Chapter 2
Historical Climate in Central Europe During the Last 500 Years

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2.1 Introduction

The climate of the past millennium is usually divided into the Medieval Warm Period (MWP; recently termed the Medieval Climate Anomaly – MCA), the 'Little Ice Age' (LIA) and subsequent Recent Global Warming (RGW) (Bradley 2000; Bradley et al. 2003b). This division has its roots in papers by the English climatologist Hubert H. Lamb (1965, 1984). Lamb, analysing data mainly derived from Western Europe and northern parts of the Atlantic, placed the MWP within the period AD 950–1200 (AD 1150–1300 in the greater part of Europe) and the LIA between the years 1550 and 1850, with its most pronounced features in AD 1550–1700. Lamb denoted the time interval between MWP and LIA as a period of gradual climate deterioration. Jones and Mann (2004) discuss the limited utility of MWP (MCA) and LIA in describing the climate of the past millennium arising out of dramatic differences between past regional and hemispheric/global trends as well as distinguishing between changes in surface temperature and precipitation/drought fields. Similarly, Bradley et al. (2003a) drew attention to non-synchronous warmest Medieval temperatures around the globe.

In terms of the concept described above, the period of the last 500 years, on which this study for Central Europe concentrates, belongs in the greater part to the LIA and from the end of the nineteenth century to the present to the RGW. The term 'Little Ice Age' was originally used to describe glacier behaviour (Matthes 1939, 1940), not for climate. Generally, it was the most recent period in which glaciers advanced to expanded positions and fluctuated around them in the greater part of the globe (for more details of the LIA see e.g. Grove 1988, 2004; Bradley and Jones 1992; Ogilvie and Jónsson 2001; Matthews and Briffa 2005). Although glacial advances and retreats are most frequently related to temperature, other meteorological elements, such as precipitation, are also important (Nesje and Dahl 2003; Steiner et al. 2008).

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While it is generally accepted that the LIA ended around the mid-nineteenth century (e.g. with reference to the nineteenth-century central and western European Alps, Zumbühl et al. (2008) mention one maximum extent around 1820 and a second around 1855), its beginning is more subject to debate. Different proposals have been made, varying according to available data, time resolution and geographical region. For example, Pfister et al. (1996, 1998) placed the start of the LIA after AD 1300, as confirmed by the three maximum advances of the Great Aletsch glacier in the Alps around AD 1350, 1650 and 1850 (Holzhauser 1997; Holzhauser and Zumbühl 1999). A period of similar synchronous glacier advances in 1300–1860 was also confirmed by Holzhauser et al. (2005) for the Great Aletsch, the Gorner and the Lower Grindelwald glaciers in the Alps. Grove (2004) moved the beginning of the LIA to the thirteenth or fourteenth century and its culmination between the mid-sixteenth and mid-nineteenth centuries. In contrast, Jones and Bradley (1992) simply opined that universal delimitation of a beginning and an end to such a period is very difficult.

The period of the last part of the past millennium, the Recent Global Warming period, is established by global/hemispheric temperature series starting in 1850 (Brohan et al. 2006). Over the past 100 years (1906–2005), the global temperature rise has reached a value of 0.74°C (Solomon et al. 2007). Contrary to the preceding IPCC report (Houghton et al. 2001), this means an intensification of the warming trend by 0.14°C, because the temperature rise in the period 1901–2000 reached a value of 0.60°C. Recent global warming is very likely to have been caused by anthropogenic activity (Solomon et al. 2007).

The climate paradigm under discussion is reflected in a different way through reconstructed temperature series based on various proxy and instrumental data covering the past millennium in the Northern Hemisphere (e.g. Mann et al. 1999; Jones et al. 2001; Esper et al. 2002; Moberg et al. 2005; for an evaluation of various millennial reconstruction methods see Lee and Zwiers 2008). Similar series have also been calculated for the whole of Europe (Luterbacher et al. 2004, 2007; Xoplaki et al. 2005), for Western Europe (Guiot et al. 2005) and for the greater Alpine area (Casty et al. 2005). The question remains as to whether the features typical of temperature fluctuations in the above series are also expressed in temperature series for Central Europe or its individual parts.

Central Europe is defined, for the purposes of this article, as the territory consisting of Germany, Switzerland, Austria, the Czech Republic, Poland, Slovakia and Hungary. With the intention of characterising climate fluctuations in this part of Europe for the last 500 years, this paper starts from a description of available climatological data, with particular attention to documentary evidence, and methods of analyzing it, together with climate reconstruction, then continues by listing available temperature and precipitation series for Central Europe with analysis of the variability of climatic patterns over the past 500 years discussed in the broader European context. Finally, perspectives on further research are formulated. This paper concentrates largely on temperature changes but also addresses issues related to precipitation.

2.2 Instrumental and Proxy Climatological Data

Central Europe is a region with a long tradition of instrumental meteorological observations (for example, Warsaw in Poland started in December 1654 – see Przybylak this volume). In 1717, the Breslau (now Wrocław, Poland) physician, Johan Kanold organised an international meteorological network of observers and correspondents and published quarterly results for 1717–1726 in *Sammlung von Natur- und Medicin-, wie auch hierzu gehörigen Kunst- und Literatur-Geschichten* in the years 1718–1727 (Fig. 2.1). This network also continued in the years 1727–1730, thanks to Andreas Elias Büchner, a professor of medicine at Erfurt (for more details see Brázdil and Valášek 2002). For several countries, this network published the very first instrumental observations on their territory, such as the measurements taken by Johann Carl Rost in Zákupy in northern Bohemia (Brázdil and Valášek 2002) and those of Johann Adam Reimann in Prešov in eastern Slovakia (Brázdil et al. 2008b). The most continuous observations from the whole period of the existence of this network come from the stations in Wroclaw (Poland; for more details of this station see Przybylak 2009), Löbau, Nürnberg (both Germany) and Zürich (Switzerland).

Another network of meteorological stations known as the *Societas Meteorologica Palatina* was established by Karl Theodor, Elector of the Palatinate, in 1780. At its maximum extension, this network comprised 39 stations, including several from Central Europe. All the stations used standardised instruments and made their observations according to regulations issued by the Society (e.g. observing times at 07.00, 14.00 and 21.00 h mean local time). The results of the observations were published for the years 1780–1792 in the *Ephemerides Societatis Meteorologicae Palatinae* in Mannheim (see e.g. Traumüller 1885; Kington 1974). Some stations were also included in a local meteorological network of 21 stations in Bavaria, operated by the Bavarian Academy of Science in Munich under the direction of Jesuit Franz Xaver Epp (Lüdecke 1997).

Further to this international effort, the development of meteorological observations was also taken up by a number of individuals who started making meteorological observations out of their own interest, mainly as part of the activities of scientific and economic societies (for example, the Meteorological Section of the Moravian-Silesian Economic Society in Moravia and Silesia – see Brázdil et al. 2005b). However, systematically organised networks of meteorological stations evolved out of the establishment of national meteorological institutes. For example, in the former Austrian empire such an institute, known as the “Imperial-Royal Central Institute for Meteorology and Earth Magnetism” (*K. k. Central-Anstalt für Meteorologie und Erdmagnetismus*) in Vienna was created at the request of the Academy of Sciences through Emperor Franz Joseph I on 23 July 1851. Its aim was to coordinate and check the work of meteorological stations, collect the results of their observations and evaluate them (Hammerl et al. 2001).

It is clear that the collection of consistent meteorological data from the eighteenth century onwards was hindered by many factors, such as changes of observation point,

Sammlung
Von
Natur- und Medicin-
Wie auch
hierzu gehörigen Kunſt- und Literatur-.
Geſchichten,
So ſich
An. 1717. in den 3. Sommer-Monaten
In Schleſien und andern Ländern begeben.
Welcher Geſtalt nemlich:
1) Die Veränderung des Gewitters von Tage zu Tage und von Zeit zu
Zeit. 2) Land- und Witterungs-Seuchen, von Monat zu Monat, nach dem Einfluß Lufft
und Wetters. 3) Zu- und Mißwachs von Feld- Wald- und Garten-Früchten, auch aller-
hand animaliſchem Proventu, in allerley Ländern Europens von einer Jahrs-Zeit zur an-
dern bemercket worden: Wie nicht weniger 4) was vor einzelne eclatante natürliche Be-
gebenheiten am Firmament, in der Lufft, auf und unter der Erde, im Waſſer, an Menſchen
und Vieh: auch 5) was vor neue phyſicaliſche und mediciniſche Erfindungen dieſe Zeit
über hervorgebracht und bekañt worden: und denn 6) was in re literaria Phy-
ſico-Medica veränderliches vorgefallen.
Alles in ordentlicher Connexion und mit allerley Reflexions
Aus vielfältiger Correſpondenz, und andern Relationibus, ſo wie groſſen
Theils aus eigener Erfahrung zuſammen geleſen;
Und
Als ein Verſuch ans Licht geſtellet
Von
Einigen Breßlauiſchen Medicis.
Sommer-Quartal 1717.

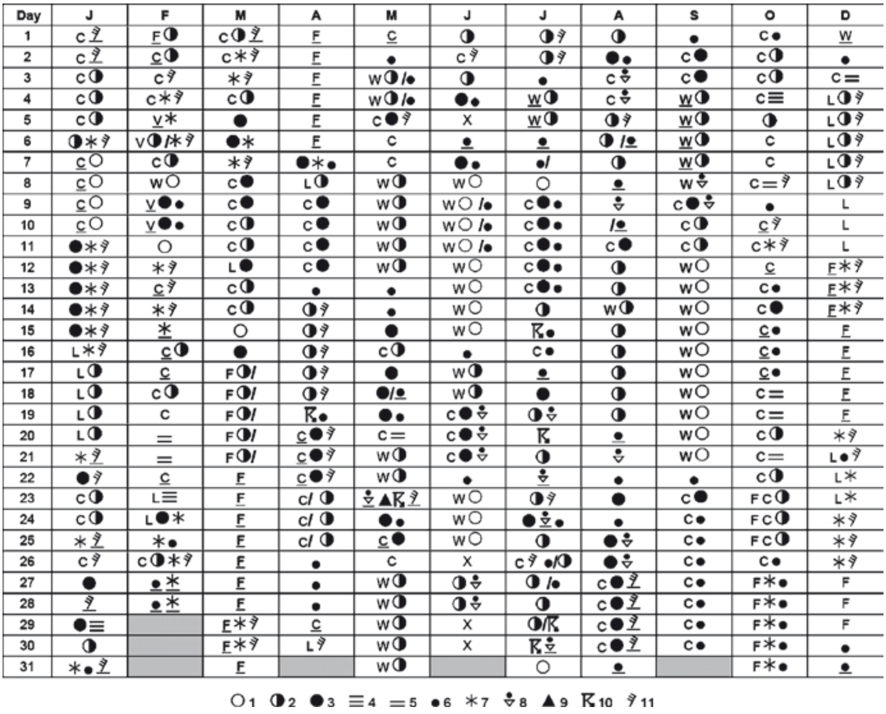
Breßlau,
Bey Michael Hubert, M DCC XVIII.

Fig. 2.1 Title page of the first volume of Kanold's *Sammlung von Natur- und Medicin-, wie auch hierzu gehörigen Kunst- und Literatur-Geschichten* with the results of meteorological observations for the summer quarter (July–September) of 1717 different observers, and a variety of instruments, observing times and procedures, as well as by changes in the station surroundings, all of which could give rise to inhomogeneities in long-term series. Great efforts must be made to detect possible artificial breaks in series and adjust them in such a way as to obtain relatively homogeneous series, concentrating not only on methods of detection and adjustment (see e.g. Peterson et al. 1998 for an overview), but also on the homogenisation proper of long-term station datasets (see e.g. HISTALP in Austria – Auer et al. 2005, 2007). Only homogenised series are useful for the study of long-term climate variability, while series consisting of only raw, measured data may produce controversial low-frequency fluctuations.

The study of climate variability in the pre-instrumental period is limited to various forms of proxy intrinsic to natural phenomena and man-made archives (Bradley 1999). The current paper concentrates mainly on the man-made proxies that are available in the form of documentary evidence. Documentary evidence is used in historical climatology, which focuses mainly on the reconstruction of temporal and spatial patterns of weather and climate, as well as climate-related natural disasters, for the period prior to the creation of national meteorological networks, that is mainly for the last millennium (see Brázdil et al. 2005a for more details and more references therein).

Basic sources of documentary data worthy of note for the past 500 years in Central Europe include (e.g. Pfister 1984, 1999; Pfister et al. 1999; Glaser 2001, 2008; Brázdil et al. 2005a):

1. *Annals, chronicles, memory books and memories* may all include information about the weather and related phenomena. To varying degrees of detail, they often describe the course of extreme weather events, material damage and even human casualties. The quality and accuracy of any given record depends on the intellectual level of the writer and particularly whether s/he was an eye-witness. Deriving reports from other, indirect, sources or from hearsay may well give rise to mistakes in dating and description of phenomena.
2. *Visual daily weather observations* were recorded by their authors more or less regularly for ephemerids, calendars and personal diaries. As well as descriptions of daily weather, they also include information about weather-related extremes and their impacts. Contemporary expressions have to be converted into current meteorological terminology (Fig. 2.2).
3. *Correspondence (letters)* contains information about weather and related extremes if the situation concerned the author of the letter in some way. Official letters sent by estate administrators to the owners of the estates, in which they often described serious weather events occurring on the estate and affecting its operation, form a special sub-category.
4. *Special broadsheets* 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 intended either to impart information about these extremes or to promote some religio-political agenda that might be derived from them.



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2	c⚑̲	c̲◑	c✱⚑	F̲	•	c⚑	◑⚑	●•	c●	c◑	•
3	c◑	c⚑	✱⚑	F̲	w◑/•	◑	•	c▽	c●	c◑	c=
4	c◑	c✱⚑	c◑	F̲	w◑/•	●•	w̲◑	c▽	w̲◑	c≡	L◑⚑
5	c◑	v̲✱	●	F̲	c●⚑	X	w̲◑	◑⚑	w̲◑	◑	L◑⚑
6	◑✱⚑	v◑/✱⚑	●✱	F̲	c	•̲	•̲	◑ /•̲	w̲◑	c	L◑⚑
7	c̲○	c◑	✱⚑	●✱•	c	●•	•/	◑	w̲◑	c	L◑⚑
8	c̲○	w○	c●	L◑	w◑	w○	○	•̲	w▽	c=⚑	L◑⚑
9	c̲○	v̲●•	c●	c●	w◑	w○ /•	c●•	▽	c●▽	•	L
10	c̲○	v̲●•	c◑	c●	w◑	w○ /•	c●•	/•̲	c◑	c̲⚑	L
11	●✱⚑	○	c◑	c●	w◑	w○ /•	c●•	c●	c◑	c✱⚑	L
12	●✱⚑	✱⚑	L●	c●	w◑	w○	c●•	◑	w○	c̲	F̲✱⚑
13	●✱⚑	c̲⚑	c◑	•	•	w○	c●•	◑	w○	c•	F̲✱⚑
14	●✱⚑	✱⚑	c◑	◑⚑	•	w○	◑	w◑	w○	c●	F̲✱⚑
15	●✱⚑	✱̲	○	◑⚑	●	w○	Ʀ•	◑	w○	c̲•	F̲
16	L✱⚑	c̲◑	●	◑⚑	c◑	•	c•	◑	w○	c̲•	F̲
17	L◑	c̲	F◑/	◑⚑	●	w◑	•̲	◑	w○	c̲•	F̲
18	L◑	c◑	F◑/	◑⚑	●/•̲	w◑	●	◑	w○	c=	F̲
19	L◑	c	F◑/	Ʀ•	●•	c●▽	◑▽	◑	w○	c=	F̲
20	L◑	=	F◑/	c̲●⚑	c=	c●▽	Ʀ	•̲	w○	c◑	✱⚑
21	✱⚑̲	=	F◑/	c̲●⚑	w◑	c●▽	◑	▽	w○	c=	L•⚑
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24	c◑	L●✱	F̲	c/ ◑	●•	w○	●▽̲•	•	c•	Fc◑	✱⚑
25	✱⚑̲	✱•	F̲	c/ ◑	c̲●	w○	◑	●▽	c•	Fc◑	✱⚑
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27	●	•̲✱̲	F̲	•	w◑	◑▽	◑ /•	c●⚑̲	c•	F✱•	F
28	⚑̲	•̲✱̲	F̲	•	w◑	◑▽	◑	c●⚑̲	c•	F✱•	F
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31	✱•⚑̲		F̲		w◑		○	•̲		F✱•	•̲

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Fig. 2.2 Example of interpretation of visual daily weather records: Jan Nádherný, Bohemia, 1805 (missing November) (Brázdil et al. 2007). Key: H – hot, W – warm, L – mild, C – cold, F – frost, V – variable, X – missing record, 1 – clear sky, 2 – half-covered sky, 3 – overcast, 4 – fog, 5 – misty, 6 – rain, 7 – snow, 8 – shower, torrential rain, 9 – hail, 10 – thunderstorm, 11 – wind. Underlined symbols express strong intensity of phenomenon. A slash (/) distinguishes night and morning from afternoon and evening occurrences of the phenomenon

5. *Economic records* include the data collected in association with any economic activity or procedure influenced by weather or weather-related extremes, for example, the dates of grape-harvest, wine quality and quantity, yields and prices of agricultural crops, wages paid for various kinds of work (e.g. cutting ice at water mills, clearing snow, repair of property damaged by weather extremes), etc. Particularly valuable are reports linked to the collection of taxes and applications for rebates on the grounds of weather-related damage (due to, for example, hail, flood, torrential rain or windstorm), preserved at different levels of state administration (Brázdil et al. 2006).
6. *Newspapers and journals* usually concentrate on descriptions of unusual weather or on weather-related extremes. They frequently contain information about the causes, the course and the impacts of extremes, sometimes with appeals for solidarity and help for the afflicted.
7. *Pictorial evidence* in the form of paintings or photos, created at various levels of technical expertise, records weather-related phenomena (e.g. glacier position) and

largely weather-related extremes and their consequences (e.g. after flood or windstorm). However, paintings are often reflections of the author's imagination rather than a real representation of events. They often fulfilled the task of generating historical "memory" to make people recall the horrors of destructive extremes and thus conveyed moral warnings of God's punishment for sins committed, thus evoking respect for such events.

8. *Stall-keepers' and market songs* often describe an extreme (e.g. a flash flood after thunderstorm and torrential rain) as a spectacular and dramatic topic, largely inspired by sudden and unexpected onset, high death toll and severe damage on a local or regional scale. Although they may describe the event, its occurrence and impacts, critical evaluation of the possible distortion of reality in the information presented (*licentia poetica*) is essential.
9. *Early scientific papers and communications* often contain information about weather and related extremes, their occurrence, causes and impacts. However, care must be exercised in relation to what are known as weather compilations (e.g. Weikinn 1958–2002), which may contain a mixture of different reports that are in some cases far from exact or even credible (for a critique of such sources see e.g. Bell and Ogilvie 1978; Brázdil et al. 2005a).
10. *Epigraphic sources* usually consist of marks or short remarks chiselled into stone or marked on houses, bridges, gates, or ancient trees. They often show the level of extremely high (or low) water or recall some extreme event (e.g. someone's death by lightning or flash flood). Water-marks, in particular, should be assessed for originality, particularly with respect to the age of the object on which they are recorded, because they may be transferring information from other places.
11. *Early instrumental meteorological observations* started in some places much before the establishment of national meteorological services (for the seventeenth–eighteenth centuries, see e.g. Kanold's Breslau network – Brázdil and Valášek 2002). They usually contain data about air pressure and temperature, wind direction, cloudiness and the occurrence of meteorological phenomena, but technical detail vital to their homogenisation (position, instruments, terms, etc.) is often absent.

In the course of primary extraction of data from documentary evidence, it is essential that further methodological work follows key requirements in handling this type of evidence (Brázdil et al. 2005a):

- Primary sources must be favoured (secondary sources may be used only after thorough checking)
- Formal errors in typing and dating must be avoided
- Descriptive information must be interpreted using recent meteorological terminology
- A knowledge of the historical context in which this data originated is essential

If documentary data makes up a continuous series (e.g. dates of grape harvests, start dates for other agricultural harvest, spring opening of harbours), they may worked up for a standard palaeoclimatological reconstruction of temperature series (see e.g. Jevrejeva 2001; Tarand and Nordli 2001; Chuine et al. 2004; Meier et al. 2007; Leijonhufvud et al. 2008, 2009). Spatially and temporally discontinuous series of temperature/precipitation indices usually have to be created from documentary data of a qualitative and descriptive character; these can be subsequently used for further analyses and reconstructions.

Depending on the density and quality of the basic information, a graded scaling into ordinal numbers may be used. Simple indices employing a three-term classification are very often applied: months are classified as index −1 (cold or dry), 0 (normal) and 1 (warm or wet). Weighted indices 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 seasonal values can fluctuate from −9 to 9 and annual values from −36 to 36) (Pfister 1984, 1992). A different scaling into ordinal numbers has occasionally been used in certain papers. For example, Koslowski and Glaser (1999) developed a winter ice severity index from ice volume along the German Baltic coast with a gradation of weak (index 0), strong (1), very strong (2) and extreme (3) winter severity. Van Engelen et al. (2001) used an ordinal scale from 1 to 9 for reconstruction of winter (from 1 – extremely mild to 9 – extremely severe) and summer (from 1 – extremely cool to 9 – extremely warm) temperatures in the Low Countries.

2.3 Methods of Climate Reconstruction

While long-term homogenised series may be used directly for statistical analyses (see e.g. von Storch and Zwiers 1999), index temperature/precipitation series must first be converted into recent meteorological units by a reconstruction procedure. The standard scheme of palaeoclimatological reconstruction (Fig. 2.3) assumes that such an index series may be calibrated and verified against instrumental observations for an overlapping period. The aim of the calibration is to determine the transfer function between the indices and the real climate variable. Prior to being used for a reconstruction, the transfer functions need to be verified for an independent period; or at least a cross-validation procedure has to be carried out if the data series is short. The relationship obtained for a calibration period and evaluated by various statistical measures (e.g. squared correlation r^2, standard error of estimate *SE* and the Durbin-Watson test for autocorrelation in residuals) is subsequently applied to a verification period for which the climate values have been estimated from the documentary data. These estimations are then compared with the measured values and evaluated again using various statistical measures (e.g. r^2, reduction of error *RE*, coefficient of efficiency CE). If the transfer function obtained expresses the variability of the climate factor under consideration

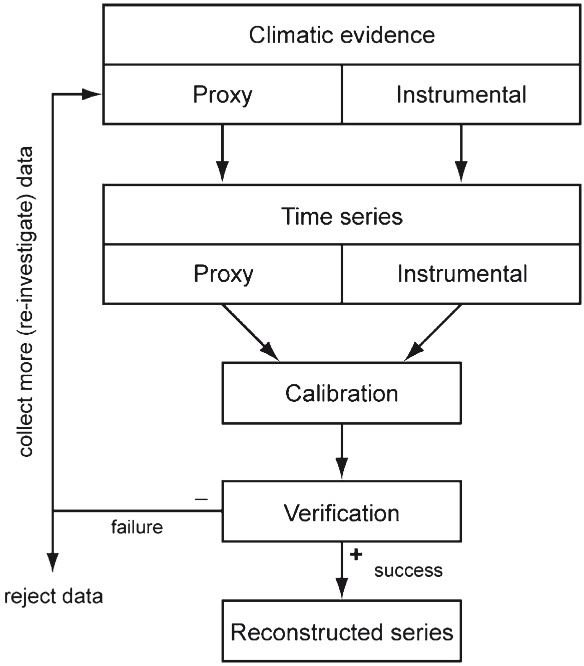

Fig. 2.3 Scheme of a standard palaeoclimatological reconstruction (modified after Brázdil 2002)

with satisfactory accuracy, the chronology of the proxy can be used for climate reconstruction. The transfer functions, usually derived from relatively modern periods, may however be non-stationary (e.g. when phenological series have been affected by changes in crop mix, the introduction of new varieties of crops or the introduction of different harvest technology – see e.g. Meier et al. 2007). This problem can, to some extent, be ameliorated by considering a sufficiently long calibration period.

Detail of a scheme of reconstruction using documentary evidence-based temperature indices is shown in Fig. 2.4. The series of temperature indices created is calibrated and verified with instrumental (measured) temperatures in the overlapping period by linear regression. This exercise allows estimation of explained variance in the reconstruction. In the final stage, the reconstructed part is joined to the instrumental part of the series and error bars for the expression of reconstruction uncertainty are determined. This approach has already been applied in calculation of the Prague temperature series for 1718–2007 (Dobrovolný et al. 2009a) and of the Central European temperature series for 1500–2007 (Dobrovolný et al. 2009b – see following section).

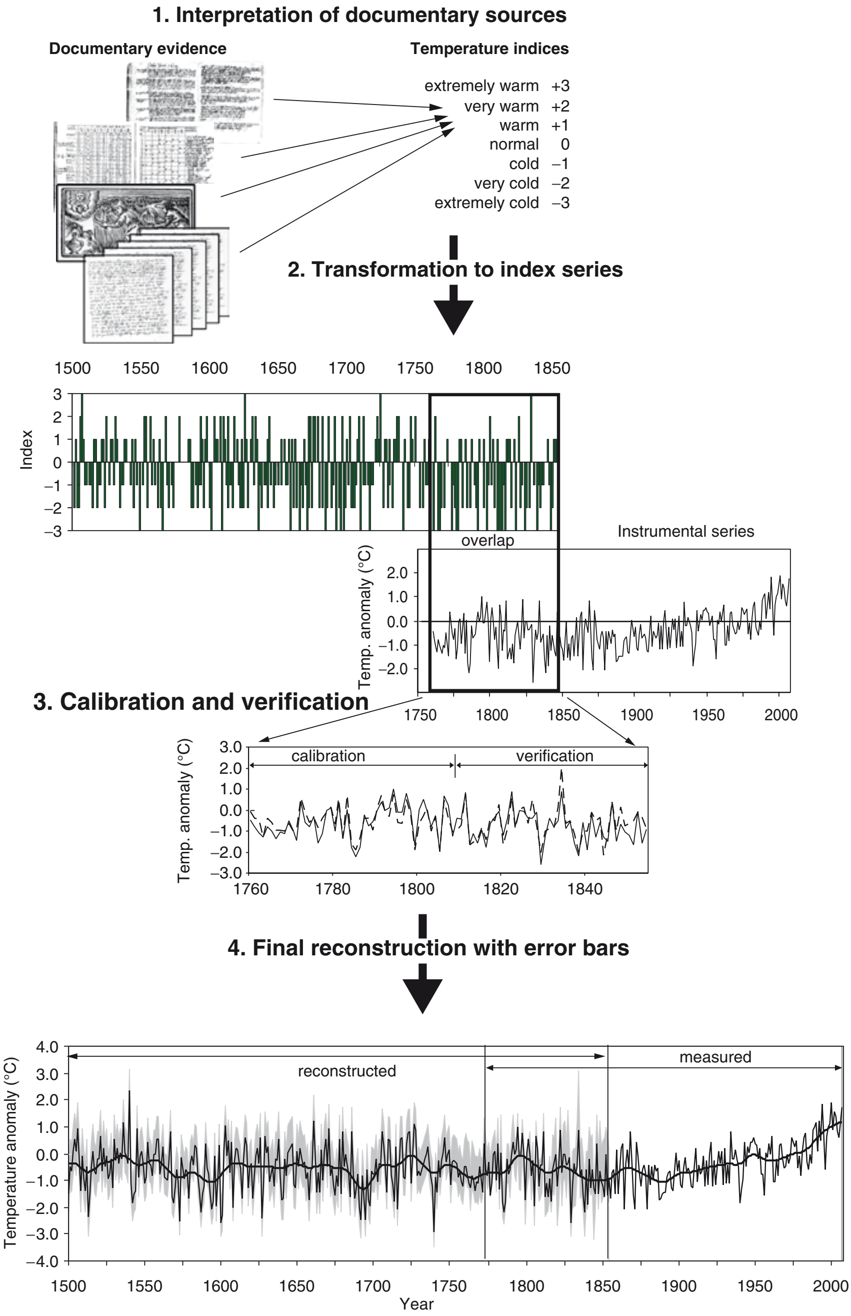

Fig. 2.4 Scheme of temperature reconstruction procedure using documentary evidence-based temperature series

2.4 Temperature and Precipitation Series Based on Documentary Evidence in Central Europe for the Last 500 Years

Temperature/precipitation series for the past 500 years may be obtained only by combining temperature/precipitation reconstructions (from related man-made or natural proxy series) and corresponding long-term instrumental series. Series of temperature or precipitation indices derived mainly from documentary evidence, as well as reconstructions based on them, have been published since the 1980s for several Central European countries or regions, as follows from the overview below (T – temperature, R – precipitation, m – monthly, s – seasonal, a – annual):

1. Austria: eastern Austria, 1700–1830, summer T/R – combined documentary and tree-ring data (Strömmer 2003)
2. Czech Republic: Prague-Klementinum, from the thirteenth century, decadal sT, aT, sR, aR reconstructions (Brázdil 1996); Olomouc 1693–1783, mT, mR indices (with gaps) (Brázdil et al. 2008a); Prague-Klementinum 1718–2007, sT, aT reconstructions (Dobrovolný et al. 2009a)
3. Germany: past millennium, decadal sT, sR indices; from AD 1500, sT, aT, sR, aR reconstructions (Glaser 2001, 2009a)
4. Historical Hungary: from the sixteenth century, mT, mR indices (with gaps) (Rácz 1999); AD 1650–1900, aT indices (Bartholy et al. 2004)
5. Poland: AD 1501–1840, decadal sT (DJF, JJA) indices (with gaps) (Przybylak et al. 2005); for the same period, decadal DJF and JJA temperatures and incomplete DJF and JJA precipitation indices (Przybylak et al. 2004)
6. Slovakia: eastern Slovakia, AD 1717–1730, mT, mR indices (Brázdil et al. 2008b)
7. Switzerland: from AD 1525, mT, mR indices and reconstructions (Pfister 1984 – indices re-worked several times later, e.g. Pfister 1999)
8. Regions: Central Europe as an average of the Czech Republic, Germany and Switzerland, sixteenth century, sT, aT, sR, aR reconstructions (Pfister and Brázdil 1999); the Swiss Alpine region (43.25°–48.25°N, 4.25°–16.25°E), aT, sT (DJF, JJA), aR, sR (DJF, JJA) from AD 1500 based on long instrumental series and documentary proxies, worked up by principal component regression analysis (Casty et al. 2005)

More recently, combined efforts within the EU Millennium project (Gagen et al. 2006) have resulted in the calculation of new monthly, seasonal and annual Central European temperature (CEuT) series combining documentary and instrumental data (Dobrovolný et al. 2009b). In applying a standard palaeoclimatological approach (Fig. 2.4; for more details see also Dobrovolný et al. 2009a), linear regression was used for calibration and verification of index temperature series and instrumental temperature series for the period 1771–1854. An index temperature series was created from corresponding series from Germany, Switzerland and the Czech Republic, derived from documentary evidence for the period 1500–1854.

The instrumental temperature series for 1760–2007 was taken as an average of 11 homogenised series from Austria (Kremsmünster, Vienna, Innsbruck), Switzerland (Basle, Geneva, Bern), Germany (Regensburg, Karlsruhe, Munich, Hohenpeissenberg) and the Czech Republic (Prague-Klementinum). These were further corrected for the insufficient radiation protection for early thermometers (see Böhm et al. 2009) and the growth of the urban heat island effect. The index series correlate well with the instrumental temperatures; the explained variance in the overlapping period is thus 83% for winter, 80% for spring, 77% for summer, 73% for autumn and finally 81% for annual mean temperatures. Verification statistics indicated high reconstruction skill for all seasons and the year.

Fluctuations in seasonal and annual CEuT series in the period 1500–2007 are shown in Fig. 2.5. These series display well-expressed inter-annual and decadal variability but, with the exception of the period of recent global warming with the highest values in all series in the most recent years, it is difficult to derive any long-term tendencies. In contrast, the coldest periods occurred mainly in the pre-instrumental period: DJF in the 1510s and 1690s, MAM in the 1740s, JJA in the 1590s, SON in the 1760s and annual values in the 1690s.

2.5 Temperature and Precipitation in Central Europe Since AD 1500 – Discussion

2.5.1 Air Temperature

Fluctuations in CEuT series can be compared with some other existing temperature reconstructions in Europe:

1. Seasonal Central European temperature series (further LUT), 1500–2004, calculated from gridded temperature data at latitudes 45°–53°N and longitudes 5°–18°E from Luterbacher et al. (2004, 2007) and Xoplaki et al. (2005); these series were created entirely from documentary and natural proxies for 1500–1658, from a mix of documentary data, natural proxies and early instrumental records for 1659–1750 and from instrumental temperature series from then onwards
2. DJF, JJA and annual temperature series for the Low Countries, 764–1998, calculated from documentary evidence (before 1706) and instrumental data by van Engelen et al. (2001) and Shabalova and van Engelen (2003)
3. JFMA Stockholm temperature series, 1502–2008, calculated from dates of the spring opening of Stockholm harbour (1502–1892) and instrumental records starting in 1893 by Leijonhufvud et al. (2009)
4. DJFM Tallin temperature series, 1500–1997, calculated from the first day of ice-break up in the port of Tallin and on the rivers in northern Estonia by Tarand and Nordli (2001)
5. Central England Temperature (CET) series, 1659–2005, compiled up to 1720 from “the results of readings of highly imperfect instruments in uncertain expo-

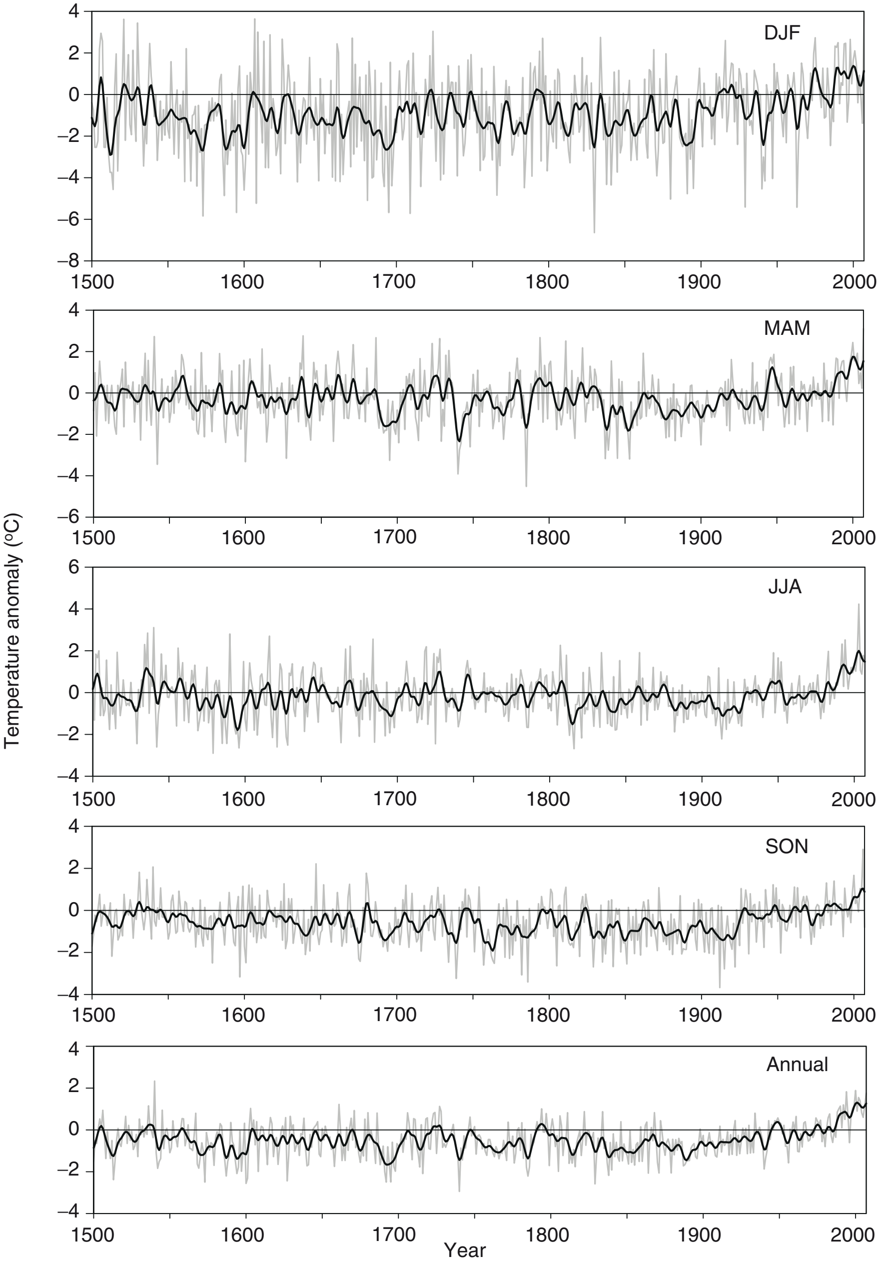

Fig. 2.5 Fluctuations of anomalies (with respect to 1961–1990) of seasonal and annual Central European temperature series for the period AD 1500–2007, smoothed by 10-year Gaussian filter (data: Dobrovolný et al. 2009)

sures 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 afterwards (Parker et al. 1992)

6. 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. June–July Bavarian Forest/Austrian Alps temperature series, before 1500–1997, created as composite chronology from tree-ring widths in stringed instruments and since 1800 from spruce *Picea abies* (Wilson and Topham 2004)
8. June–September temperatures of European Alps, 755–2004, reconstructed from larch *Larix decidua* Mill. tree-ring density series by Büntgen et al. (2006)
9. 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. 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. 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)

The ice winter severity index for the western Baltic, 1500–1997, derived from classified values of accumulated areal ice volume along the German Baltic coast by Koslowski and Glaser (1999), was also used for comparison.

To estimate spatial relations between CEuT series and other parts of Europe, the instrumental part of CEuT was correlated with 5° × 5° gridded temperatures of HadCRUT3 (Brohan et al. 2006) for the period 1850–2007. Figure 2.6 demonstrates spatial correlations for the four seasons of the year. As expected, the highest correlations are obtained for the Central European grids and decrease with increasing distance from this core region. Correlations are better expressed in the winter, with its strong circulation patterns, than in the summer when temperatures are strongly influenced by local solar radiation and clouds. Moreover, the instrumental part of the CEuT series since 1760 is further correlated with corresponding instrumental parts of other reconstructions (such as LUT, the Low Countries or CET).

Comparison of CEuT series with Central European LUT series (Luterbacher et al. 2004, 2007; Xoplaki et al. 2005) and with the Low Countries series (Shabalova and van Engelen 2003) has already been discussed in detail by Dobrovolný et al. (2009b). High 31-year running correlations (Fig. 2.7) between CEuT and LUT series before 1650 and after 1800 indicate the similar data sets used in both reconstructions (temperature indices for Germany and Switzerland and instrumental records, respectively) while weaker correlations between 1650 and 1800 show up the wider variety of original datasets used. The most dramatic drop in correlations occurs in JJA temperatures during the 1750s (consequently in annual series as well), in similar fashion to the correlations between the Low Countries and CET series, in which correlation coefficients even fade to the statistically insignificant. However, similar sudden drops in the 31-year running correlations may also be observed in other cases (e.g. the 1890s in CET series for JJA). Because both CET and the Low Countries series have been utilised in the LUT European gridded temperature reconstruction, all three series are not fully independent. Possible reasons for the lost coherency in JJA temperatures around the 1750s must therefore be further investigated.

The "winter" CEuT series shows weaker coherency in its fluctuations when compared with series farther north or north-east of Central Europe (Fig. 2.8a). While its correlations with the ice winter severity index of the western Baltic (Koslowski and Glaser 1999) are statistically significant, with lowest values during the second half of the nineteenth century, for both remaining reconstructions – Stockholm (Leijonhufvud et al. 2009) and Tallin (Tarand and Nordli 2001) – the correlations are often insignificant, and even negative before AD 1650. These

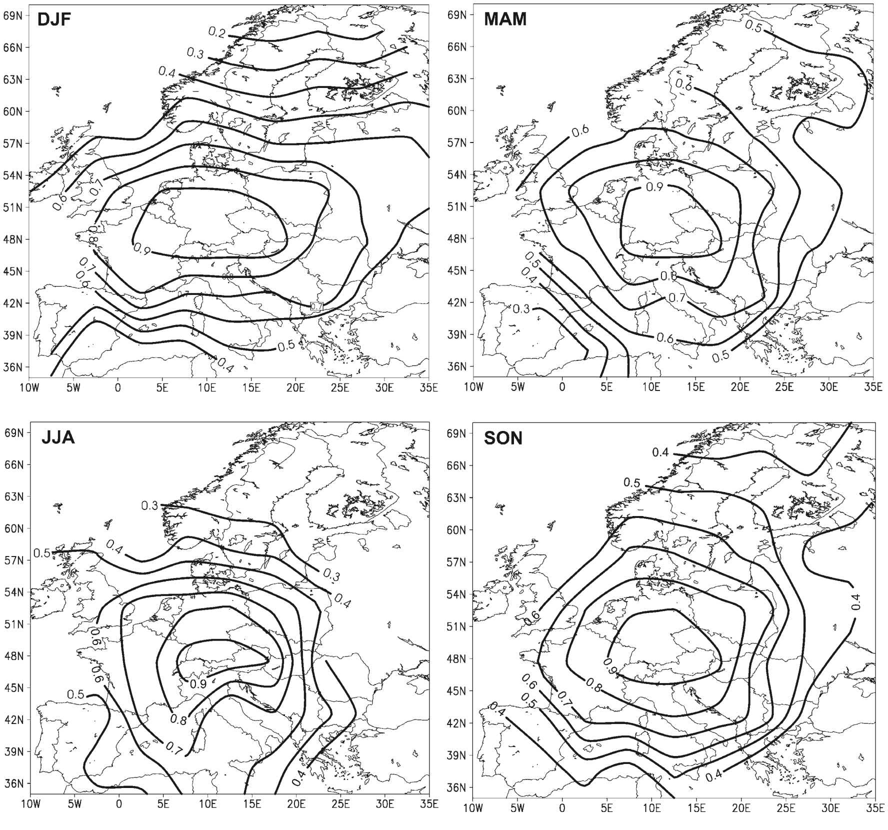

Fig. 2.6 Spatial correlations between seasonal CEuT series (the instrumental part) and HadCRUT3 5° × 5° gridded temperatures (Brohan et al. 2006) for 1850–2007

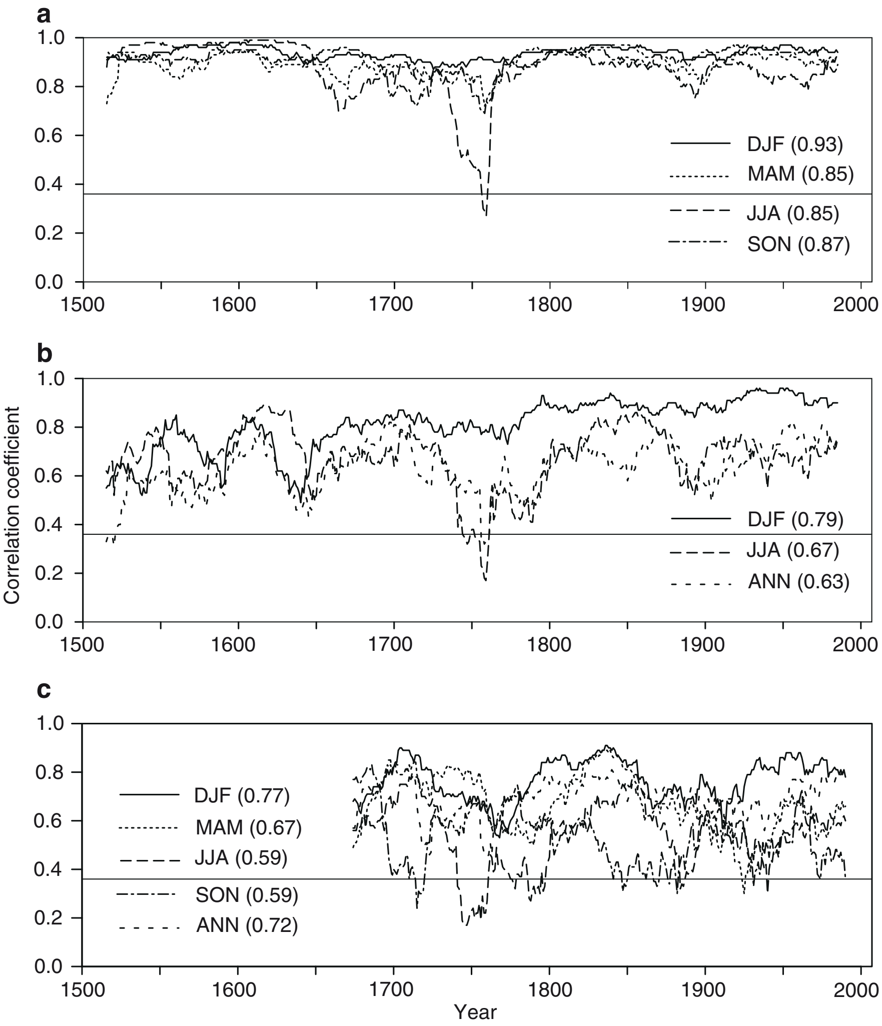

Fig. 2.7 Running 31-year correlation coefficients of seasonal and annual CEuT series with (**a**) Central European LUT series (data: Luterbacher et al. 2004; Xoplaki et al. 2005), (**b**) the Low Countries series (Shabalova and van Engelen 2003) and (**c**) CET series (Manley 1974). Correlation coefficients with CEuT series for the whole length of the three series used are indicated in brackets. Horizontal line – critical value of correlation coefficients for $\alpha = 0.05$ according to *t*-test

discrepancies cannot be explained only by decreasing temperature correlations with increasing distance (compare Fig. 2.6) between studied regions/stations; they are probably related to weaknesses in the actual reconstructions. The highest long-term correlation coefficient is shown by the winter CEuT series with the Central Europe LUT series (0.93), while the lowest are shown with the Tallin and Stockholm series (0.36 and 0.45, respectively).

Similar correlations are also obtained in comparison of "summer-half" CEuT series with reconstructions based on tree-rings (Wilson and Topham 2004; Niedźwiedź 2004; Büntgen et al. 2006) (Fig. 2.8b) and much higher ones for reconstructions using wine harvest data (Chuine et al. 2004; Meier et al. 2007), or rather multi-proxy reconstruction combining various proxies (Guiot et al. 2005) (Fig. 2.8c). The coherency between CEuT and vintage-based series is much higher compared to correlations between CEuT and tree-ring-based series. The 31-year running correlations between CEuT and tree-ring-based series are mostly insignificant before 1800 and show much higher variability throughout the period. An important decrease in correlations with April–August Swiss series occurs around 1750 and 1890 (similar to the April–September series for Western Europe). It reflects the higher coherency of summer temperature patterns in Western and Central Europe as well as the territorial overlap of the CEuT series with the reconstruction for Western Europe. Some differences in the series compared can perhaps be attributed to individual extreme years/seasons. However, it is difficult to establish the extent to which some of the longer-term losses of coherency (e.g. in the eighteenth century when CEuT is compared with tree-ring-based series, Fig. 2.8b) are related to natural climate variability or to the homogeneity and quality of proxy series.

The summer CEuT series shows the highest long-term correlation coefficient with the Central European LUT series (0.85); notably high are the overall correlations with wine-harvest dates series, which achieve 0.64 to 0.70 (Fig. 2.8c). Three of the tree-ring series employed show relatively lower correlations, between 0.41 and 0.46 (Fig. 2.8b).

2.5.2 Precipitation

Reconstruction of precipitation generally presents greater problems than that of temperatures, due to the large spatial and temporal variability involved. Even instrumental precipitation measurements are biased by significant systematic errors and by the different types of the rain-gauges used for measurements in individual countries (see e.g. Sevruk 2004). Despite these facts, Pauling et al. (2006) applied principal component regression technique to reconstruct seasonal gridded European precipitation series spanning AD 1500–2000, combining instrumental precipitation records, precipitation indices derived from documentary data and several natural proxies (tree-rings, ice cores, corals and speleothems). Although the highest reconstruction skill was found for winter over Central Europe, the reconstruction method was designed to capture continental-scale precipitation fields while small-scale variations are not resolved, by definition. Therefore care should be exercised in the interpretation of comparison based on selected grid points.

Taking these limitations into account, Central European seasonal precipitation series were calculated from 0.5° × 0.5° resolved grids by Pauling et al. (2006) for latitudes 45°–53°N and longitudes 5°–18°E (Fig. 2.9). These series mainly show inter-annual and decadal fluctuations, without long-term trends. With respect to the

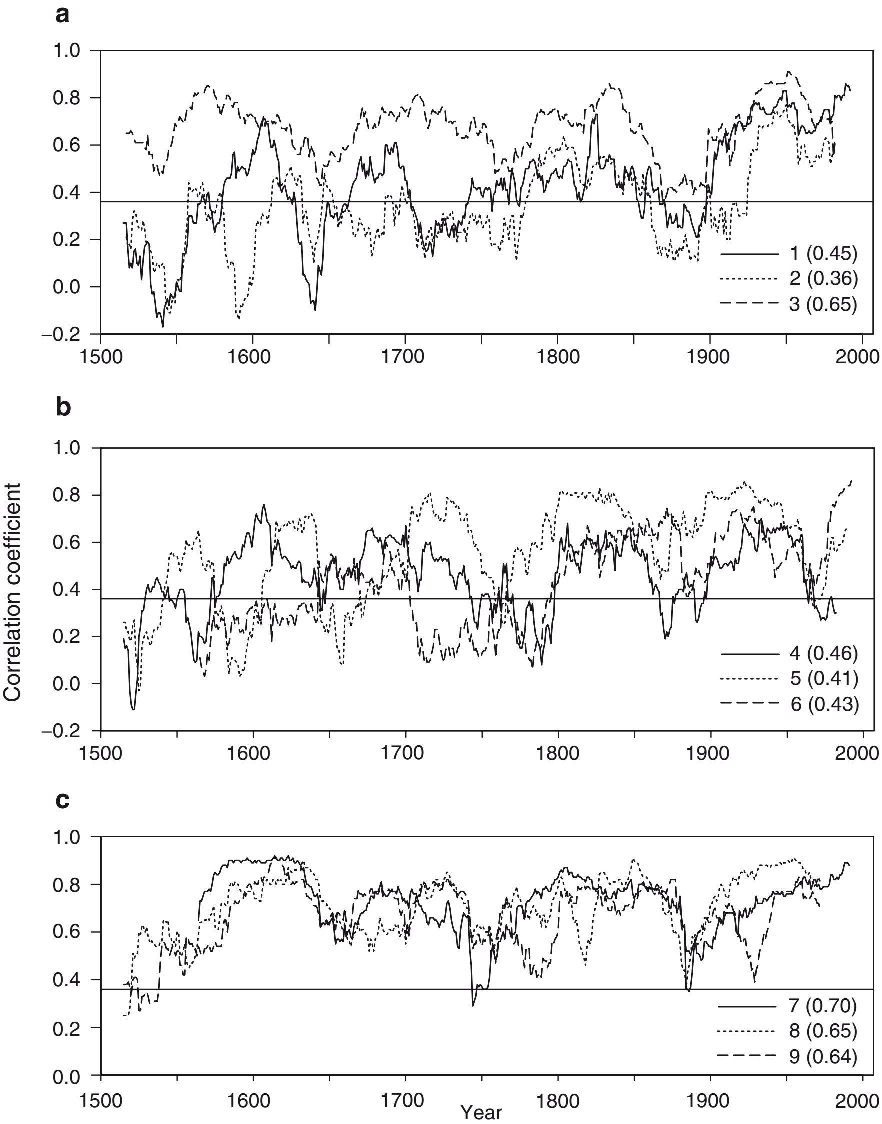

Fig. 2.8 Running 31-year correlation coefficients of (**a**) "winter" CEuT series with (1) JFMA Stockholm series (Leijonhufvud et al. 2009), (2) DJFM Tallin series (Tarand and Nordli 2001), (3) ice winter severity index (Koslowski and Glaser 1999) and (**b**, **c**) "summer-half" CEuT series with (4) 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). CEuT series are always calculated for the same months as corresponding series (1)–(9) used for comparisons. Correlation coefficients with CEuT series for the whole length of series used are indicated in brackets. Horizontal line – critical value of correlation coefficients for α = 0.05 according to *t*-test

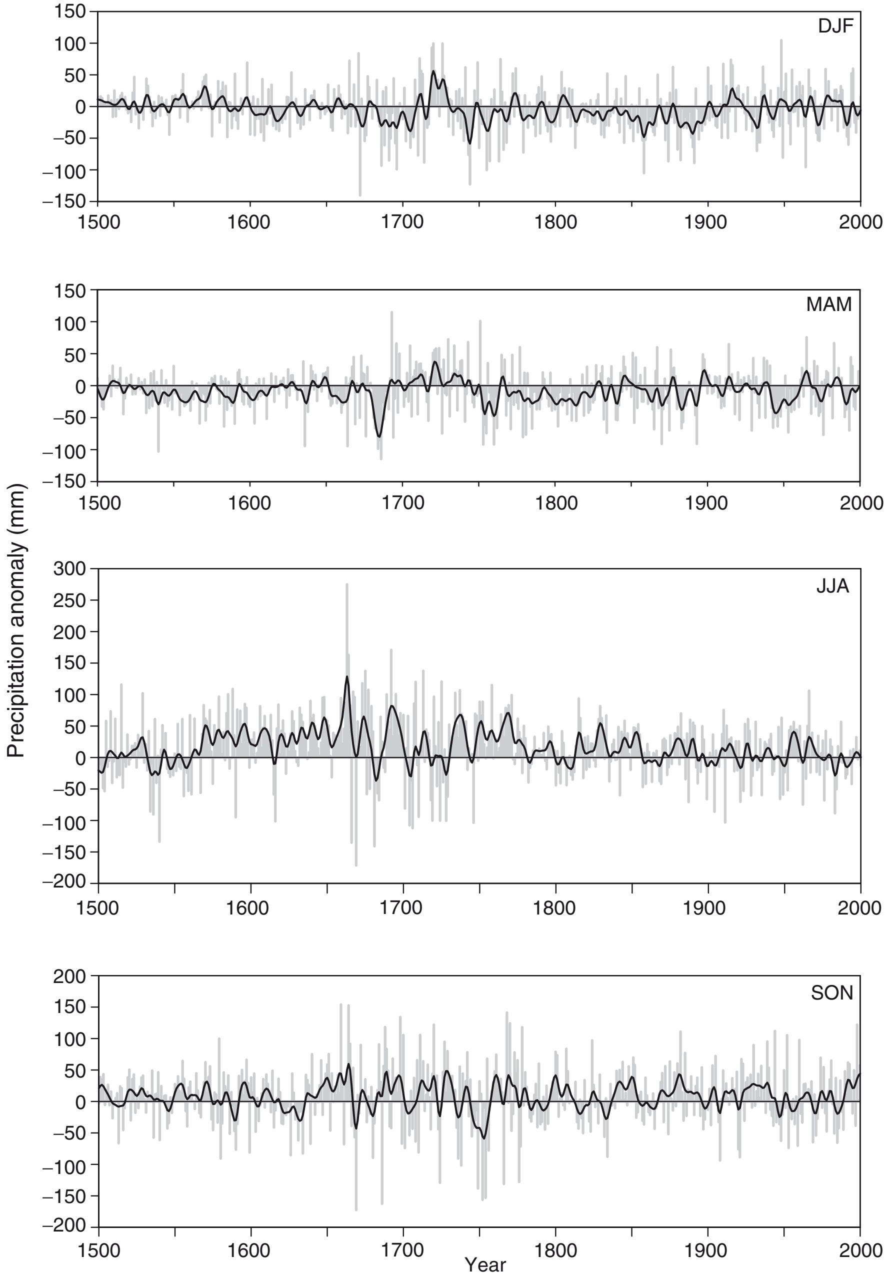

Fig. 2.9 Fluctuations of anomalies (with respect to 1961–1990) of seasonal Central European precipitation series (calculated from grids at latitudes 45–53°N and longitudes 5–18°E from data by Pauling et al. 2006) for the period AD 1500–2000, smoothed by 10-year Gaussian filter

reference period 1961–1990, different periods of above- or below-mean precipitation totals may be identified. The most spectacular is the prevailing higher summer precipitation from the 1560s to the 1770s. An increasing trend can be observed in the sixteenth–seventeenth centuries, while a general decrease in summer precipitation appears afterwards. Remarkably dry were the precipitation patterns of MAM in the 1680s and SON around 1750. On the other hand, the highest winter precipitation occurred around the 1720s and summer precipitation around the 1660s.

Because series of precipitation indices for Switzerland (Pfister 1984, 1999) and Germany (Glaser 2001) are not fully independent of the reconstruction by Pauling et al. (2006), series based on tree-ring reconstructions may be used for comparison with the calculated Central European series. Using fir *Abies alba* tree-rings, Brázdil et al. (2002) reconstructed series of March–July precipitation for southern Moravia AD 1376–1996, explaining 38% of tree-ring width variability. Wilson et al. (2005) used tree-ring width series of Norway spruce for March–August precipitation reconstruction in the Bavarian Forest region AD 1480–2000, explaining 40% of tree-ring width variability (cubic smoothing spline chronology). Comparison of all series on a decadal scale (Fig. 2.10) shows good agreement in some time intervals but even contradictory fluctuations in others. Moreover, large fluctuations in the southern Moravian series after 1950 are related to the destruction of relationships between fir growth and precipitation, as discussed in a more detail by Brázdil et al. (2002).

The 500-year correlations between all three series are rather weak (Central Europe with southern Moravia 0.27 and the Bavarian Forest region 0.45, between the latter two series 0.36). Running correlations are highest for the first part of the seventeenth century. However March–July precipitation totals from southern Moravia do not show significant correlations with Central European gridded reconstructions for the majority of the 500-year chronology (Fig. 2.11). Differences among the three precipitation series may be related to uncertainties in corresponding reconstructions as well as to greater spatial variability of precipitation patterns in Central Europe.

2.5.3 Caveats for Temperature/Precipitation Reconstruction

Temperature/precipitation reconstructions based on documentary evidence are biased by several factors, among which the creation of index series, the reconstruction methods used and expression of the low-frequency signal should be mentioned (see also Dobrovolný et al. 2009a for more details).

2.5.3.1 Deriving Index Series

The key factor in temperature/precipitation reconstructions based on index series is the quality and completeness of monthly indices derived from documentary evidence. This is a great challenge, requiring a broad statistical and dynamic understanding.

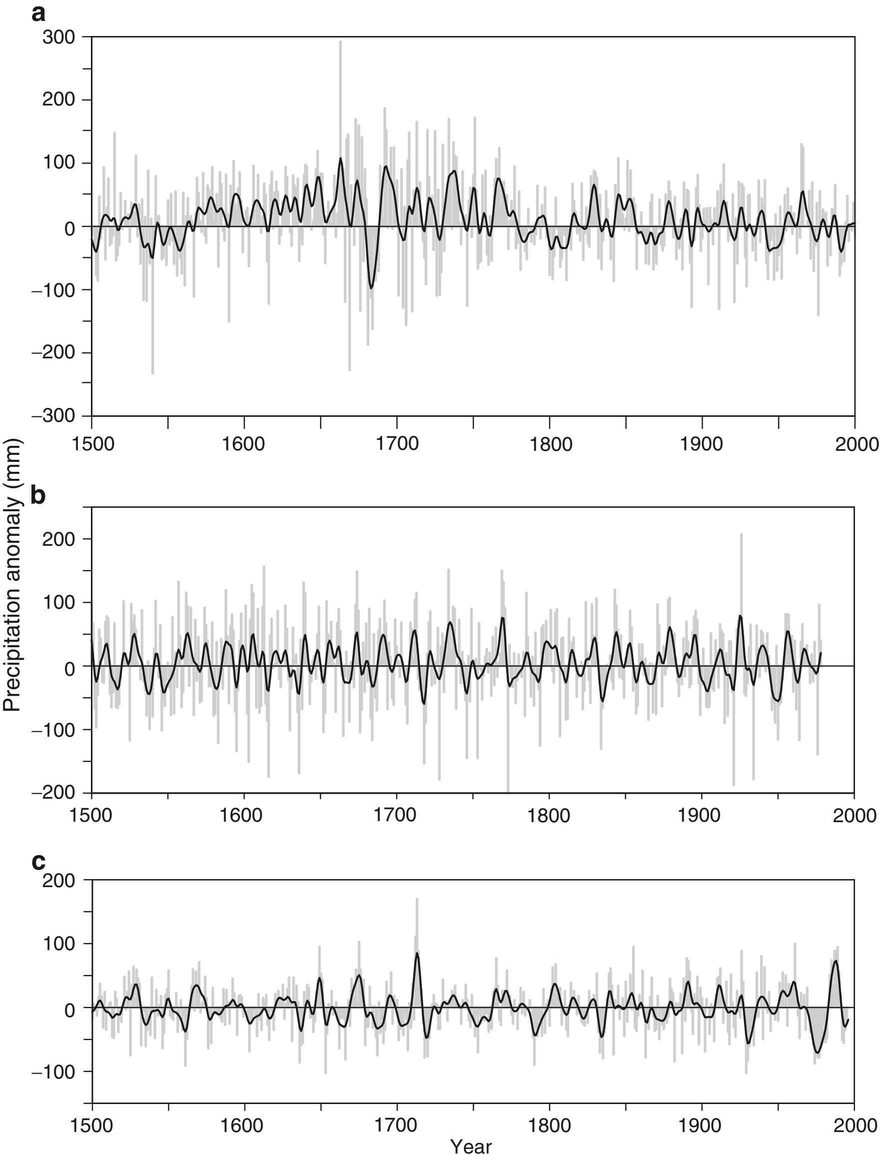

Fig. 2.10 Fluctuations of precipitation anomalies (with respect to 1961–1990) smoothed by 10-year Gaussian filter for precipitation series of (**a**) Central Europe (March–August) calculated from data by Pauling et al. (2006), (**b**) the Bavarian Forest region (March–August) (Wilson et al. 2005) and (**c**) southern Moravia (March–July) (Brázdil et al. 2002)

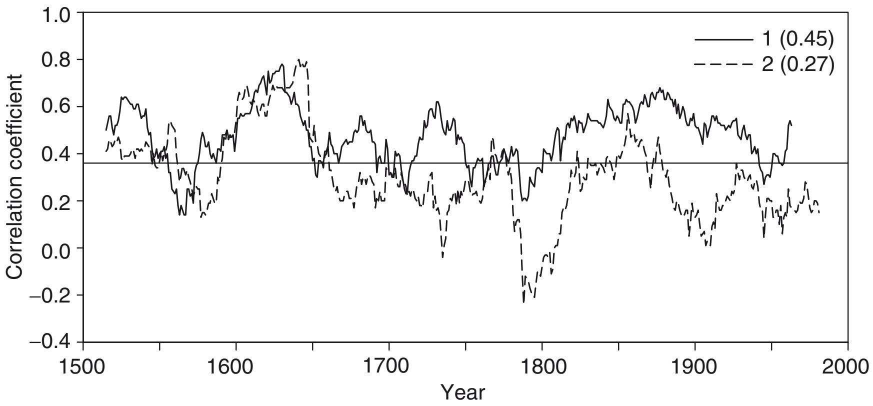

Fig. 2.11 Running 31-year correlation coefficients of Central European "summer-half" precipitation anomalies (with respect to 1961–1990) calculated from data by Pauling et al. (2006) with reconstructed precipitation series of (1) the Bavarian Forest region (March–August) (Wilson et al. 2005) and (2) southern Moravia (March–July) (Brázdil et al. 2002). Central European series is calculated as the sum of MAM and JJA series. Correlation coefficients with Central European series for the whole 500-year period are indicated in brackets. Horizontal line – critical value of correlation coefficients for α = 0.05 according to *t*-test

High application and expertise of any given researcher is essential to minimise the degree of subjectivity in this process. However, some more or less objective facts complicate the procedure:

- Missing monthly indices: documentary data for some months may be missing or the character of the information does not allow interpretation in terms of temperature and precipitation (months without written records cannot then be taken correctly as "normal")
- Changes in observer focus on the weather over the course of the year: observers tended to pay greater attention to more strongly expressed weather contrasts or indicators (e.g. heavy frosts, severe heat-waves) and to periods which were economically important for agriculture or other human activities
- Extreme values: the selection of any ordinal scale does not allow the expression of real extremes typified by very high deviations from normal weather patterns
- Non-climatic signal: changes related to other non-climatic causes may be wrongly interpreted as climatologically forced (e.g. arising out of changes in variety of plants, land-use, agricultural practices, etc.)

Some of these problems can be alleviated by further archive research, looking for additional documentary data, combining different data sources and comparing index series from different regions (more useful for temperature than for precipitation because of diminishing decrease in correlations with increasing distance between stations/regions).

2.5.3.2 Reconstruction Methods

Most of the reconstructions mentioned in the current paper are based on a linear regression model (LRM) constructed between the proxy data as an independent variable and temperature/precipitation instrumental measurements. Critical to documentary-based reconstructions is the establishment of a period with sufficiently long overlap to instrumental series. With the onset of the first instrumental measurements, mostly during the eighteenth century in Europe, some traditional documentary sources gradually fade and are replaced with only instrumental data. It is often difficult, therefore, to assemble a sufficiently long calibration/verification period. Even though some calibration approaches can be based on pseudo-proxies (Mann and Rutherford 2002) or on recent measurements (Pfister 1992), independent comparison of proxy series with target measurements is the crucial point for a standard palaeoclimatological approach (Cook et al. 1994). Such an approach permits the use of generally accepted statistics and objectively evaluates the reconstruction skill of documentary proxies.

Linear regression is relatively simple in application. However, the regression line is “averaging” a possibly existing trend into one “mean line” valid for the calibration period. This means that any long-term trend can be obtained only for a case in which certain positive (negative) indices appear more frequently in one period in comparison with prevailing negative (positive) indices in another period.

However, the values of independent variables (proxies) are not gathered without error and, considering the general rules of LRM applicability (see e.g. von Storch and Zwiers 1999), reconstruction results should be interpreted with care. Reconstructed series should be accompanied by uncertainty estimates, usually expressed as standard error and its multiples. However, it is sometimes necessary to inflate the value of standard error with some factors that consider, for example, the number of replicated series used for construction of a proxy series or mutual correlations between individual 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). Methods of estimating error are particularly well developed in dendroclimatology (Esper et al. 2005).

Compared to other proxies such as tree-ring data, documentary evidence is often extreme-oriented. This means that outliers and extreme values are mostly well characterised, while descriptions of less significant departures from “normal” conditions are sometimes missing from man-made archives. This feature can further complicate the establishment of a relatively long and homogeneous overlapping period. On the other hand, information on frequency and intensity of extreme events may be utilized for reconstruction in the way suggested by Rodrigo (2008). Bürger (2007) gives an overview of several methods used for temperature reconstruction from various proxies. Although originally related to Northern Hemisphere field reconstructions, possible approaches can be roughly divided into two main groups. The first includes construction of a transfer function between predictor and predictant(s). Regression-based methods may be mentioned at this point. The second group encompasses iterative techniques, for example the RegEM algorithm (see Mann et al. 2005). Although Pfister (1999) characterised documentary evidence as a proxy type that can be used for climate reconstruction with the help of relatively simple and robust methods, as has been demonstrated by several recent papers (Leijonhufvud et al. 2008, 2009; Dobrovolný et al. 2009a, 2009b), the statistical techniques above can be successfully used in reconstructions based on documentary data.

2.5.3.3 High- and Low-Frequency Signals

Zorita et al. (2009) compared seasonal and annual CEuT series with the outputs of two temperature simulations modelled by ECHO-G. This series, in contrast to the JFMA temperatures in Stockholm (Leijonhufvud et al. 2009) and CET series (Manley 1974), shows weaker agreement with model simulations at selected grid points, mainly in expression of the low-frequency signal. Similarly, von Storch et al. (2004) mentioned underestimation of low-frequency variability in Northern Hemisphere temperature reconstructions based on regression methods, something that is reflected in stronger decadal fluctuations. However, several other papers (e.g. Mann et al. 2005; Goosse et al. 2005) have suggested that these results are overstated.

The weak low-frequency signal in CEuT reconstruction may be explained by the application of LRM to temperature indices derived from documentary data. This, in turn, is related to the fact that the authors of documentary records described the weather with respect to their own perception, in terms appropriate to the weather patterns prevailing in the contemporaneous period. This means that every one of them had a different concept of what constituted “normal”, something that obviously cannot be reflected in the interpretation of indices. Rather, the index series created express deviations from normal patterns typical of the selected recent reference period (e.g. 1901–1960 or 1961–1990). Thus temperature reconstructions based on the creation of temperature indices are less able to express the low-frequency signal. This situation may be partly improved if we can combine a particular reconstruction with other proxies expressing certain long-term trends (e.g. series of phenophases, freezing of rivers and lakes, start of agricultural and viticultural harvests, etc.). On the other hand, reconstructions based on such long-term bio-physically-based proxies might lack this bias (e.g. Chuine et al. 2004; Meier et al. 2007; Leijonhufvud et al. 2008, 2009).

2.6 Perspectives on Further Research in Central Europe

In Central Europe, a long tradition of meteorological observation and a relatively rich body of documentary evidence come together to create a good background for further investigations into the climate variability of the area over the past 500 years. Any corresponding climatic time series covering this long time interval may be obtained only as a combination of reconstruction based on proxy data and instrumental records. Reconstructions based on documentary evidence are capable of providing monthly, seasonal and annual temperature/precipitation series, that is there are no time constraints, while many natural proxies such as tree-rings, ice cores, lake sediments, etc. (e.g. Bradley 1999; Jones and Mann 2004; Jones et al. 2009) can be used for climate reconstructions only for periods in terms of a combination of a number of months, a season or the whole year.

It follows from this article that a great deal of effort has been devoted to the study of the last 500 years of Central European climate. Despite this, there still exists a largely unfulfilled potential for further research, mainly on:

- Homogenisation of long-term temperature and precipitation series (outside HISTALP – Auer et al. 2005, 2007), including utilisation of early instrumental meteorological measurements
- Revision of existing weather compilations, documentary datasets and their completion by other new archival sources
- Creation of new temperature/precipitation index series based on documentary evidence and filling of existing gaps in available series
- Further collection of documentary data for the overlapping period with instrumental records for correct calibration/verification using the standard palaeoclimatological method
- Development and application of new methods of temperature/precipitation reconstruction and calculation of error bars
- Cross-checking of documentary data, temperature/precipitation reconstructions and results of model runs
- Deepening of co-operation between environmental historians and climatologists, as well as with climate modellers
- Cross-checking and combining of reconstructions based on man-made and natural climate proxies.

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