufvud et al. 2008, 2009), and information about the beginning and end dates of freezing on rivers, lakes (Kajander 1993; Nordli et al. 2007) and canals (van den Dool et al. 1978). When biophysically-based proxies cannot be formulated into a continuous temperature proxy series, they may be nonetheless used as objective information to assist in the creation of other climate index series.

2. Climate (temperature, precipitation) indices

Depending on the quantity and quality of the raw information, a graded scaling system can be used to express the derived evidence in an ordinal number system. Simple (unweighted) indices employing a three-term classification are often applied: months being classified as index −1 (cold or dry), 0 (normal) and 1 (warm or wet). More sophisticated schemes are weighted indices which use a seven-term classification for months (temperature: −3 extremely cold, −2 very cold, −1 cold, 0 normal, 1 warm, 2 very warm, 3 extremely warm; and for precipitation: −3 extremely dry, −2 very dry, −1 dry, 0 normal, 1 wet, 2 very wet, 3 extremely wet). Seasonal or annual indices may be obtained by summation of monthly values (i.e. the three-month seasonal values can fluctuate from −9 to 9 and annual values even from −36 to 36; see Pfister 1984). Different classification schemes into ordinal numbers on other scales have, however, occasionally been used (Wang et al. 1991; Koslowski and Glaser 1999; Rodrigo et al. 1999; van Engelen et al. 2001; Diodato 2007).

The creation of monthly indices presents however a significant challenge, requiring a broad statistical and dynamical understanding of the evidence base in addition to a deep knowledge of the regional climates and familiarity with the strengths and weaknesses of each source. The approach known as "weather hind-casting" is most straightforward. It focuses upon the evidence for a specific season (e.g. winter) and proceeds in descending chronological order beginning with the most recent and usually best documented winter. Subsequently, the more ancient winters are interpreted for which the information is usually more fragmentary. The other three seasons, or the individual months, can be treated in the same way (Pfister 1999).

An index value for a particular time point is derived from contemporary reports comprising all the interpretational indicators needed such as date, time, location, observation code, author, source quality etc. The original source text needs to be transcribed and related to the code to check for reliability. The processing of the information involves coding the evidence according to an agreed scheme, sorting it into chronological order and according to classification, region etc. (Pfister and Schüle 1994; Dietrich-Felber 2004). Such reports can be generated with the use of commercial data-base software or by specially designed information systems such as CLIMDAT (http://mitglied.lycos.de/mili04/index.html; see also Militzer S (1998) Climdat: Klima-Umwelt-Mensch (1500–1800), Leipzig, CD ROM), HISKLID (http://www.hisklid.de/) or EURO-CLIMHIST (http://www.euroclimhist.com/).

A high degree of expertise is essential to minimise subjectivity in the process of transforming the information in narrative accounts to numbers on a scale. If new evidence becomes available, indices need to be revised. Approximation to strict objectivity is intended but without any guarantee that it can always be achieved. The reasons for this are as follows:

– missing data: documentary data may be missing for some months or the character of the information does not allow for reliable interpretation in terms of temperature and precipitation indices,
– bias in observer focus on the weather over the course of the year: observers often paid greater attention to more strongly expressed weather contrasts or indicators (e.g. heavy frosts, severe heat-waves) and to seasons which were economically important for agriculture or other activities,
– extreme values: the selection of any ordinal scale does not allow a quantitative expression of the most severe extremes that are typical of the very high deviations that can occur from normal weather patterns (weighted temperature indices +3 and −3 should be supported by (bio)physically based proxies if possible),
– "normal" weather patterns: authors of records described the weather with respect to their own perceptions of the period in which they lived, i.e. each one of them had a different concept of what constituted "normal"; a concept that cannot be adequately reflected in the indices,
– non-climatic signals: changes related to non-climatic causes may be wrongly interpreted as climatologically forced, e.g. those arising out of changes in the variety of plants, land-use, agricultural practices.

4 Application of standard palaeoclimatological reconstruction methods in the context of historical climatology

Long series of (bio)physically-based documentary proxies as well as temperature and precipitation indices can be converted into present-day meteorological units by employing statistical climate reconstruction procedures, some of which have been developed in other palaeoclimatological fields—in particular dendroclimatology. The scheme of standard palaeoclimatological reconstruction (Fig. 1) assumes that temperature and precipitation proxies are available for a period that allows them to be calibrated and then verified against contemporary instrumental observations for an overlapping interval of time. The aim of the calibration is to determine the transfer function between the proxy and the measured climate variable. Before being used for a reconstruction, the transfer function needs to be verified for an independent period or subset of the data; or at least a cross-validation procedure has to be carried out if the time period of data overlap is short. The transfer function derived from a

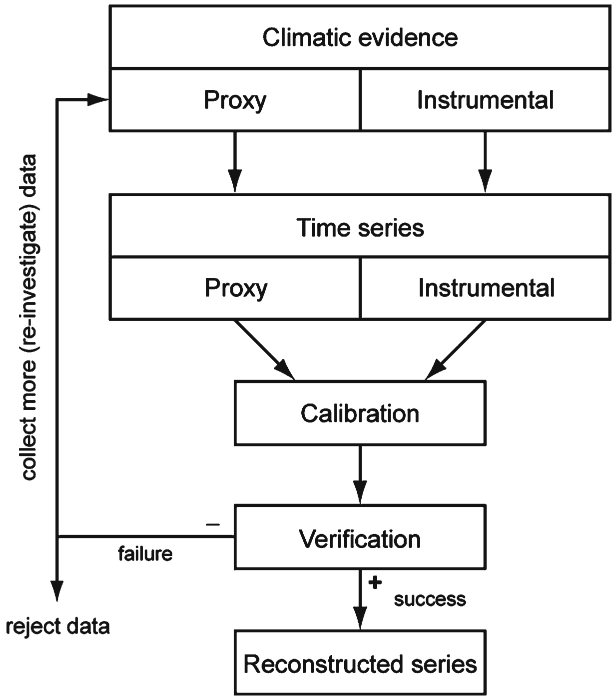


Fig. 1 Scheme of a standard palaeoclimatological reconstruction (modified after Brázdil 2002)

calibration period (and evaluated by various statistical measures such as squared correlation r^2, standard error of estimate SE and the Durbin–Watson test for autocorrelation in residuals if the calibration is based on linear regression) is subsequently applied to a verification period for which the climate values are estimated from the proxy data. In the verification period, the estimates are compared with the measured values and evaluated using statistical measures such as r^2, reduction of error RE and coefficient of efficiency CE (for definition of these measures see e.g. Cook et al. 1994; Wilson et al. 2006). If the calibrated proxy data series, derived by applying the transfer function obtained for the calibration period, expresses the variability of the climate factor under consideration with satisfactory accuracy in the verification period, then the time series of the proxy can be considered as useful for a more comprehensive climate reconstruction back beyond the instrumental period. However, the transfer functions, usually derived from relatively modern periods, may be non-stationary, as, for example, when phenological series have been influenced by changes in crop composition, the introduction of new varieties of crops, changes in the economic environment (Meier et al. 2007) or the introduction of different harvest technology, as in the transition from manual to mechanical grain harvesting (Pfister 1984). This problem can, to some extent, be ameliorated by critically evaluating changes in the boundary conditions of source generation and by considering a sufficiently long calibration period (e.g. Cook et al. 2002). Nevertheless, it is impossible to evaluate fully the robustness of the transfer function solely from the period of overlap between any proxy and instrumental data.

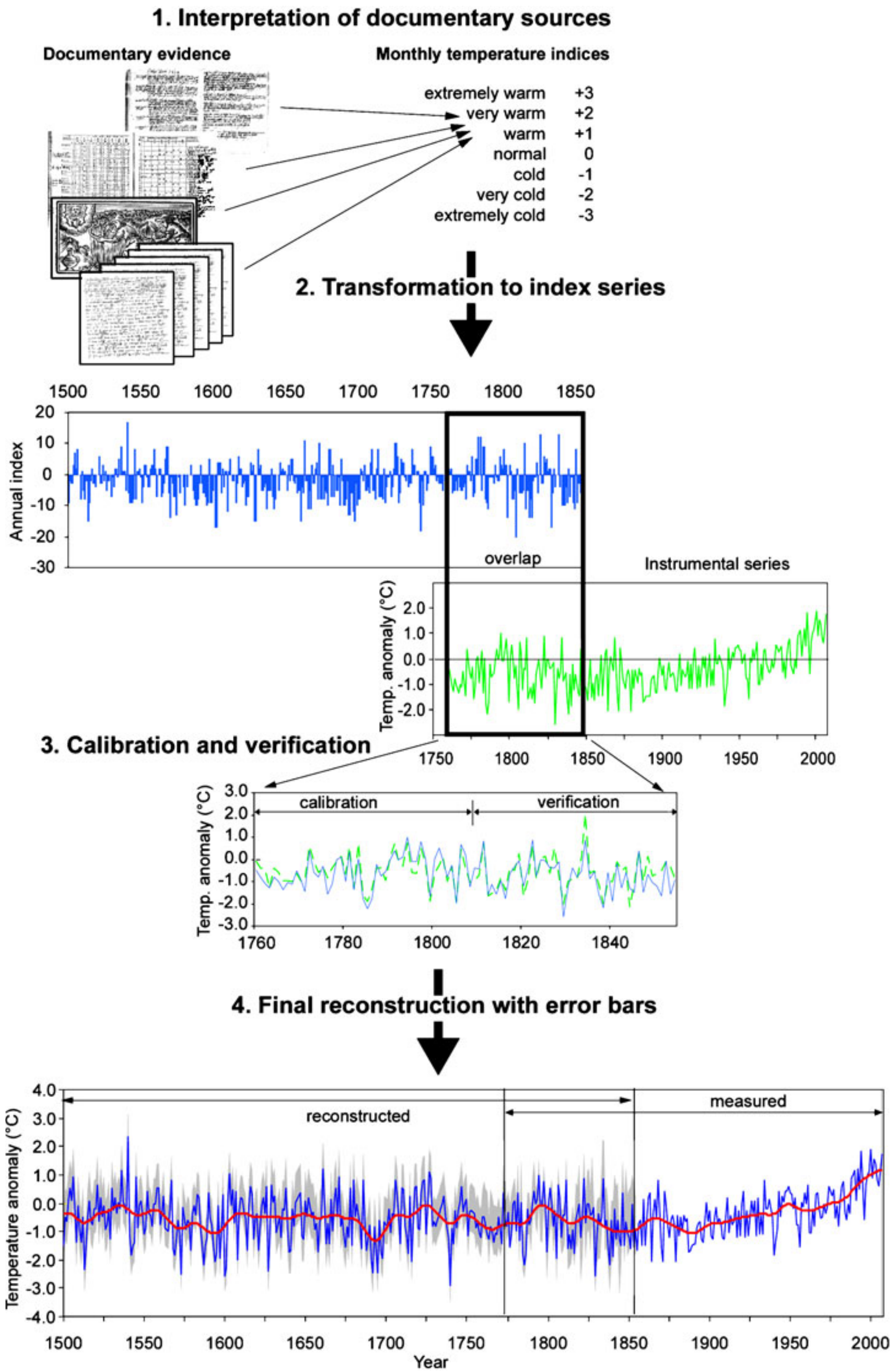


Fig. 2 Simplified diagram of the temperature reconstruction procedure using documentary evidence-based temperature index series (modified after Brázdil and Dobrovolný 2010)

A detailed scheme of reconstruction using temperature indices based on documentary evidence, which follow the standard palaeoclimatological approach outlined above, is presented in Fig. 2. In this case, time series of temperature indices are calibrated and verified using instrumental temperatures in the overlapping period by linear regression. This also yields an estimation of the explained variance in the reconstruction under the assumption of stationarity over time. In the final stage, the calibrated index series is spliced with the instrumental series to create one long and continuous time series. (Splicing, however, is normally not needed with natural proxies which typically extend to the present). Error bars expressing the reconstruction uncertainty (usually expressed as the unexplained variance within the instrumental calibration period; the contribution of the uncertainty in the regression coefficient itself being usually much smaller at inter-annual timescales) in the proxy-data part are principally determined from the calibration statistics. This approach has been applied in the calculation of the Prague-Klementinum temperature series for 1718–2007 (Dobrovolný et al. 2009a) and of the Central European temperature series for 1500–2007 (Dobrovolný et al. 2009b). The new seasonal temperature reconstruction for Stockholm 1502–2008 (Leijonhufvud et al. 2009) was prepared in a similar manner, although the raw documentary data are of the physical type and hence no indexing was made.

The two above mentioned new reconstructions introduced in other papers in this special issue (Central Europe and Stockholm) were calibrated and verified by their original investigators using linear regression models (LRM) constructed with proxy data as the independent variable (predictor) and instrumental temperature measurements as the dependent variable (predictand). This calibration approach has the property of minimizing the prediction error of the reconstruction, but it also leads to underestimation of the amplitude of the true but unknown underlying temperature signal. To partly remedy this, palaeoclimatologists sometimes adjust the variance of the reconstruction (after it has been verified) so that it becomes equal to that of the instrumental data in the period of overlap; this is called 'variance scaling' (Esper et al. 2005). This approach was also applied to the two new reconstructions discussed here.

The availability of a period with sufficiently long overlap with an instrumental series is critical to documentary-based reconstructions (as for any proxy series). With the onset of the first instrumental measurements, mostly during the eighteenth century in Europe, some traditional documentary sources gradually faded and were replaced with exclusively instrumental data and therefore it is often difficult to assemble a sufficiently long calibration/verification period. Even though some calibration approaches can be based solely on recent measurements (Pfister 1992), independent comparison of proxy series with some form of target measurements is a critical point for a standard palaeoclimatological reconstruction (Cook et al. 1994). The existence of a sufficiently long period of data overlap permits the use of conventional statistics. However, statistics derived for the period of overlap with instrumental data cannot alone provide information about the reliability of the reconstruction before the calibration period. For the objective assessment of the reconstruction skill of documentary proxies (or any type of palaeoclimatic proxies) before the calibration period, comparisons with other reconstructions are therefore important.

5 New climate reconstructions based on documentary data

5.1 Stockholm and Central European temperature series

As already mentioned, two new five-century long temperature series for Stockholm and Central Europe have been developed using the approach described above, combining documentary and instrumental data such that the calibration and verification is undertaken for reasonably long time periods of data overlap. The documentary data used for the Stockholm reconstruction belongs to the (bio)physical category, whereas the Central European reconstruction is based on the climate index type of data (see above). The full details of the derivation of the reconstructions are given in Dobrovolný et al. (2009b) and Leijonhufvud et al. (2009), but the essentials are summarized here for convenience of further reading of the current paper.

For the Stockholm case, the temperature reconstruction has been calibrated against the average for the months from January to April (JFMA). The rationale is related to the geographic setting of Stockholm, being located at the innermost part of an archipelago on the Swedish east coast of the Baltic Sea at near 60° N, where some amount of water is frozen each winter. The underlying hypothesis for the JFMA temperature reconstruction is that the date of ice break-up in the archipelago after each winter is strongly related to the mean temperature of the late winter and early spring. Hence, information about the start of the sailing season each year has been sought in historical documents; assuming that the start of sailing season is strongly associated with the date of ice break-up (Leijonhufvud et al. 2008).

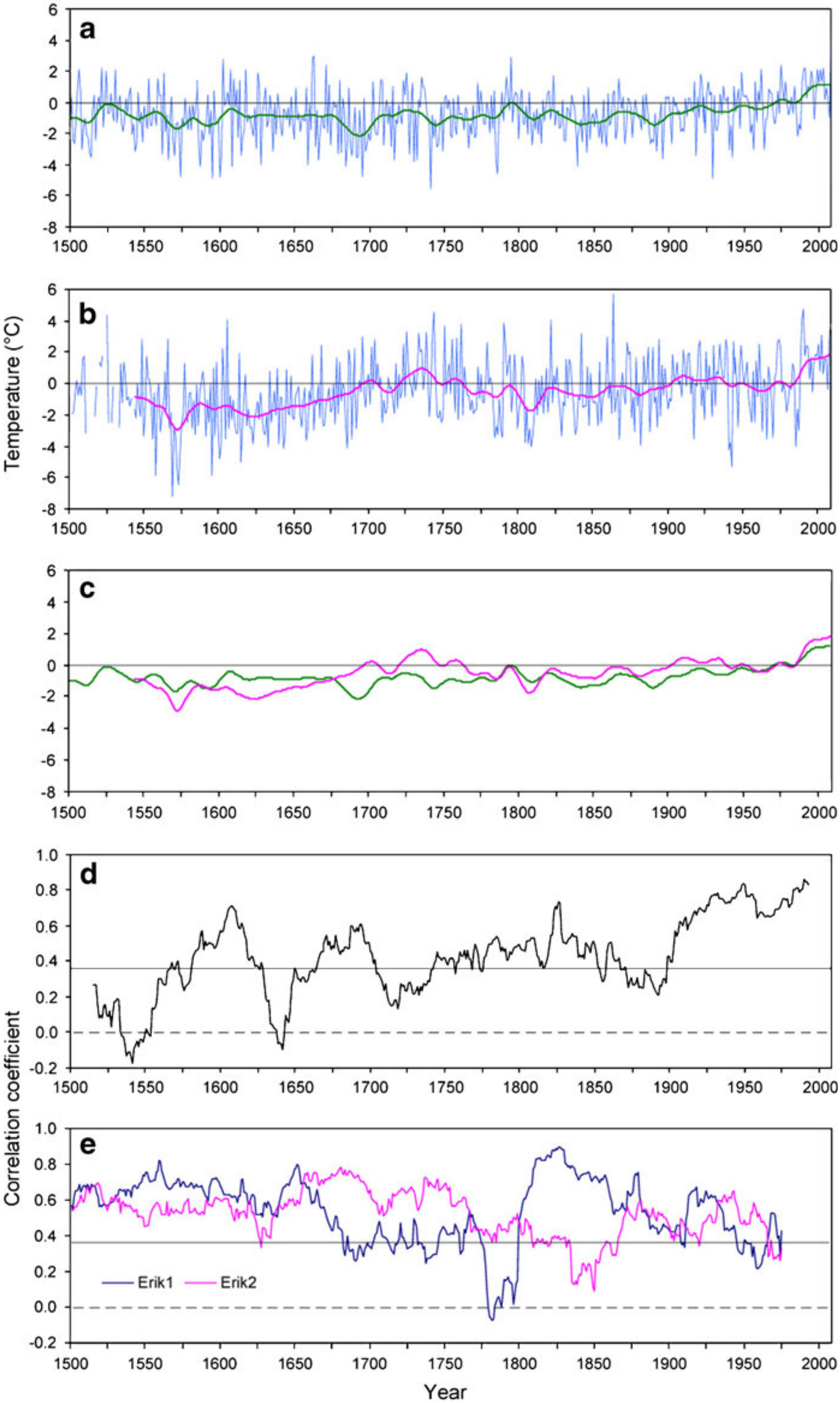
The start of the sailing season in the Stockholm harbour, derived from custom ledgers and other documents related to port activities, was estimated for the period 1502 to 1892. Several, partly overlapping, time series derived from these records were first standardized and averaged. The resulting composite series was then calibrated and verified against Stockholm JFMA instrumental temperatures over the overlapping period 1756 to 1892 (Leijonhufvud et al. 2009). The instrumental observations were obtained from the old astronomical observatory in the city, which has a record starting in 1756. The temperature series has previously been homogenized with respect to changing observation hours, number of observations per day, known instrumental errors and the urban heat island effect (Moberg et al. 2002). After successful calibration and verification, the reconstruction for the period 1502–1892 was adjusted to obtain the same mean and variance as the instrumental temperatures in the overlapping period. Finally, the variance adjusted reconstruction was spliced with instrumental temperatures for 1893–2008 (Leijonhufvud et al. 2009). Although the date of ice break-up in each spring is not solely dependent on a specific seasonal mean temperature and, further, most of the documentary data used are not direct proxies for the ice break-up but rather indicators of various human activities related to this event, the calibration and verification statistics reported by Leijonhufvud et al. (2008, 2009) are strong in comparison many natural proxy records, including tree-rings. This indicates that the type of proxy they used is of a quality comparable to the strongest natural proxies. However, just as for all proxy records, there are uncertainties associated with the data and the reconstructed climate signal is obscured by some degree of noise (see Leijonhufvud et al. 2008, 2009, for discussion of uncertainties).

In the other new temperature reconstruction discussed here, 'Central Europe' (henceforth CEuT), temperature index series were constructed for each individual month for which data exist, using documentary data from Germany, Switzerland and the Czech Republic. Monthly 'national' temperature index series were developed separately for each country. These monthly index series were standardized and the three national series were averaged to obtain a comprehensive Central European monthly temperature index series covering the period 1500–1854. An overlap with instrumental temperature series from Central Europe for the period 1760–1854 allowed the use of linear regression for calibration, followed by calculation of generally strong verification statistics. Hence, it was possible to derive a quantitative temperature reconstruction from documentary-based indices back to AD 1500.

The instrumental series used for calibration and verification was developed as an average of 11 homogenized temperature series. Ten of these series are from the HISTALP database (Auer et al. 2007) from Austria (Kremsmünster, Vienna-Hohe Warte, Innsbruck), Switzerland (Basel, Geneva, Bern), Germany (Regensburg, Karlsruhe, Munich, Hohenpeissenberg). The 11th series is for the station Prague-Klementinum (the Czech Republic). All 11 station series have been corrected for the bias of early thermometers caused by the insufficient radiation shielding against direct radiation (see Böhm et al. 2009), the intensification of the heat urban island effect and other sources of inhomogeneities (Auer et al. 2007). The proxy-based reconstructions before 1760 were adjusted to have the same mean and variance as the instrumental data over the overlapping period. Finally, the variance scaled reconstruction for 1500–1760 was spliced with instrumental data for 1761–2007 (Dobrovolný et al. 2009b).

Because the proxy-data parts of the Stockholm and CEuT series were derived from different types of documentary evidence (physically based seasonal proxies versus monthly temperature indices), one may expect that these two reconstructions will differ especially in the low-frequency domain (see discussion by Zorita et al. 2009). Figure 3, which compares the two reconstructions for the JFMA season, illustrates that there is somewhat higher variance (both at high- and low-frequency domains) in the Stockholm data. This holds both for the instrumental part and the documentary part of the records. Notably, however, in the pre-instrumental part there is clearly more low-frequency variability in the Stockholm record compared to CEuT than what might be expected from comparison of the instrumental parts of the two series. A pre-instrumental period when the Stockholm series is notably warmer relative to the CEuT series is seen between the 1680s and 1760s. This period includes the warm 1730–1745 period previously observed in northwestern Europe (Luterbacher et al. 2004, 2007; Xoplaki et al. 2005; Jones and Briffa 2006). Cool periods around the 1570s and 1810s are expressed in both reconstructions, but they are more pronounced for Stockholm.

Fig. 3 Comparison of reconstructed JFMA Stockholm (1502–2008) and CEuT (1500–2007) temperatures (anomalies from the 1961–1990 mean). Original series of CEuT (**a**) and Stockholm (**b**) are smoothed with a 30-year Gaussian filter (**c**) and compared using 31-year running correlations between unfiltered data (**d**). Running correlations (31-year window) between ECHO-G modeled JFMA temperatures (Erik1 and Erik2 forced runs) for Stockholm (grid point coordinates: 18.75° E, 61.23° N) and Prague (14.4° E, 50.09° N) in the period 1500–1990. The horizontal solid lines in **d** and **e** denote the critical value of correlation coefficients for $\alpha = 0.05$ for one-tailed t test ▶


a
b
c
d
e
Temperature (°C)
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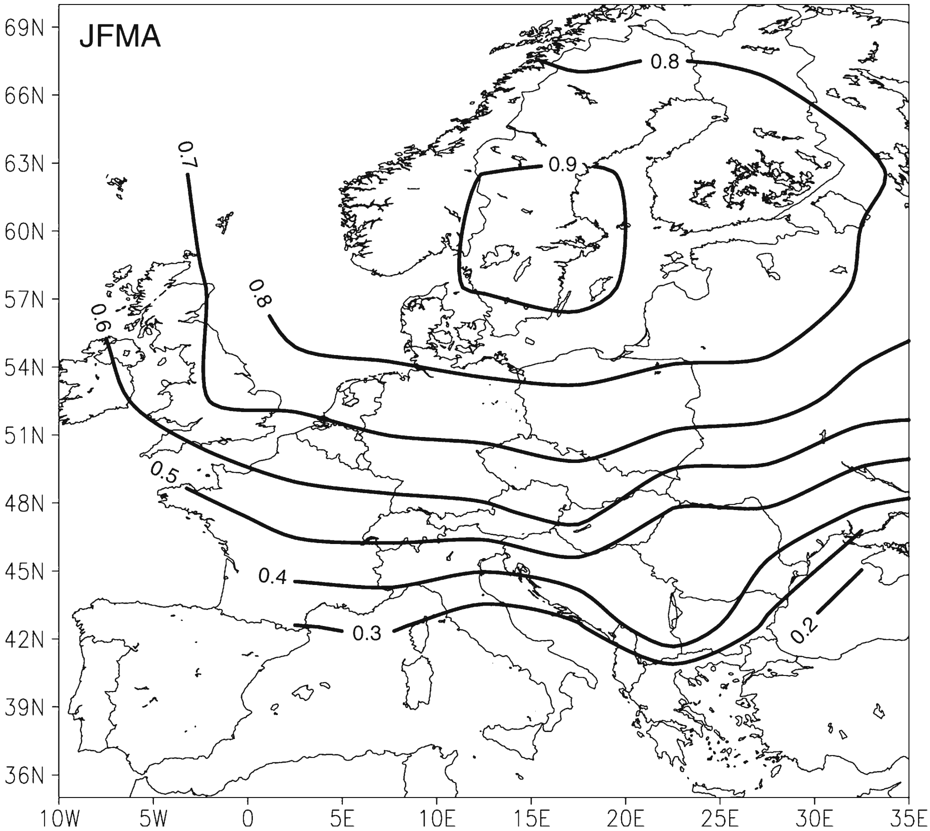

Fig. 4 Spatial correlations between the JFMA Stockholm instrumental temperature series and HadCRUT3 5 × 5° gridded temperatures (Brohan et al. 2006) for 1850–2007

It must be stressed that a substantial part of the differences between the two reconstructions can be related to natural differences in the spatial–temporal temperature variability over Southern Scandinavia and Central Europe. This is exemplified in Fig. 4 by showing the spatial correlation fields between mean JFMA Stockholm data and gridded temperatures over Europe based on data for the period 1850–2007. From this analysis, correlations between JFMA temperature variations at Stockholm and in Central Europe can be expected to lie in the range between 0.5 and 0.7. Figure 3d, however, shows that correlations may be even stronger in the instrumental period. A drop in correlations between the two series before 1900, to near or below the 0.05 significance level, may be explained by the change from instrumental to documentary data at 1892 in the Stockholm series. Other sudden decreases in correlations between the series occur before 1560 and around 1640, even becoming negative (see Fig. 3d). However, colder sub-periods of the documentary part of the records (1575–1625 and 1670–1700) show quite strong and significant correlations, and in some periods the correlation between the documentary data series are nearly as high as in the instrumental data. Because of lack of instrumental data for the full five-century period, it is questionable whether correlations between temperatures in Stockholm and Central Europe are relatively stable in the long-term. As a substitute for instrumental data, correlations were calculated using model simulations with ECHO-G (Zorita et al. 2009) by means of grid-point model data corresponding to the two places in question (see Fig. 3e). This comparison shows that periods with both high and low correlations may occur, which indicates clear spatial–temporal instability in the simulated temperature relations. Although this does not prove that the reconstructions are error-free, it does illustrate that large variations in this correlation can be partly attributable to real climatic fluctuations.

Further differences and similarities between the Stockholm and CEuT series can be demonstrated by analyzing their frequency-dependent behaviour using suitable methods of spectral analysis. One such method is wavelet analysis, which can be

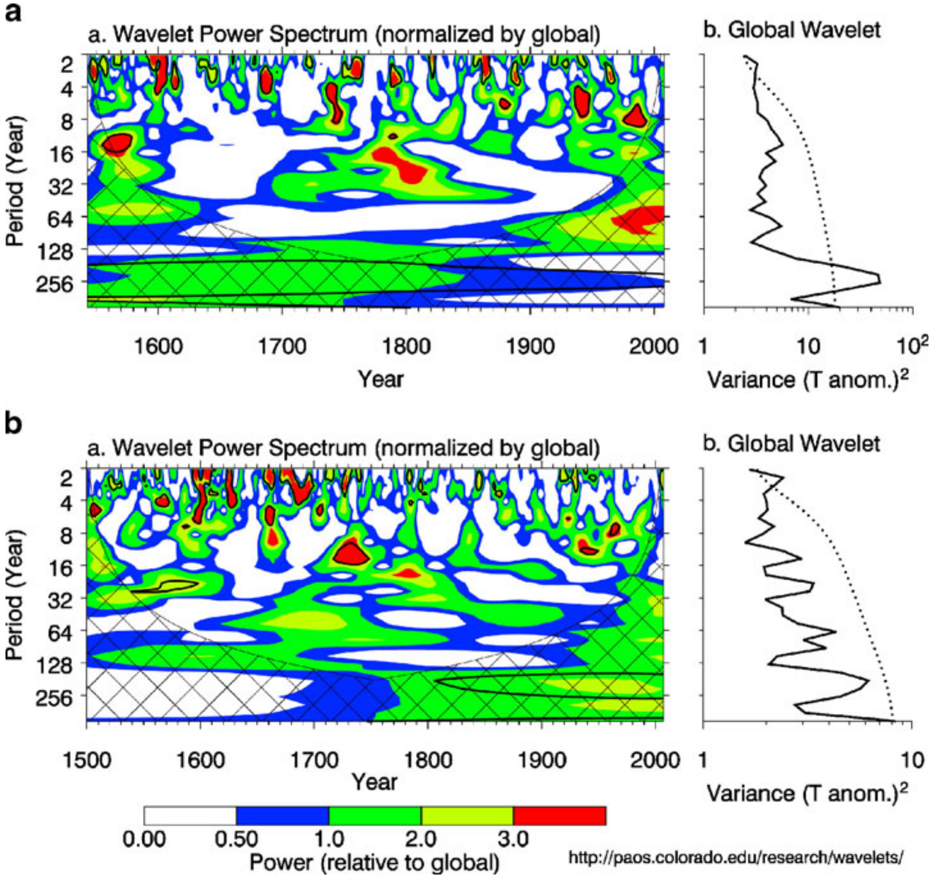

Fig. 5 *a* The wavelet power spectrum (Torrence and Compo 1998) of JFMA reconstructed temperature from Stockholm (1543–2008, **a**) and CEuT (1500–2007, **b**). The power has been scaled by the global wavelet spectrum (*right*). The *cross-hatched region* is the cone of influence, where the spectrum is less certain. The *black line* is the 10% significance level, using a red-noise (autoregressive lag 1) background spectrum as null hypothesis. *b* The global wavelet power spectrum (*black line*). The *dashed line* is the significance level for the global wavelet spectrum, assuming the same significance level and background spectrum as in *a*

used to analyse both the ‘global’ spectral character over the entire time series and to provide information about temporal changes in the spectrum (Torrence and Compo 1998).

Wavelet analysis of the two reconstructions (JFMA season in both cases) are shown in Fig. 5. The global wavelets (right panels) clearly distinguish one difference between two series; the Stockholm reconstruction has variance at the timescale of 256 years that significantly exceeds the level expected from a null hypothesis of a red noise spectrum, whereas the variance in the CEuT series at the same timescale does not reach the 10% significance level. Visual inspection of the full wavelet power spectra (left panels) reveals that the Stockholm series has significant power at the 256-year scale consistently from the start to the end of the record. The CEuT series, on the other hand, has significant power at the 256-year scale in its instrumental part, but not in its documentary data part. Although this part of the wavelet spectrum falls within the so-called cone of influence (where the analysis method is uncertain due to the relative shortness of the records compared to the timescale of interest), the result points to a difference in spectral character between the index-data based CEuT series and the physical-based Stockholm series, which quantitatively reinforces the visual difference seen in the time series plots in Fig. 3. This analysis alone is not sufficient to judge if any of the two records has significant frequency-dependent biases, but our interpretation is that the results point to a potential deficiency of the index-type of documentary evidence to fully capture low-frequency temperature variability.

Among other observations that can be made in the wavelet power spectra, it can be noted that there is no indication of any significant time-stable spectral peaks in either of the two series. Moreover, the details of the wavelet spectra differ between the two series, which illustrates a substantial degree of differences in regional climate variability between the locations, in general agreement with the correlation map in Fig. 4, which shows correlations of about 0.5 to 0.7 for JFMA; meaning that roughly only between 25% and 50% of the variance is in common.

5.2 Comparison of the Stockholm and Central European temperature series with other European reconstructions

To further illuminate the characteristics of the new Stockholm and CEuT reconstructions, they can be compared with several previously available temperature or temperature-related reconstructions from Europe. We have identified the following records with monthly to annual resolution as interesting objects for comparison:

1. the seasonal Central European temperature series (henceforth LUT), 1500–2004, calculated for the region 45–53° N and 5–18° E from the gridded temperature reconstructions by Luterbacher et al. (2004, 2007) and Xoplaki et al. (2005). These datasets were created from documentary and natural proxies for 1500–1658, a mixture of documentary data, natural proxies and early instrumental records for 1659–1750 and solely from instrumental temperature data from then onwards;
2. the DJF, JJA and annual temperature series for the Low Countries, 764–1998, derived from documentary evidence before 1706 and instrumental data thereafter by van Engelen et al. (2001) and Shabalova and van Engelen (2003);
3. the DJFM temperature series for Tallinn, 1500–1997, estimated from the first day of ice-break up in the port of Tallinn and on the rivers in northern

Estonia (1500–1756), combined with instrumental temperature observations (after 1757), by Tarand and Nordli (2001);

4. the Central England Temperature (CET) series, 1659–2005, compiled up to 1720 from "the results of readings of highly imperfect instruments in uncertain exposures at a considerable distance… or on estimates based on interpretation of daily observations of wind and weather" (Manley 1974) and followed by instrumental temperature records for Central England from 1720 (Parker et al. 1992);
5. the winter ice severity index for the western Baltic, 1500–1997, derived from classified values of accumulated aerial ice volume along the German Baltic coast by Koslowski and Glaser (1999);
6. the April–September Western Europe temperature series, 1068–1987, for latitudes 35–55° N and longitudes 10° W–20° E based on tree-ring widths, grape harvest dates, Greenland ice oxygen isotope series and temperature indices derived from documentary data by Guiot et al. (2005);
7. the June–July Bavarian Forest/Austrian Alps temperature series, before 1500–1997, created as a composite chronology from tree-ring widths measured in string instruments and since 1800 from spruce *Picea abies* (Wilson and Topham 2004);
8. the June–September temperatures of the European Alps, 755–2004, reconstructed from larch *Larix decidua* Mill. tree-ring density series by Büntgen et al. (2006);
9. the summer temperatures in the Hala Gąsienicowa (Tatra Mountains), 1550–2007, reconstructed from tree-rings from the Tatras and the eastern Alps and compiled instrumental series since 1791 by Niedźwiedź (2004);
10. the spring–summer Burgundy temperatures series, 1370–2003, reconstructed from records of grape-harvest dates in the French region of Burgundy by Chuine et al. (2004);
11. the April–August Swiss temperature series, 1480–2006, based on grape-harvest dates from the Swiss Plateau region and north-western Switzerland by Meier et al. (2007).

Because some comparisons of the Stockholm and CEuT series with the above mentioned European series are presented already in the papers by Leijonhufvud et al. (2009) and Dobrovolný et al. (2009b), we will not repeat those graphical presentations here. Rather, we focus on some new comparisons. Among those made in Dobrovolný et al. (2009b), we particularly draw the readers' attention to the detailed comparisons with the LUT series, which partly, and sometimes to a large extent, share the original data with the new CEuT series. Therefore, the correlation coefficient is very high between CEuT and LUT (for example, $r = 0.93$ for DJF and $r = 0.85$ for JJA covering the period 1500–2002). Nevertheless, there are some notable differences between the two series which were discussed by Dobrovolný et al. (2009b).

The spatial field of correlations between the CEuT series and HadCRUT3 5 × 5° gridded temperature data (Brohan et al. 2006) across the whole of Europe is shown for the winter and summer seasons in the instrumental period in Fig. 6. These maps can help to evaluate relations to other European reconstructions including temporal stability of their relations. This temporal stability was checked calculating

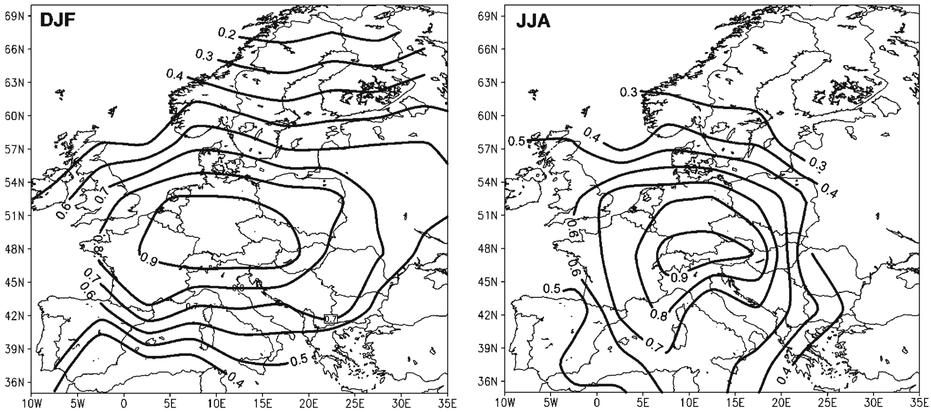

Fig. 6 Spatial correlations between seasonal DJF and JJA CEuT series (the instrumental part) and HadCRUT3 5 × 5° gridded temperatures (Brohan et al. 2006) for 1850–2007 (after Brázdil and Dobrovolný 2010)

correlations fields for 30-year non-overlapping periods from 1851 to 2000 (not shown here) and the spatial patterns presented in Fig. 6 suggest relative stability.

As can be expected, the "winter" CEuT series shows weaker correlations when compared with series farther to the north or north-east of Central Europe (Fig. 7a). Correlations with the winter ice severity index of the western Baltic (Koslowski and Glaser 1999), calculated over the entire period of data, are statistically significant ($r = 0.65$), although 31-year running correlations show lower values in particular during the second half of the nineteenth century. The correlations with Stockholm and with the Tallinn reconstruction (Tarand and Nordli 2001) are weaker ($r = 0.45$ and 0.36 respectively), and the two 31-year running correlation sequences show a broadly similar picture, with correlations fluctuating around the significance level, but sometimes even being negative before AD 1650. These fluctuations may be explained by spatial–temporal instability of temperature correlations considering the distance between studied regions/stations; however, they are probably partly related also to weaknesses in the actual reconstructions. For example, around AD 1600 the correlation with Stockholm is positive and significant, whereas the correlation with Tallinn is clearly non-significant and even negative. This points to a possibly poorer quality of the Tallinn record for this particular period, which would call for further investigations of the raw data for a better understanding of the records.

Notable fluctuations in the running correlations are also seen in the comparison of the "summer-half" CEuT series with reconstructions based on tree-rings (Niedźwiedź 2004; Wilson and Topham 2004; Büntgen et al. 2006) (Fig. 7b). Correlations are mostly higher and more stable in time with reconstructions using wine harvest data (Chuine et al. 2004; Meier et al. 2007; $r = 0.64$ and $r = 0.70$) or based on multi-proxy data (Guiot et al. 2005; $r = 0.65$) (Fig. 7c) compared to those with tree-ring data (r between 0.41 and 0.46). The 31-year running correlations between CEuT and the tree-ring-based series are often insignificant before 1800. Notable decreases in correlations with the April–August Swiss grape harvest series also occur albeit for rather short periods around 1750 and 1890 (the latter are similar to the April–September multi-proxy series for Western Europe). Some differences in the series

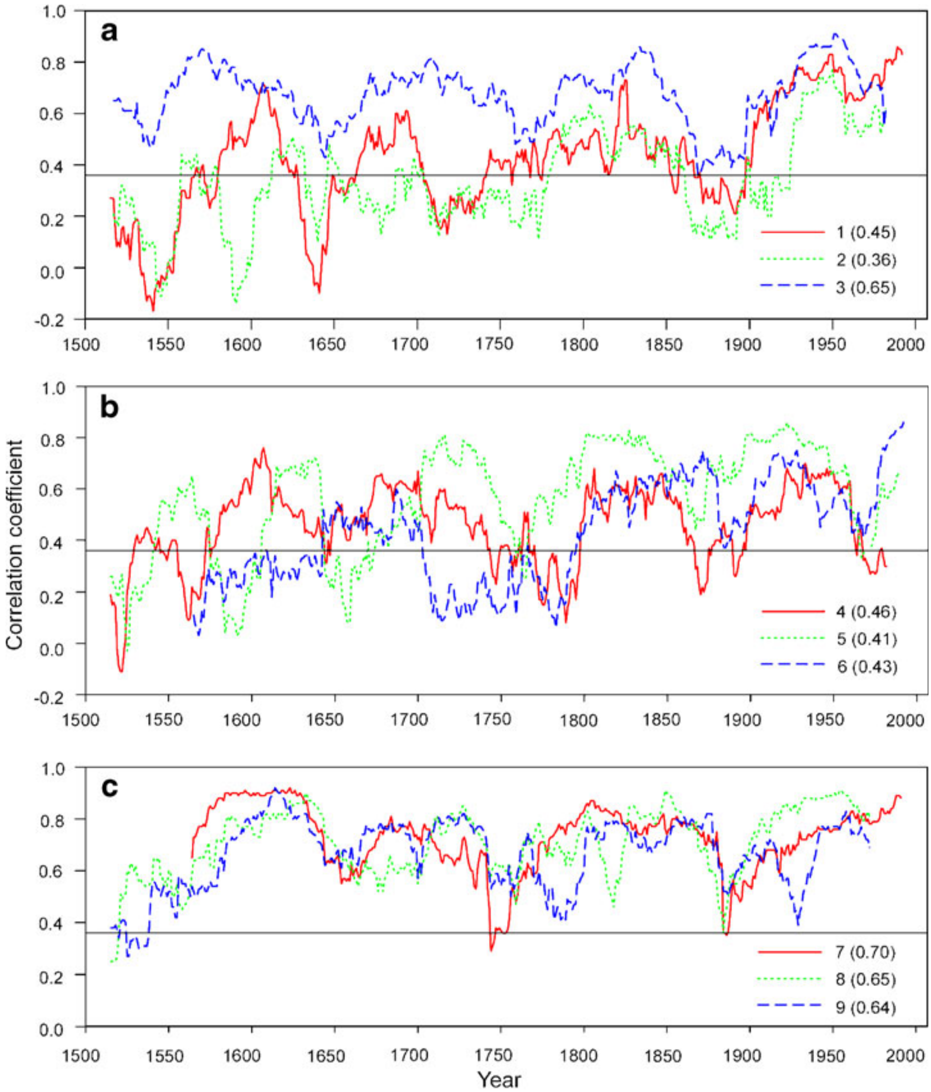

Fig. 7 Running 31-year correlation coefficients of **a** "winter" CEuT series with *1* JFMA Stockholm series (Leijonhufvud et al. 2009), *2* DJFM Tallinn series (Tarand and Nordli 2001), *3* western Baltic winter ice severity index (Koslowski and Glaser 1999) and **b**, **c** "summer-half" CEuT series with *4* June–July Bavarian Forest/Austrian Alps series (Wilson and Topham 2004), *5* June–September Alpine series (Büntgen et al. 2006), *6* JJA Hala Gąsienicowa (Tatra Mountains) series (Niedźwiedź 2004), *7* April–August Swiss series (Meier et al. 2007), *8* April–September Western Europe series (Guiot et al. 2005), *9* April–August Burgundy series (Chuine et al. 2004). The CEuT series are defined for the same months as the corresponding series *1–9* used for comparisons. Correlation coefficients between the CEuT series and each other series are indicated in parentheses. *Horizontal line* critical value of correlation coefficients for $\alpha = 0.05$ for a one-tailed t test, assuming no autocorrelation

can possibly be attributed to extreme years or seasons. However, it is difficult to establish the extent to which some of the longer-term losses of coherence (e.g. in the eighteenth century when CEuT is compared with tree-ring-based series, Fig. 7b) could be related to the spatial–temporal natural temperature variability or to the non-climatic component of variance in the proxy series.

5.3 The Stockholm and Central European temperature series and circulation indices

Luterbacher et al. (2009) used long-period instrumental, documentary proxy and three-dimensional climate model simulations to analyse the relations between European temperature extremes and atmospheric circulation patterns. They demonstrate that the strong relationship between European winter climate and the atmospheric circulation allows for the use of observed spatial patterns associated with JFMA temperature extremes that occur within the period for which instrumental sea level pressure (SLP) data are available (1760–2007) as modern analogues with which to reconstruct SLP fields back to AD 1500 when widespread direct pressure information is not available. It was also found that cold European JFMA periods are related to positive SLP anomalies in higher latitudes and below normal pressure in the south; a feature that resembles a strong negative North Atlantic Oscillation Index (NAOI). The associated temperature anomaly pattern indicates continental cold with the strongest negative anomalies over north-eastern Europe and warm anomalies over Iceland and the south-eastern Mediterranean. Consistent with the anomalous SLP distribution, reduced precipitation is found over large parts of northern Europe and wetter conditions over parts of the Mediterranean (Luterbacher et al. 2009).

To illustrate further some characteristics of the relationships between circulation and temperature reconstructions, comparisons are made here of the Stockholm and CEuT series with three reconstructions of NAO indices (NAOI); those by Cook et al. (2002), Luterbacher et al. (2002), and Trouet et al. (2009). As shown in many previous papers (e.g. Hurrell 1995; Casty et al. 2005; Hirschi and Sinha 2007; Beranová and Huth 2008; Brázdil et al. 2009), the NAO effects on temperatures in Central Europe are best expressed from December to March.

The reconstructed Stockholm JFMA temperatures often correlate positively and significantly with DJF and MAM NAOI after Luterbacher et al. (2002) in several, but not necessarily coincidental, periods. There is, however, a significant decrease in the correlation with MAM NAOI after the mid-twentieth century (Fig. 8a). As the Luterbacher et al. (2002) NAOI is available at monthly resolution from 1659 (but only for three-month seasons earlier), it is possible to compare the latter with Stockholm for an identically defined season (i.e. JFMA) after this year. The resulting correlations have been found to be statistically significant for the whole period with exception of a short interruption after 1700.

Nevertheless, the observed recent drop of correlation between Stockholm JFMA temperatures and MAM NAOI indicates a change in the influence of NAO on spring temperatures in southern Sweden since about half-a-century ago. Correlations at the same weak, or even negative, level in the sixteenth century may reflect similar climatic conditions as at the present, but poorer data quality both in NAOI and temperature reconstructions offer an alternative explanation.

The CEuT series show very high and time-stable positive correlations with the Luterbacher et al. (2002) NAOI for three of the seasons (MAM, SON and DJF)

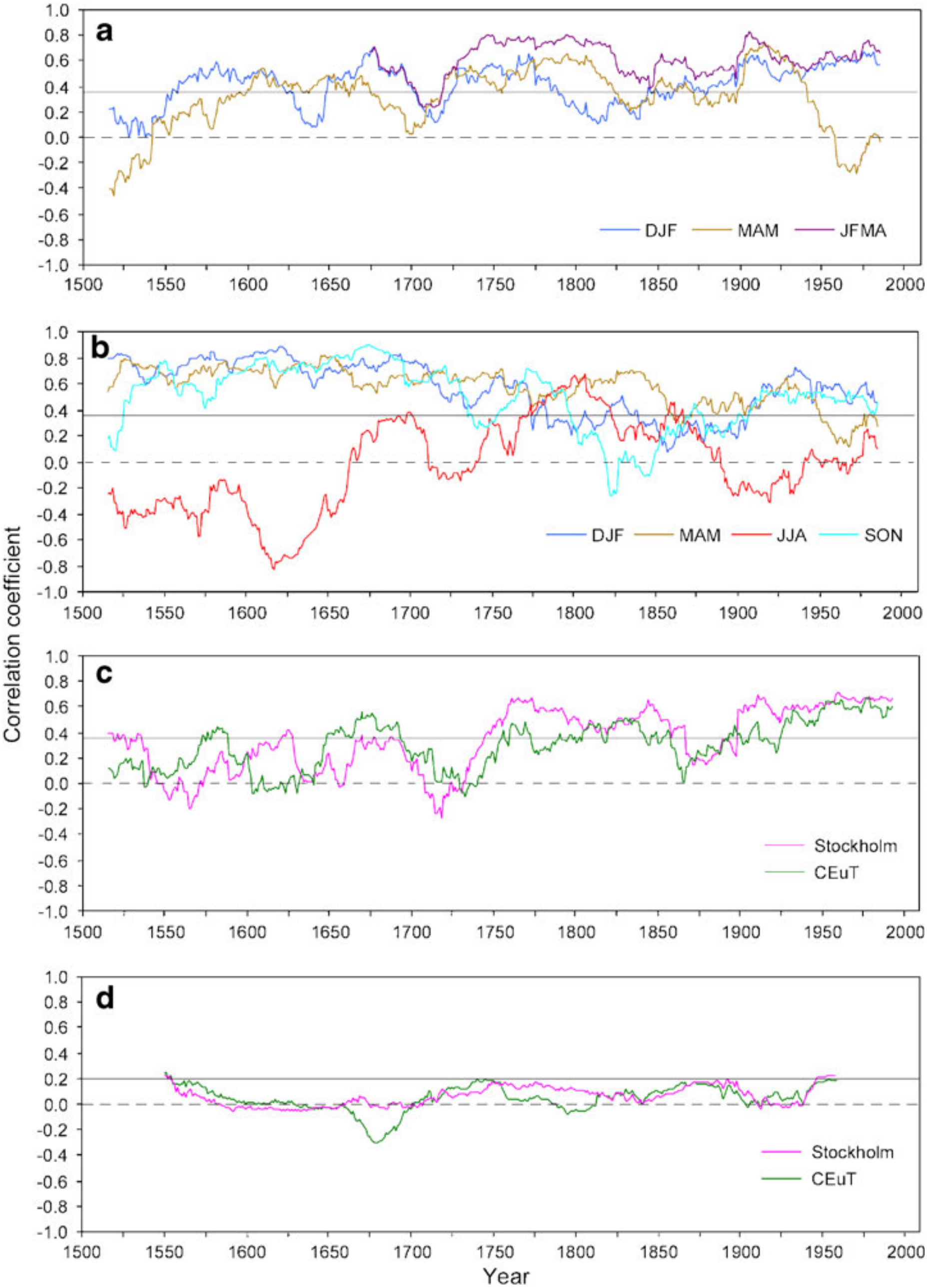

Fig. 8 Running 31-year correlation coefficients between temperature series and NAOI: **a** Stockholm JFMA temperatures and NAOI after Luterbacher et al. (2002; data after 2000 updated from http://www.cru.uea.ac.uk/~timo/projpages/nao_update.htm, a web page of T. Osborn); **b** seasonal CEuT series and NAOI after Luterbacher et al. (2002); **c** JFMA Stockholm and CEuT series and NAOI after Cook et al. (2002); **d** JFMA Stockholm and DJF CEuT series correlated (running 101-year correlation coefficients) against NAOI after Trouet et al. (2009). *Horizontal line* – the critical value of correlation coefficients for $\alpha = 0.05$ according to a one-tailed t test, assuming no autocorrelation

before 1750 (Fig. 8b). As correlations for these seasons are notably weaker and also less stable over time in the instrumental period, one must suspect that the high pre-1750 correlations can be related to use of some identical proxies in both reconstructions. More complicated is the behaviour of the correlations in summer with change from negative values before 1660 to positive correlations afterwards, becoming statistically significant around 1800, but then negative correlations again in the instrumental period (approximately between 1890 and 1940).

A comparison of the Stockholm and CEuT series (here for the JFMA season) with the DJFM NAOI by Cook et al. (2002) provides further information. In particular, the Cook et al. (2002) NAOI is based on an entirely different dataset than Luterbacher et al. (2002), and can be considered as wholly independent of the CEuT. The running correlations in Fig. 8c show two distinct parts for both series. Correlations are mostly non-significant before 1750 (documentary-based part of temperature reconstructions) and often significant after that time (mixed documentary-based and instrumental part for the Stockholm series and instrumental only for the CEuT series). After 1750, the correlation of the Cook et al. (2002) NAOI with Stockholm temperatures is systematically stronger than with CEuT. However, weaker correlations are typical also for the second part of the nineteenth century for both the Stockholm and the CEuT series.

Weaker correlations are found when the two temperature reconstructions are compared with the Trouet et al. (2009) NAOI series; the running 101-year correlation coefficients are only episodically above the significance level (Fig. 8d). This is a consequence of the fact that this particular NAOI express decadal fluctuations instead of the year-by-year variability that is so strongly represented in both of the above temperature reconstructions.

Besides the possible data quality problems typical for all proxy-based reconstructions (from natural as well as documentary proxies and for NAOI as well as temperatures), the existence of periods with weaker correlations in the modern period (e.g. Jacobeit et al. 2001; Slonosky and Yiou 2002; Jones et al. 2003; Casty et al. 2005) suggest that there can be similar temporal instabilities in relations between NAOI and European winter temperatures further back in time. Such inconsistencies complicate the interpretation of the proxy data in terms of distinguishing real changes in climate behaviour from the consequences of changes in data quality. Clearly, additional long proxy records of good quality are needed to improve our understanding of climate variations and our ability to distinguish between such true climate variations and those brought about by variations in data properties.

6 Discussion and conclusions

The paper by Brázdil et al. (2005b) was devoted to an appraisal of the state of the art of historical climatology in Europe summarising developments in this field up to the early 2000s. Although only a few years have passed since that paper was written, substantial progress has been made in historical climatology as is evidenced by several papers in this special issue and further references. In particular, attention can be drawn to the completion of existing and development of new documentary databases and to the successful application of standard palaeoclimatological calibration and verification methods in the preparation of climate (temperature or precipitation) reconstructions derived from documentary evidence. The latter can, importantly, be shown to be comparable with reconstructions based on other, longer-standing, natural proxies. Moreover, the possibility of obtaining a temporal resolution down to individual months (and even days) and subsequent seasonal combinations of these data singles out documentary sources as being uniquely valuable in palaeoclimatological studies.

The possibility of assessing the reliability of proxy-based temperature (or any climate variable) reconstructions is however dependent on the length and quality of instrumental series used for calibration and verification of the transfer functions. Additionally, the instrumental data need to be adjusted where necessary to eliminate possible inhomogeneities in these series (Peterson et al. 1998; Brandsma and Können 2005; Della-Marta and Wanner 2006; Kuglitsch et al. 2009; Štěpánek et al. 2009). Such procedures are important to avoid the inclusion of any non-climatic signal in the reconstructions. An example is the need to eliminate any intensified urban heat island signal consequent on the growth of cities (Brázdil and Budíková 1999; Brandsma et al. 2003; Stone 2007). Moreover, when developing temperature reconstructions, one needs also to be aware of the so-called 'early instrumental paradox' when reconstructions based on proxies representing summer temperatures sometimes depict cooler conditions than shown by instrumental observations before the mid-to-late nineteenth century (Moberg et al. 2003; Böhm 2005; Frank et al. 2007). The relatively higher instrumentally-based temperatures are probably a consequence an over-exposure of the thermometers to radiation in the summer season in the years before the invention of the Stevenson screen. Analysis of 32 stations from the Greater Alpine Region by Böhm et al. (2009) demonstrated, for example, that recorded mean April–September temperatures before 1850 show a warm bias of about 0.4°C. Moberg et al. (2003), undertaking a more preliminary and indirect study, concluded that summer temperatures at Stockholm and Uppsala before the 1850s probably need a slightly larger correction.

Reconstructed series should, for all the above reasons, be accompanied by uncertainty estimates, for example expressed as standard errors. Such estimates can be approximately obtained from a calibration period of overlap between proxy and instrumental data. However, it is sometimes necessary to inflate the value of the standard error that is derived from calibration by taking into account also factors that consider, for example, the changing number of replicated series used in the construction of a proxy series or the mutual correlations between the constituent proxy series. Moreover, there are various uncertainties specific to individual proxy types, as well as those typical of documentary evidence, as discussed in Dobrovolný et al. (2009b). Statistical methods for estimating errors are particularly well developed in dendroclimatology (Cook et al. 1994; Briffa et al. 2002; Esper et al. 2007), but it has been demonstrated in this special issue (Dobrovolný et al. 2009b; Leijonhufvud et al. 2009) that similar methods can be applied in historical climatology.

The creation of long-term documentary-based temperature reconstructions also provides the possibility of making comparisons with climate model simulations of the past several centuries. Zorita et al. (2009), for example, compares the JFMA temperatures for Stockholm (Leijonhufvud et al. 2009) and seasonal and annual Central European temperatures (Dobrovolný et al. 2009b) with the temperature output of three climate simulations with the global model ECHO-G and with the regional model RCA/FLAKE. The Central European series, in contrast to the Stockholm reconstruction, shows weaker agreement with model simulations at the relevant grid points, as regards the amplitude of the low-frequency signal.

Although the amplitude of low-frequency variability in the ECHO-G simulations is largely determined by the choice of the forcing time series imposed on the model, the resulting temperature field must still be regarded as physically consistent given the external forcing imposed. Therefore, even if the simulations were unrealistic; the fact that the Central European temperature reconstruction has weaker low-frequency variability than the simulations, and the fact that the Stockholm reconstruction shows a similar magnitude of low-frequency temperature variability as in the model, together with the observed weaker variability at the bi-centennial scale in the documentary part (but not in the instrumental part) of the Central European temperature series compared to Stockholm (see Figs. 3 and 5), may indicate an inherent incapability of the index type of documentary data to capture low-frequency variability compared to the (bio)physical type of documentary data. The problem appears to be related to the fact that the authors of documentary records often described the weather with respect to their own perception and experience and everyday understanding of 'normal' weather. This means that every one of them may have had a different concept of what constituted such "normality", the result of which is a tendency to lose any low-frequency signal in their collective interpretation. However, this is not always a problem where the evidence used to derive temperature indices is more directly physically based (e.g. dates of frost, days of harbour ice thaw etc.). Nevertheless, reconstructions based on the creation of temperature indices often involve some degree of subjectivity by the scientist who transforms the raw information to the monthly index form, and this may lead to reconstructions that only weakly express any low-frequency signal. This explanation is compatible with the fact that the magnitude of the simulated and reconstructed interannual variations is much closer in agreement. On the other hand, it needs to be stressed that monthly indices are needed to address the issue of natural disasters, climatic impacts on and the perception of extremes by societies (Pfister and Brázdil 2006; Rohr 2007; Glaser et al. 2009; Pfister et al. 2009).

The inherent incapability of documentary index data to capture low frequencies may be improved if a particular reconstruction (which supposedly suffers from a low-frequency variance problem) can be combined with other proxies in which low-frequency signals are potentially better preserved, for example series of phenophases, freezing of rivers and lakes, ship logbook data, start of grain and vine harvests, etc. Reconstructions based wholly on such long-term (bio)physically-based proxies may be expected to be less influenced by low-frequency difficulties. But even in those cases there are some unavoidable steps in the data processing when, sometimes, more or less subjective decisions have to be made in order to define the particular date of occurrence of an event of interest (e.g. Chuine et al. 2004; Meier et al. 2007; Rutishauser et al. 2008; Leijonhufvud et al. 2008, 2009).

On the other hand, there are also indications that model simulations may be underestimating the decadal climate variability at regional scales. For instance, the warm decades detected in several temperature reconstructions and early instrumental data around 1730 (e.g. Luterbacher et al. 2004; Xoplaki et al. 2005; Jones and Briffa 2006) are missing in the model simulations, and seem not to be consistent with reconstructions of past external climate forcing (solar variations or volcanic activity).

Luterbacher et al. (2009) have shown that the reconstructed patterns of the extreme temperatures in late winter/early springs are in good overall agreement with the two coupled climate models (ECHO-G and HadCM3). This suggests that the latter can be a useful tool to provide approximate estimates of past large-scale fields related to extreme regional climate variations in the absence of spatial details in the observational information. Further, this agreement underscores a reasonable model skill, which is essential when simulating the spatial pattern of extreme temperature and precipitation in future climate simulations. The observed overall agreement between proxy/instrumental-based and simulated temperature patterns also suggest that it is possible to constrain model states on the basis of the spatial structure of anomalies observed in proxy data. This important feature supports the use of documentary evidence in data assimilation experiments, which explicitly combines the information in the proxy data with climate modelling efforts, as discussed by Luterbacher et al. (2009).

The preceding paragraphs and all the other papers in this special issue present the recent and significant research efforts that have been achieved in the context of historical climatology of Europe for the past 500 years. Nevertheless, this field still offers much potential for future research building upon recent experiences. These can be briefly summarised as follows:

1. the revision of existing weather compilations, documentary datasets and their completion drawing on new archival sources such as administrative records
2. the creation of new temperature/precipitation index series based on documentary evidence and completion of gaps in the existing series
3. the further collection of documentary data for the periods of overlap with instrumental records, thereby allowing for calibration/verification exercises using standard palaeoclimatological methods
4. the development and application of new methods for temperature/precipitation reconstruction and calculation of associated uncertainties (error bars)
5. whenever possible, the undertaking of direct comparison between reconstructions from the same (or nearby) region(s), but derived separately from the index-type and the (bio)physical type to improve understanding of the potential deficiency of index data to capture low-frequency information
6. the development of better homogenized long instrumental records for many sites, including assessment and corrections for the warm bias in the early instrumental period related to thermometer exposure
7. the cross-checking of documentary data against temperature and precipitation reconstructions and outputs of coupled climate model
8. deepening of co-operation between environmental historians, climatologists and the climate modelling community
9. cross-checking and combining of reconstructions based on man-made and natural climate proxies (tree-rings, speleothems, etc.)
10. relating high resolution climate data to the occurrence of natural disasters, famines, epidemics within pre-industrial societies.

A further comment should be made in connection with point 3 on the list above; there are other good reasons to extend the documentary records to well within the instrumental period than just for making the statistical calibration and verification. As pointed out by Jones et al. (2009), the general lack of documentary data in the instrumental period is a severe impediment to their use in gridded or large-scale mean climate reconstructions together with other climate proxy data. Currently, when they have been used in such reconstructions, they are generally represented by degraded temperature data to extend the series to the present, and this may give a false sense of their reliability. Thus, to make documentary data records more comparable with natural proxy records, it is desirable to extend the documentary series as far up to the present as possible.

Lastly, it needs to be emphasised that Europe possesses a rich, diverse and extensive collection of documentary evidence also for the climate before AD 1500, thereby opening the possibility of extending some reconstructions and analysis to the period from the twelfth century (particularly with respect to Medieval Climate Anomaly), and sometimes even further back, and broadening further horizons of historical climatology.

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