Climatic Change (2010) 101:41–67
DOI 10.1007/s10584-009-9649-4

The early instrumental warm-bias: a solution for long central European temperature series 1760–2007

Reinhard Böhm · Philip D. Jones · Johann Hiebl · David Frank · Michele Brunetti · Maurizio Maugeri

Received: 14 July 2008 / Accepted: 14 July 2009 / Published online: 4 September 2009

Abstract Instrumental temperature recording in the Greater Alpine Region (GAR) began in the year 1760. Prior to the 1850–1870 period, after which screens of different types protected the instruments, thermometers were insufficiently sheltered from direct sunlight so were normally placed on north-facing walls or windows. It is likely that temperatures recorded in the summer half of the year were biased warm and those in the winter half biased cold, with the summer effect dominating. Because the changeover to screens often occurred at similar times, often coincident with the formation of National Meteorological Services (NMSs) in the GAR, it has been difficult to determine the scale of the problem, as all neighbour sites were likely to be similarly affected. This paper uses simultaneous measurements taken for eight recent years at the old and modern site at Kremsmünster, Austria to assess the issue. The temperature differences between the two locations (screened and unscreened) have caused a change in the diurnal cycle, which depends on the time of year. Starting from this specific empirical evidence from the only still existing and active early instrumental measuring site in the region, we developed three correction models

R. Böhm (✉) · J. Hiebl
Central Institute for Meteorology and Geodynamics (ZAMG),
Hohe Warte 38, 1190 Vienna, Austria
e-mail: reinhard.boehm@zamg.ac.at

P. D. Jones
Climatic Research Unit (CRU), School of Environmental Sciences,
University of East Anglia, Norwich, UK

D. Frank
Swiss Federal Research Institute WSL, Birmensdorf, Switzerland

M. Brunetti
Istituto di Scienze dell'Atmosfera e del Clima (ISAC)–CNR, Bologna, Italy

M. Maugeri
Dipartimento di Fisica, Università degli Studi, Milan, Italy

for orientations NW through N to NE. Using the orientation angle of the buildings derived from metadata in the station histories of the other early instrumental sites in the region (sites across the GAR in the range from NE to NW) different adjustments to the diurnal cycle are developed for each location. The effect on the 32 sites across the GAR varies due to different formulae being used by NMSs to calculate monthly means from the two or more observations made at each site each day. These formulae also vary with time, so considerable amounts of additional metadata have had to be collected to apply the adjustments across the whole network. Overall, the results indicate that summer (April to September) average temperatures are cooled by about 0.4°C before 1850, with winters (October to March) staying much the same. The effects on monthly temperature averages are largest in June (a cooling from 0.21° to 0.93°C, depending on location) to a slight warming (up to 0.3°C) at some sites in February. In addition to revising the temperature evolution during the past centuries, the results have important implications for the calibration of proxy climatic data in the region (such as tree ring indices and documentary data such as grape harvest dates). A difference series across the 32 sites in the GAR indicates that summers since 1760 have warmed by about 1°C less than winters.

1 Introduction

Instrumental networks of surface air temperature recorded at 1.25 to 2 m above the ground are frequently used to provide data on global climate change (Jones et al. 1999; Jones and Moberg 2003; Vose et al. 1992; Brohan et al. 2006). Such networks are based on hundreds to thousands of stations distributed across all continents. While much work has been undertaken on data rescue, digitisation, quality improvement and homogenization (Aguilar et al. 2003; Peterson et al. 1998; Moberg and Alexandersson 1997; Auer et al. 2004), insufficient data coverage does not currently allow the global mean temperature series to be extended back earlier than the 1850s. This starting point, perhaps paradoxically but not coincidentally, corresponds to the onset of industrialisation and the associated increase in fossil fuel emissions. The mid-nineteenth century also is recognized as an unusually cold period compared with much of the Holocene with one of the largest glacier extensions of the past 10,000 years (e.g., Zemp 2006; Hormes et al. 2001). Both of these facts would make an extension of the instrumental period further back beneficial. The extension of such records into an "early instrumental period" (EIP. i.e. prior to 1850), which may be considered "pre-anthropogenic" as well with respect to fossil energy consumption, would broaden the sample of observations of truly natural climate variability. This is not possible for the global record, but it is possible and it makes sense at regional scales in some parts of the globe.

There is one such region which provides a plethora of such EIP-data: Europe. This continent has a clear potential to extend the instrumental period roughly by another century—back into the second half of the eighteenth century, and even earlier in northwestern Europe (see Jones 2001). At least for the surface climate elements air pressure and air temperature which have a high spatial correlation, pre-1850 network density should be sufficient to provide representative information at a spatial resolution adequate for decadal scale variability and trends. But even high-frequency interannual variability is spatially more coherent than one might expect as shown for the region and for wider Europe by Efthymiadis et al. (2007). Although such early data have been analyzed almost since they were taken (see e.g. the review by von Rudloff 1967) and the global data collections contain many European EIP-series, the establishment of an adequate continental data set and the analysis of climate variability between 1750 and 1850 based on instrumental measurements has not yet been satisfyingly accomplished. In addition to the necessary recovery and digitalization of early records, barriers to this objective include less uniform or even unknown protocols for data collection and a lower density of records. Such characteristics of the EIP data particularly challenge efforts to account for and eliminate non-climatic biases and noise in the data due to changes in equipment, practice, location, algorithms and observers.

Within Europe, a number of single-site or regional attempts at EIP instrumental climate data reconstruction and analysis have provided insights into climate variability in the pre-industrial period (e.g., Manley 1974; Parker et al. 1992; Di Napoli 1996; Winkler 2006; Brunet et al. 2006; Brunetti et al. 2001; Chlistovsky et al. 1997; Trepinska 1997; Camuffo and Jones 2002; Moberg and Bergström 1997; Moberg et al. 2003; Auer et al. 2001a, b; Vinther et al. 2006). More recently, a collaborative international activity (HISTALP) has established a dense and homogenized multiple-variable monthly climate dataset (Auer et al. 2007) for the "Greater Alpine Region" (GAR) in south-central Europe which now allows a more integrated understanding of temperature, precipitation, radiation, humidity and pressure variability. Notably, such early instrumental data were utilized by Trenberth and Jones (2007), who show in chapter 3 of IPCC's 2007-WG1-report a central European JJA-temperature record (box 3.6, Fig. 2). As in many other analyses of the early instrumental data (e.g., Auer et al. 2007), this long European summer record indicates summer temperatures during the eighteenth century almost at the same level as those of the late twentieth century. These early measurements, however, broadly contrast with evidence of a Little Ice Age in Europe (e.g. the advanced position of most Alpine glaciers during this period), leading to doubts about these warm summer temperature data in particular and possibly affect our understanding of temperature during the critical transition into today's "Anthropogenic Era". At least two approaches may be followed to better understand this apparent contradiction, (1) obtaining evidence from proxy data and (2) analysing results from "modern vs. historical" measurement protocols coupled with careful analyses of station metadata.

Examples of the former approach include a study by Moberg et al. (2003), who scrutinised early Swedish April–August temperatures compared with proxy evidence from Norwegian harvest data which suggested cooler summers (Nordli 2001). Building upon these results in Scandinavia and also compiling evidence for the GAR, Hiebl (2006) collected and analyzed evidence for the "EIP-problem" from different proxies, climate model integrations, and early instrumental records. His final result was not unambiguous, but the majority of facts were in favour of a "cooler solution" to the warm EIP-summer temperatures for both regions. Within the GAR and for single sources of proxy information, inconsistencies between the nineteenth century glacial advances and temperature data were noted by Vincent et al. (2005) who assumed (unlikely to be the case, see Auer et al. 2005; Brunetti et al. 2006a) higher precipitation amounts. Meier et al. (2007) developed a 400-year April–August temperature reconstruction based on Swiss-plateau grape harvest dates which shows a moderate, but significantly lower temperature maximum near

1800 than the two recent ones near 1950 and 2000 respectively. Wagenbach (2008, personal communication) and Bohleber (2008) provided ambiguous evidence from high elevation Alpine ice core studies for a relatively high EIP-summer temperature level derived from $\delta^{18}O$ in contrast to a lower one derived from the mineral dust content. Mangini et al. (2005) extracted climate information from speleothems in a central Alpine high elevation cave which is in favour of a colder EIP-temperature level, but their findings are not specifically targeting summer temperatures. Koinig et al. (2002) and von Gunten et al. (2007) found good agreement for high rather than low EIP-spring and summer temperatures in lake sediment proxy series from high elevation central Alpine lakes. Pfister (1975) describes evidence for warm season snowfall events reaching low elevations within the GAR—suggestive of cooler conditions during the late eighteenth century. Frank et al. (2007) and Büntgen et al. (2006) pointed to a systematic decoupling of (warmer) early instrumental summer temperatures from (colder) tree-ring based reconstructions in the first half of the nineteenth century. Similar decouplings are also observed between hemispheric-scale climate reconstructions and warm-season instrumental data during the second half of the nineteenth century (Jones et al. 2003).

While the proxy evidence is not without uncertainties, perhaps the leading argument which has been invoked to explain the tendencies of warmer measured temperatures than cooler reconstructed temperatures, is based on a suspected insufficient shading of early thermometers from direct and reflected solar radiation. This argument has been evident within various archives since as early as the nineteenth century as early observers often performed simultaneous measurements when replacing older versus newer (e.g., Stevenson) thermometer shelters (see Parker 1994 and references therein). However few of these and other studies (exceptions being Brunet et al. 2006 and Moberg et al. 2003) tried to correct for the suspected systematic bias—likely due to the lack of available quantitative information and necessary metadata, particularly in relation to the potential scope of this bias.

The aim of our study is to identify and to quantitatively estimate an early instrumental bias and to eliminate or reduce it based solely upon metadata and "shelter experiments". For this data-rich region in which much preliminary work was already invested into conventional data quality and homogenization there should be a fairly good chance to provide a solution or at least a reduction of the biases likely present during the EIP.

2 The long series subset (LSS) of the HISTALP database

The data basis for our study consists of the 32 monthly LSS-temperature records available in the GAR shown in Fig. 1. Table 1 gives details of names, locations and starting points.

Compared to the 65 temperature series starting before 1850 identified and described by von Rudloff (1967) for the whole European continent, the existence of 32 such early series in the central part 4 to 19°E and 43 to 49°N (the GAR) distinguishes our target region as one of exceptional high early instrumental data potential. Earlier attempts have produced homogenized versions of each HISTALP series. This was accomplished according to the usual procedure based on relative homogeneity tests for the detection of break points in records, the assumption of

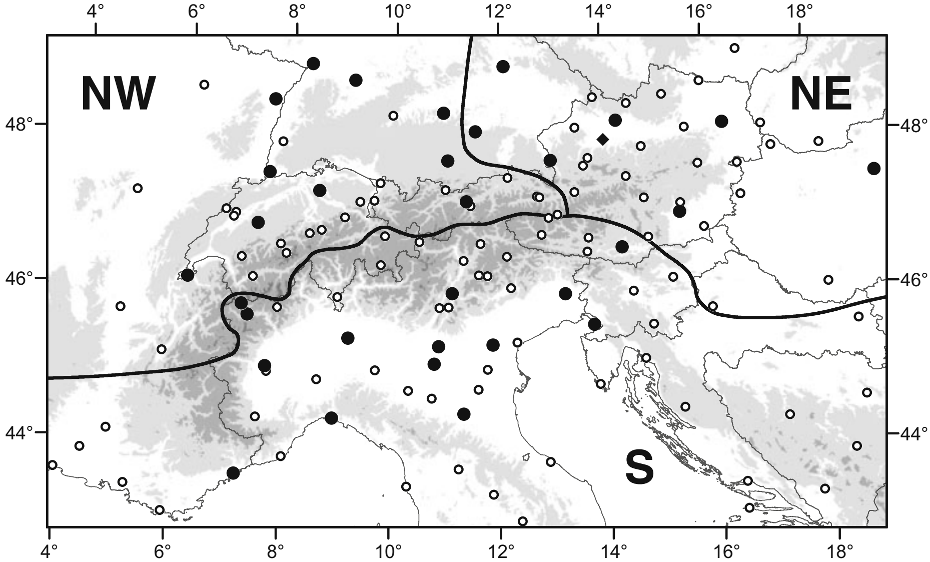


Fig. 1 The HISTALP instrumental temperature network. *Small white dots* 102 locations with temperature records starting in the second half of nineteenth century, *black dots* the long series subset (LSS) with 32 records starting earlier than 1850, *black diamond* the comparative site Kremsmünster, *bold lines* principal subregions in respect to temperature according to Auer et al. (2007)

stationarity of difference series of highly correlated records and additional decision support through metadata (see Auer et al. 2007 for details). These homogeneity exercises determine the break points that occur randomly throughout all the records. This approach, however, has problems to detect consistent biases affecting all series in a similar manner in a relatively short subinterval.

Figure 2 shows the original and the homogenized (but not EIP-bias corrected) temperature series for the 32 LSS-sites. For illustrative purposes, the series are shown in smoothed form and as anomalies relative to a common reference period (chosen as 1851–2000 to highlight any early instrumental differences compared to the modern period). The graphs underline the necessity for homogenizing and also, that the task was well undertaken. All the adjusted series generally track each other for both the warm and cold seasons from the beginnings of observations. The range of the individual homogenized series is slightly less than 0.5°C in the summer half year and slightly more than 0.5°C in the winter half year. Both graphs show this to be in sharp contrast to the chaotic patchwork of the original series. The original series had been subject to a month-by-month semi-automatic testing and adjustment of outliers. Apart from some remaining single site uncertainties, 0.5°C may be regarded as real sub-regional climate variability. Even the early period does not show a significant tendency such as a widening of the bandwidth of the homogenised series, despite the fact that the early unhomogenized series contain more non-climatic noise in comparison to the twentieth century.

Mathematical/statistical procedures for homogenizing have difficulties in break detection when many breaks or systematic changes happen at the same time. Typical examples are the current automation of the climate networks, the simultaneous

Table 1 Basic metadata of the subset of 32 long HISTALP temperature series

HISTALP code	Station name	HISTALP acronym	Country code	Deg E	Deg N	Alt (m asl.)	Sub-region	Start of series
15	Basel	BAS	CH	7.60	47.60	316	NW	1760
48	Genève	GNV	CH	6.15	46.19	380	NW	1760
59	Innsbruck	INN	AT	11.38	47.27	609	NW	1777
17	Bern	BER	CH	7.42	46.93	565	NW	1777
173	Karlsruhe	KAR	DE	8.35	49.03	112	NW	1779
136	Stuttgart	STU	DE	9.20	48.83	311	NW	1792
135	Strasbourg	STR	FR	7.64	48.55	150	NW	1801
157	Zürich	ZUR	CH	8.57	47.38	556	NW	1830
67	Kremsmünster	KRE	AT	14.13	48.05	389	NE	1767
193	Regensburg	RBG	DE	12.10	49.03	366	NE	1773
152	Wien	WIE	AT	16.35	48.22	209	NE	1775
215	Budapest	BUD	HU	19.22	47.45	130	NE	1780
56	Hohenpeißenberg	HOP	DE	11.02	47.80	986	NE	1781
92	München	MUN	DE	11.55	48.18	525	NE	1781
159	Augsburg	AUG	DE	10.93	48.42	463	NE	1813
75	Linz	LIN	AT	14.28	48.30	263	NE	1816
53	Graz	GRA	AT	15.45	47.08	377	NE	1837
122	Salzburg	SAL	AT	13.00	47.80	430	NE	1842
100	Padova	PAD	IT	11.88	45.40	14	S	1774
143	Udine	UDI	IT	13.24	46.06	51	S	1803
64	Klagenfurt	KLA	AT	14.33	46.65	459	S	1813
142	Trieste	TRI	IT	13.77	45.65	67	S	1841
139	Torino	TOR	IT	7.67	45.07	275	S	1760
88	Milano	MIL	IT	9.19	45.47	103	S	1763
251	Verona	VER	IT	10.87	45.38	67	S	1788
96	Nice	NIC	FR	7.20	43.65	4	S	1806
19	Bologna	BOL	IT	11.34	44.50	60	S	1814
141	Trento	TRT	IT	11.12	46.07	199	S	1816
83	Mantova	MAN	IT	10.79	45.15	20	S	1828
49	Genova	GOV	IT	8.93	44.42	53	S	1833
5	Aosta	AOS	IT	7.30	45.73	544	S	1841
52	Gr. St. Bernhard	GSB	CH	7.18	45.87	2472	H	1818

introduction of new observing regulations, and short periods when institutional changes were made to better co-ordinate the networks. These issues may also happen when many gaps are present for a shorter period (e.g. World War II) or a sudden increase of network density following the establishment of national meteorological services (NMSs), typically in the GAR between the 1850s to the 1870s. This may cause incorrect homogeneity decisions to be made. This happens if the majority of a sample of tested series have a systematic break and the truth happened to be only evident in the minority of records. This dilemma can only be solved if either parallel measurements are available which document the break and/or if the problem is well documented in station history files.

Three such suspicious periods exist in the 250 years of the HISTALP dataset. One is happening just now due to the automation of the network. It can only be hoped that the future will confirm that NMSs in the GAR have done their job well, according to their own quality regulations, and have documented this appropriately

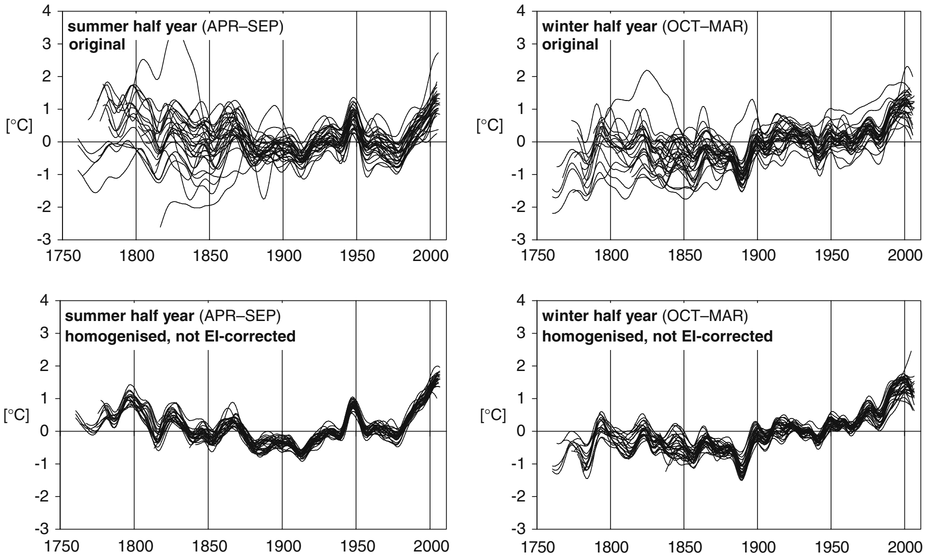


Fig. 2 The 32 seasonal temperature series of the HISTALP long series subset in the GAR before (*upper graphs*) and after (*lower graph*) homogenization but before EI-bias correction. The "original" series were only subject to outlier correction and completing of gaps. The homogenized version is identical to the one described by Auer et al. (2007). All series are 20-year Gaussian low-pass filtered

to readily allow for any necessary adjustments in the future. The second problem period was World War II which caused many interruptions of series, reorganizations, and relocations. During this period, many stations were relocated from historic city centre sites to airfields or airports which caused a systematic decrease of urban sites in the region. World War II also resulted in a general decline of climate networks with simultaneous gaps in many station series. Fortunately, not all parts of the GAR were similarly affected and this gap could be well bridged by the Swiss network (Auer et al. 2007). The effect of a decreasing urban bias in the original GAR data has already been discussed in Auer et al. (2001a) and in Böhm et al. (2001).

While these two suspicious periods are positioned in the data rich twentieth century with more than 100 temperature series available for high quality homogeneity testing and adjusting, the third period was the two decades from 1850 to 1870 when the NMSs were being established all over Europe. This caused a fundamental reorganization (better termed as a relatively sudden change) from sparser individual activities typically at astronomical observatories to well organised, spatially dense and internationally coordinated networks. Although this caused an increase in quality and data volume it also often caused relatively simultaneous breaks across the GAR. In this case, we do not have possibilities to assess unaffected information—all subregions were affected in a short interval: 1851 (Austria, Czech Republic, Slovakia, Slovenia, Croatia, Bosnia, Hungary), 1864 (Switzerland), 1866 (Italy), followed shortly thereafter by the then independent German regional services.

In such problematic periods there is nevertheless a possibility to detect a masked systematic bias using "third party evidence" from independent sources. In our case this is the documentary and proxy information outlined in the introduction. These data show, as argued already, that there is a potential warm bias in the “pre-weather-service period”.

The evidence for a systematic EIP-bias suggested by the majority of proxies would open a possibility for correction by simply adding the average proxy-instrumental difference to the instrumental records. There are at least three arguments against making adjustments in this way. Firstly, none of the natural proxies provide monthly information. Secondly, the different proxies show different deviations from the instrumental evidence, and even some of them only provide qualitative hints but no reconstructed temperature values which could be used for adjustment. Thirdly, and most significant in terms of the further use of the EI-corrected dataset, a proxy-based correction would cause the loss of independence of the purely “instrumental dataset”. The instrumental dataset would loose value for any comparative studies with the respective proxies (e.g. for calibration), as it would have been developed from the proxy information. Therefore we decided to look for another way to find quantitative adjustments for the GAR EIP-records. Fortunately, one of the HISTALP long-term records (Kremsmünster) provides such a possibility.

3 The Kremsmünster comparative dataset

The original measuring site at the NNE-facing wall of the astronomical tower of the Benedictine monastery in Upper Austria is trustworthy and reported to be unchanged from the start of the record in March 1767 until now (Austaller 1988). Notably, this site was not discarded during the automation of the Austrian climate network in the 1980s. A modern garden site has been installed, but the historic site was also equipped with the temperature and humidity sensors of a TAWES-type climate station (TAWES is the semi automatic modern Austrian standard of a climate network of 200 online stations combining automatic measurements with manual observations).

The left photo of Fig. 3 shows the N-30°-E facing window of the unheated meteorological observing room 6.9 m above ground at the historic Kremsmünster site

Fig. 3 The historic measuring site for temperature and humidity, 6.9 m above ground at the NNE-facing front of the historic astronomical tower of the Monastery Kremsmünster (48°03′21″ N,14°08′01″ E, 380 m asl.). *Left* The first three floors of the eight-floor “baroque skyscraper” built 1729 to 1758. *Right* Fish-eye photo taken from inside the meteorological observing room. Note that the strong wide-angle perspective of the right photo makes the instruments appear more shaded than they are in reality (Photos: 21 March 2007, R. Böhm)

Fig. 4 *Left photo*: The modern garden installation of the automatic measuring devices of the Austrian standard "TAWES". Temperature and humidity sensors are in a permanently ventilated Stephenson type screen 2.2 m above ground. *Right photo* A panorama of the monastery with the astronomical tower at the left (Photos 21 March 2007, R. Böhm)

on March 21st 2007 at 0815 hours. The arrow indicates the "measuring basket", which can be seen from inside the observing room on the right photo. The instruments are shaded by a metal plate against scattered sky-radiation and by a plastic device on the right side against direct insolation from a low sun in the NNE in early morning hours. It is reported in documents of the astronomical observatory that these two devices have always been as indicated, only the material used to be white painted wood in the early period. The left photo of Fig. 4 shows the temperature screen of the modern TAWES station in the monastery garden.

Since the mid 1980s, the automatic sensors of the two Kremsmünster sites have produced a continuous hourly dataset plus daily maximum and daily minimum temperatures. The 8 years from 1995 to 2002 are without any short interruptions, and this sample was used for the comparisons henceforth. The long-term mean daily courses of temperature differences "historic minus modern" are shown in Fig. 5 for January to June (left) and for July to December (right). The term "historic" henceforth will be used for a still preserved EIP-site with modern instruments. The

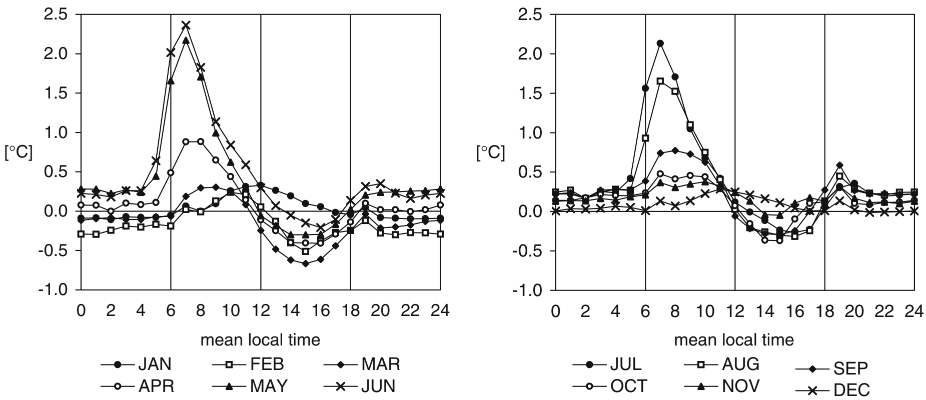


Fig. 5 Mean daily courses of temperature difference "historic minus modern" at Kremsmünster. Data source: eight consecutive years (1995–2002) with complete hourly data for both sites

term “modern” for the recent standard. The difference “historic minus modern” is our specific target. Other inhomogeneities due to instrument changes and a number of other reasons are expected to have been eliminated already by Auer et al. (2007). The historic Kremsmünster installation (30°east of N) does shade the instruments against direct insolation quite well, but analysis of the results shows a clear temperature excess of the historic site relative to the modern installation. May, June, July and August morning temperatures are positively biased by +1.5 to +2.5°C at 7am local mean time. April and September show a reduced but still >0.5°C bias. The (shaded) historic position at noon and in the early afternoon tends to be cold biased, but this bias is generally less than 0.5°C. In general, cold season months are not much affected and remain within a band of less than 0.5°C all the time.

Frequency distributions of the difference dataset show a range of up to 7°C temperature differences in extreme single hourly cases. Figure 6 gives two examples of daily courses of the range of the historic minus modern temperature differences for January and July. The variability of the differences clearly points to difficulties yet to be overcome in homogenizing climatic time series at daily to sub-daily resolution, as adjustments of individual minima or maxima cannot be assumed to behave like monthly averages (e.g. Della-Marta and Wanner 2006). For the purpose here—trying to find EIP-corrections for monthly means—the mean daily courses of Fig. 5 are an adequate basis for further work.

Of course the mean daily temperature courses do not directly reflect the corrections to be applied. Neither the strongly affected morning values nor those of the less affected hours during the rest of the day are alone used for the calculation of averages. The correction depends on the respective algorithms used to estimate the daily means in the EIP. Figure 7 gives examples of how different algorithms may be affected. Monthly means calculated from the two daily extremes are least affected. The second best performance is the true mean (values measured every hour) but this calculation algorithm was never used at a typical EIP-station. The frequently-used algorithms based on 7 A.M., 2 P.M. and twice the 9 P.M. evening reading perform similar to a typical EIP-algorithm based on 6 A.M., 1 P.M. and 8 P.M. Both algorithms do lead to systematic biases. All curves show the expected warm bias in summer

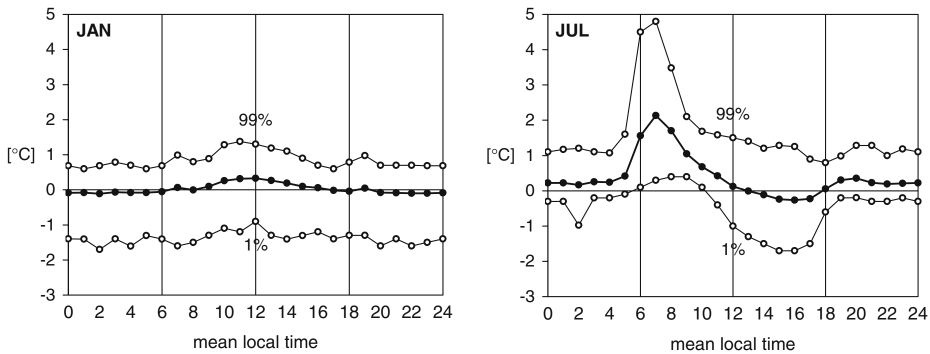
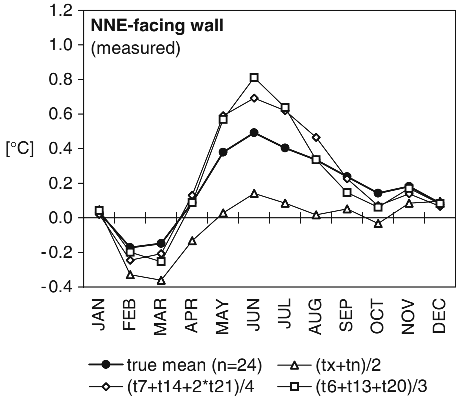


Fig. 6 Daily courses of the range of temperature differences “historic minus modern” at Kremsmünster for January (*left*) and July (*right*)—here visualized through the thin lines of the 1%- and the 99% quantiles respectively. The bold lines are the mean differences shown in Fig. 5. Data source: same as for Fig. 5

Fig. 7 Mean monthly differences "historic minus modern" for Kremsmünster based on four different algorithms of means calculation. Data source: same as for Fig. 5



months of up to 0.8°C and a generally weaker cold bias in winter which is strongest for the (tx+tn)/2 algorithm.

The still preserved historic Kremsmünster measuring site can be described as an important basis for developing quantitative EIP-temperature bias corrections. However, we must take into account that the Kremsmünster empirical results may be most appropriately applied for Kremsmünster itself and for similar sites facing towards the same direction and at similar altitudes. In the next section, we adapt the method to consider other locations which are north facing, but not the same orientation as Kremsmünster. We apply the bias estimates from Kremsmünster to provide algorithm-specific corrections for each site. We realize that biases will also differ with respect to latitude, but the range of latitudes across our GAR network is only just over 5°.

It can be assumed that the question of height above ground at the given typical north-wall-EIP-installations of several metres plays a minor role for EIP correction models. Although the series metadata show a clear trend of decreasing altitudes of the thermometers from 10 to 15 m in the EIP towards the modern standard of 1.25 to 2 m (Fig. 8), knowledge of the typical temperature gradients of air temperature near the surface (e.g. Geiger et al. 1995) indicates that most of the vertical changes happen below 2 m with only minor ones in the typical "historic layer" from 5 to 40 m.

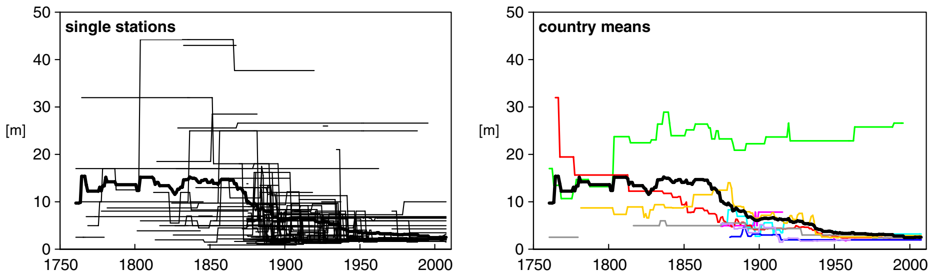


Fig. 8 Timeseries of height above ground of thermometers in the GAR. *Left* At 98 GAR stations. *Right* Grouped in seven national subgroups. *Red* Austria, *dark green* Italy, *dark blue* Germany, *violet* Switzerland, *light green* Hungary, *pink* Slovenia, *orange* Bosnia and Herzegovina; *bold black* the mean of all sites (Source: HISTALP metadata inventory)

Therefore the Kremsmünster findings from a 6.9 m high historic installation, which is well within the typical range of historic EIP installations, may be reasonably applied to other heights without modifications. Interesting, but not relevant for this study, is the special feature of the Italian LSS-series. Whereas all other stations (since the late nineteenth century organised by NMSs) indicate a tendency to decreasing heights, the classical Italian sites keep their individuality and remain at their historical high observing heights.

The orientation of the typical historic window installations, on the other hand, can not be neglected. The historic sites did not all follow the Kremsmünster example with a NNE-orientation. The ideal orientation was directly northwards, but the orientations of existing buildings mean that there was always a certain variation from NNW to NNE. In fact Kremsmünster is one of the most extreme cases in terms of degrees from true North. This allows us to develop a "best we can do" possibility to develop simple, but likely, EIP-bias estimates for other orientations. We use the phrase 'best we can do' as there are no other comparisons of EIP and modern installations. As our intensive metadata studies of the EIP-sites did not provide usable information to consider possible time lags of the insolation effects due to heat storage in the walls of the buildings, the best way to proceed was to simply mirror the daily courses of temperature differences shown in Fig. 5 at the line of 12 mean local time (MLT) and thus receive an estimate for the effect to be taken into account for a NNW-orientated window installation. The mean of the two NNW- and NNE-courses then was accepted as the best available estimate for a N-facing installation. Figure 9 shows these two derived mean daily courses for the first 6 months of the year, Fig. 10 displays the respective monthly correction models—again for the four monthly-mean algorithms already used in Fig. 7.

The neglection of any time lags due to heat storage of the building is a shortcoming of the simple method of mirroring the daily courses measured at the NNE-installation to produce an estimate at a NNW-orientated site. It may be qualitatively expected that peak values near 5 P.M. MLT would in reality happen later, as they will likely be a reflection of the respective lag in the morning due to storage effects. But as long as there are no other preserved historic EIP-sites available with existing long-term

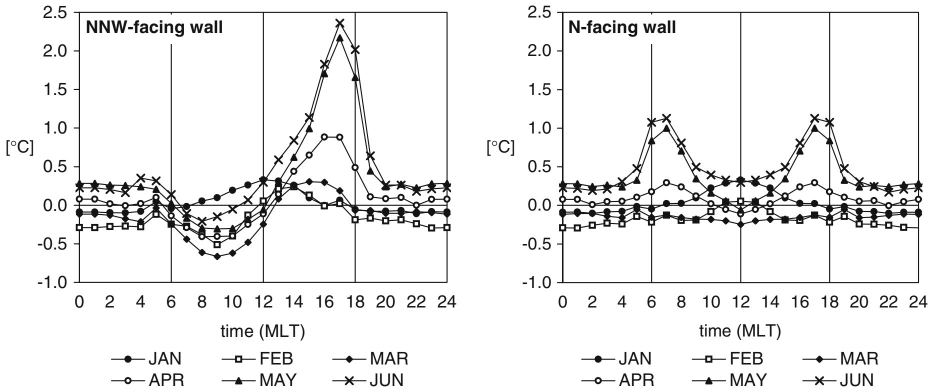


Fig. 9 Mean daily courses of temperature difference "historic minus modern" for NNW- and N-orientated EIP-installations derived from the empiric (NNE-orientated) Kremsmünster evidence

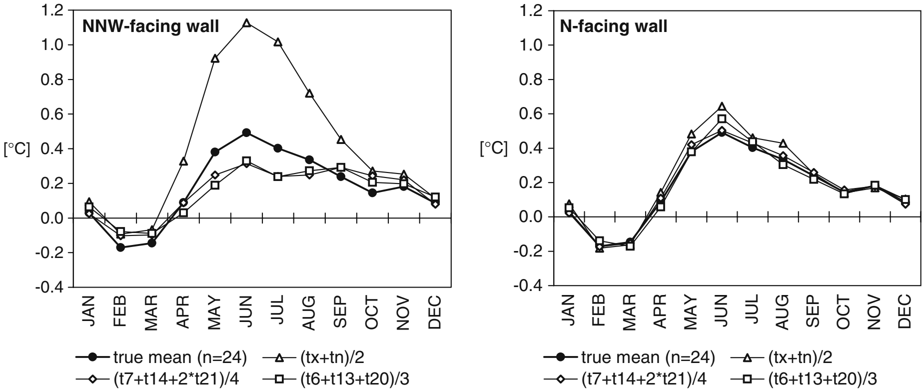


Fig. 10 Mean monthly differences "historic minus modern" based on four different algorithms of means calculation, left for NNW-orientated, right for N-orientated installations

comparative datasets, and also anticipating the general lack of metadata about wall-dimensions, surface colours, building materials of the historic sites, we proceed with the simple mirror-model to estimate biases at all sites.

Comparing the left graph of Fig. 10 of monthly mean EIP-corrections for a NNW-facing window with the respective one in Fig. 7 for NNE-orientation, illustrates the necessity to develop individual models for each orientation and also how metadata are fundamental for the algorithms used for the calculation of monthly means. We show, for example, that the best NNE-performing $(t_x+t_n)/2$ algorithm yields the strongest bias of more than 1°C in June for NNW-orientations, whereas the other three algorithm examples perform better for NNW-orientation than for NNE. N-orientation shows a much lower variability for the different formulae, but also this ideal installation is far from being immune to insolation problems.

Having extended the Kremsmünster findings to all kinds of possible monthly-mean calculation procedures and for other orientations, sufficient independent evidence has been accumulated to underline the necessity of a correction of the assumed EIP-bias. At the same time these findings are directly usable in the form of three correction models. The variability of the corrections clearly indicates that it would be less than ideal to use one general correction for all series or for the regional mean of all long GAR temperature series. Further, this variability, clearly indicates the necessity to delve more deeply into the metadata for each stations history and apply, if metadata allows, individually-tailored EIP-bias corrections station by station and—in the case of changes within the EIP—sub-period by sub-period. To achieve this, a re-examination of the metadata of the LSS was performed.

4 Metadata reanalysis and the development of individual EIP-correction models

The intensive reassessment of the vast amount of existing but scattered historic metadata in the region enabled us to collect much new information about the way early climatological data were measured and processed. The principal sources were the yearbooks of the NMSs (e.g.: Austrian Meteorological Yearbooks (since 1848), Badische Meteorological Yearbooks (since 1868), Bavarian Meteorological

Yearbooks (since 1878)). Particularly the first volumes often addressed the years preceeding the weather service period. But as a consequence of the predominance of individual approaches, many other sources such as monographs, articles in other than meteorological journals and also unpublished material had to be scanned. Published information on the pre-NMS period came from: Andrighetti et al. (2007), Austaller (1988), Bider (1964), Brunetti et al. (2001), Buffoni et al. (1996), Camuffo (2002), Carlini (1833), Chlistovsky et al. (1997), Häfner (1994), Herrenschneider (1815, 1825), Klemun (1994), Lang (1882), Lauscher et al. (1959), Maugeri et al. (2002), Maurer et al. (1909), Mercalli et al. (2003), Müller-Westermeier (1992), Di Napoli (1996), Di Napoli and Mercalli (2008), Peppler (1922), Plantamour (1863, 1876), Polli (1950), Prettner (1865), Riggenbach (1892), von Schmöger (1835), von Schoder (1882), Stravisi (2006), Venerio (1851), Wild (1879), Winkler (2006) and Zallinger (1833).

Table 2 displays some examples of the kind of metadata that could be collected. Despite the lower degree of systematic network organisation and international coordination in the EIP, the amount of information we have gathered is often very detailed. Most of the sub-periods could be identified and assigned to either a known location or address or to the name of an observer.

The descriptions of the way the thermometers were shaded against direct insolation were sometimes vague, although the frequent indications like "in a shadowy position" point to the awareness of the problem. Real screens guarding against scattered radiation or indicating reflected radiation from below are neither described nor mentioned in the starting periods of the EIP-series. This underlines the necessity of a respective bias correction. The basic necessity for adjustment was the identification in these starting sections of insufficient or no screens. It seems that the awareness of the problem grew in the middle of the nineteenth century, in many cases before the foundation of NMSs. The introduction of standardised screens—smaller generally metal screens—mounted again at higher positions outside windows of the observing rooms, seemed to have been a change worthy of mention in station descriptions. Therefore changes such as when screens were introduced at each station were relatively easy to detect. In uncertain cases, we preferred to place the time of change nearer to 1850 than earlier. A much later introduction in fact never happened—it seems that the official NMS which took over responsibility during the decades soon after 1850 were all aware of the necessity of thermometer screens. The consequent lengths of the EIPs of the single sites are shown in the left graph of Fig. 11. The earliest indications of screens were detected in the 1830s, the latest free installation ended in the 1870s.

The next essential for choosing the appropriate correction model was the orientation of the building or the wall on which the thermometer was fixed. This EIP-feature could be identified for 26 of the 32 EIP-series. 14 of the sites orientated towards north within a range of $-5°$ to $+5°$, five deviated form north by more than $-5°$ NNW (the strongest deviation from north being $-40°$), seven by more than $+5°$ towards NNE (maximum: $+30°$). In many cases the exact identification of the historic orientations could be based on original building plans, photographs, contemporary maps or even recent maps (e.g. Google earth) in the cases when the original historic building still exists.

The last "conditio sine qua non" for EIP-bias correction was knowledge about observing times and/or the respective algorithms for the calculation of monthly means.

Table 2 Excerpt of the EIP-metadata files for five of the 32 LSS-HISTALP sites (*n.i.a.* "no information available")

ID	Name	acr.	Nat	Alt	From–to	Name od subseries	Height above ground (m)	Orienation N-deg-E	Observing times or means calc.	Additional remarks
139	TORINO	TOR	IT		1760–1786	Ignazio Somis, mostly Università, via Po, but also other locations	10 to 25	28°	Variable (a)	In a shady position, no screen—outside a window before unheated observing room
		TOR	IT	250	1787–1802/05	Accademia delle Scienze, biblioteca	12.5	28°	Variable (a)	In a shady position, no screen
		TOR	IT	282	1802/06–1802/12/21	Accademia delle Scienze,	44.2	0°?	Sunrise, 14, sunset	In a shady position, no screen,
		TOR	IT		1802/12/22–1851/01/05	specola			Sunrise, 12, sunset	on a flat roof, higher than
		TOR	IT		1851/01/06–1857/07				09, 12, 15	surrounding buildings
		TOR	IT		1857/08–1865/06				(max + min)/2	
		TOR	IT	232	1865/07–1865/11	Castello del Valentino	2.0	28°	08, 16	In a shady position
		TOR	IT	276	1865/12–1919/02	Palazzo Madama	37.7	20°	T_{min}, T_{max}	Wooden louvered screen outside a window before unheated observing room
REF: di Napoli and Mercalli 2008										
59	INNSBRUCK	INN	AT	576	1777–1784	Jesuiten Colleg Sillgasse (Franz v. Zallinger)	second floor	–9°	4, 13.30	No screen but "in a shady position"
		INN	AT	576	1784–1828	Kapuziner Kloster, Universitätsstrasse (Franz v. Zallinger)	8	15°	Near min, near max	No screen but "in a shady position"
		INN	AT	590	1828/09–1855/12	Prämostratenser Kloster	8	–19°	6, 13.30	No screen
		INN	AT	590	1856/01–1859/12	Wilten (Prantner)			(7 + 14 + 2 × 21)/4	Metal screen before 2nd floor window
		INN	AT	590	1860/01–1870/12				6, 14	Metal screen before 2nd floor window
		INN	AT	576	1865/01–1870/12	Old University-	8	15°	(7 + 14 + 2 × 21)/4	Metal screen
		INN	AT	576	1871/01–1875/07	Botanical Institute			6, 14, 22	Metal screen
REF: Zallinger 1833; Auer et al. 2001a										

Table 2 (continued)

ID	Name	acr.	Nat	Alt	From–to	Name od subseries	Height above ground (m)	Orienation N-deg-E	Observing times or means calc.	Additional remarks
135	STRAS-BOURG	STR	FR		1801–1843 (?)	Astronomical observatory, Place de St. Thomas (J.L.A. Herrenschneider)	3.9	0°	6–7/noon/21–22	"...à l'ombre et a l'air libre, à l'abri de l'action tant directe qu'indirecte des rayons du soleil..."
		STR	FR		Several years	Vorstadt Neudorf (Besson)	1.5	n.i.a.	n.i.a.	Metal screen inside large wooden Wild-screen
		STR	D		1891/04–before 1915	Institut de Physique du Globe	6	0°	$(7 + 13 + 2 \times 21)/4$	Moving metal screen between 2 windows
		STR	FR		Before 1915–	Institut de Physique du Globe	6	0°	$(7 + 14 + 2 \times 21)/4$	Moving metal screen between 2 windows
REF: Herrenschneider 1815, 1825, Annales de l'Institut de Physique du Globe (before 1918: Elässische Jahrbücher)										
52	GR. ST. BERNARD	GSB	CH	2,472	1817–1826	Hospiz St. Bernhard	3rd floor	NE	(sunrise + 13)/2	n.i.a.
		GSB	CH	2,472	1826–1835/09				9, 12, 15	n.i.a.
		GSB	CH	2,472	1835/10–1847/01				Sunrise, 9,15,18,21 h	n.i.a.
		GSB	CH	2,472	1847/02–1850				6, 9, 15, 18, 21 h	n.i.a.
		GSB	CH	2,472	1851–1884				6, 8, 10, 12, 14, 16, 18, 20, 22 h	n.i.a.
REF: Mercalli et al. 2003; Maurer et al. 1909										
159	AUGSBURG	AUG	DE		1812–1822	station Stark 1 (western part of historic centre)	12	WSW and ENE	$(7 + 14 + 2 \times 21)/4$	No screen, 2 thermometers alternatively used
		AUG	DE		1822–1829	station Stark 2 (near cathedral)	5.5	WSW and ENE		
		AUG	DE		1829–1836	station Stark 3 (same building—new astronomical tower)	12	WSW and ENE		
		AUG	DE		1838–1872 1872	Benedictine Monastery St.	8.3	W and E	True mean	No screen, 2 thermometers alternatively used
		AUG	DE		1872–	Stephan	8.3	3°		Metal screen before another room at same floor
Ref: Bavarian Meteorological Yearbooks (since 1878), DWD—Archive of historic metadata and station histories										

From the total of 1,735 EIP-years, this essential piece of knowledge could be detected for 1,331 years (the accumulated EIP-periods without screens), which is a mean detection rate of 77%. Although this is a reasonable number for the early period, for some single sites (compare the right graph of Fig. 11) this was the determinant for directly establishing an individual EIP-correction model. For some stations, which were run in close collaboration to another EIP-site (e.g. the station pair of Genève and Grand Saint Bernard) the model of one station was adopted for the other. The remaining two sites (Genoa and Aosta) for which no EIP-correction model was possible were subject to a final routine mathematical homogenising procedure (described in Auer et al. 2007) together with the respective EIP-corrected reference series. In addition to this, routine mathematical homogeneity testing was re-applied after EIP-corrections allowing nine previously undetected inhomogeneities in the dataset to be corrected.

The metadata rescue, compilation, and analyses enabled us to individually adjust the EIP-bias based using the three essentials (i.e., date of screen installation, orientation of thermometer, and algorithms for computing means) to apply the empirical evidence of the Kremsmünster data. Therefore, assuming that the masked EIP-biases had not been detected in the earlier work of Auer et al. (2007), the corrections shown in Fig. 12 were used to adjust this homogenised individual LSS-series (lower line in Fig. 2) for the suspected insolation-induced bias for the periods shown in Fig. 11. Note that Kremsmünster itself, although remaining unchanged from its original EIP-installation for all its +240 years, needed the additional

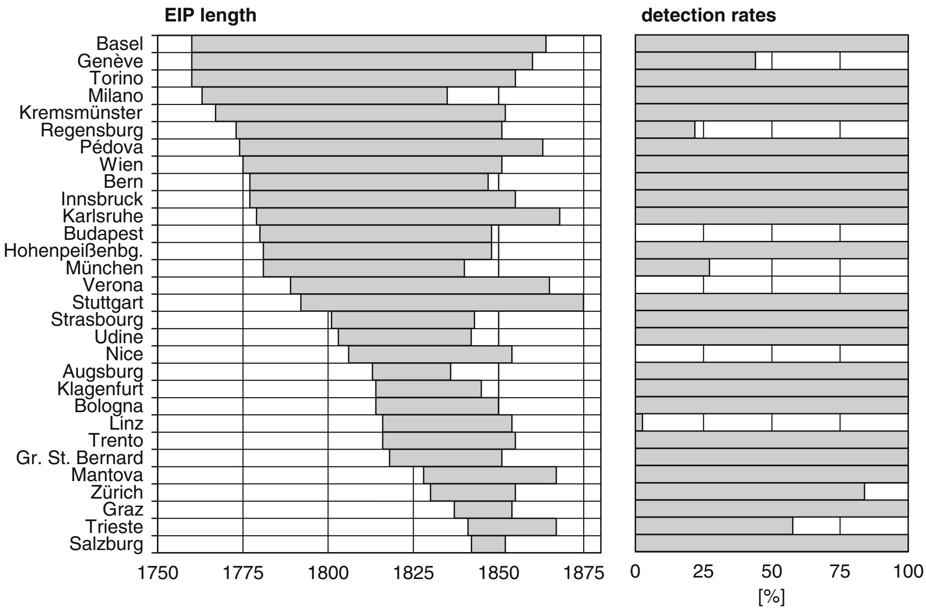


Fig. 11 *Left* The reconstructed early instrumental periods for the single EIP-sites for which there is evidence for inefficient or non-existing screens against insolation. *Right* Detection rates of EIP means calculation algorithms for the single stations. The percent values refer to the total lengths of the EIPs shown in the *left graph*. Note that no EIP length was detectable for two sites (Genova and Aosta) so they are not included here

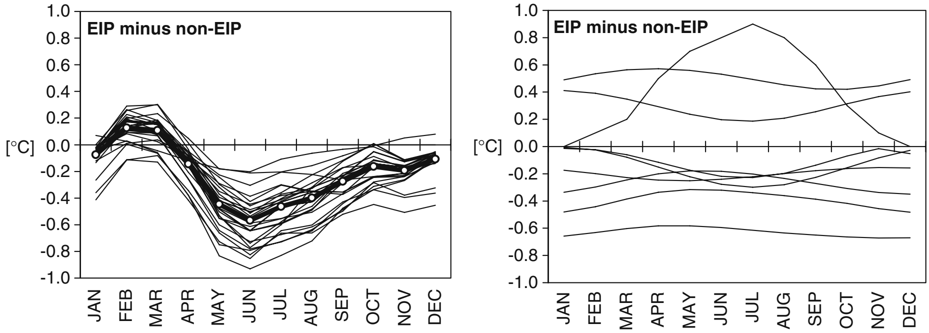


Fig. 12 *Left* EIP adjustments applied to the 32 LSS-HISTALP series, *bold line* mean of all adjustments, *thin lines* individual adjustments. *Right* Additional adjustments for nine detected new breaks after having applied the EIP-adjustments

correction because it had been adjusted to the majority of biased records before. The EIP-adjustments, although spanning a wide range, follow a mean course of two slightly positive corrections in February and March and ten negative (cooling) ones from April to January. June requires the strongest mean negative correction of −0.57°C with a range from −0.21 to −0.93°C.

The right graph of Fig. 12 shows the additional nine "post-adjustments" which resulted from the final general homogeneity testing of the EIP-bias-corrected LSS series. Together with the majority of metadata-based direct EIP-adjustments this whole exercise has produced a new version of 32 central European longterm monthly temperature records, henceforth referred to as HISTALP-LSS-Tm-08.

We have argued that LSS-Tm-08 is another step towards a more realistic assessment of the course of climate change during the past two and a half centuries in the region. Our approach is based on empirical evidence and goes along with physical reasoning. So we are confident we have reduced a systematic bias in early instrumental temperature series, and we have developed it strictly within the instrumental domain. No other-than-measured temperature information was used. This makes the dataset fully independent of proxy climate data as well as of other climate elements than temperature. Thus, HISTALP-LSS-Tm-08 may be used as an autonomous comparative measure for other climate elements and as a basis for calibrating natural and documentary proxies.

5 Discussion of the new EI-bias corrected dataset

Figure 13 illustrates the results of the EIP-corrected HISTALP-LSS-Tm-08 (bold black lines) compared to the original status of the series (thin lines) and to the Auer et al. (2007) version (LSS-2007, bold grey lines). Shown are the means over all 32 LSS-records which are highly representative for any subregion (compare Fig. 2 of this paper or the respective discussion in Auer et al. 2007 or Böhm et al. 2001). All series are smoothed to easily allow them to be distinguished and are presented as anomalies to the most recent common 30-year reference period (1978–2007). This is in accordance with the way the series have been homogenized: stepwise adjusting the earlier sub-periods to the more recent ones.

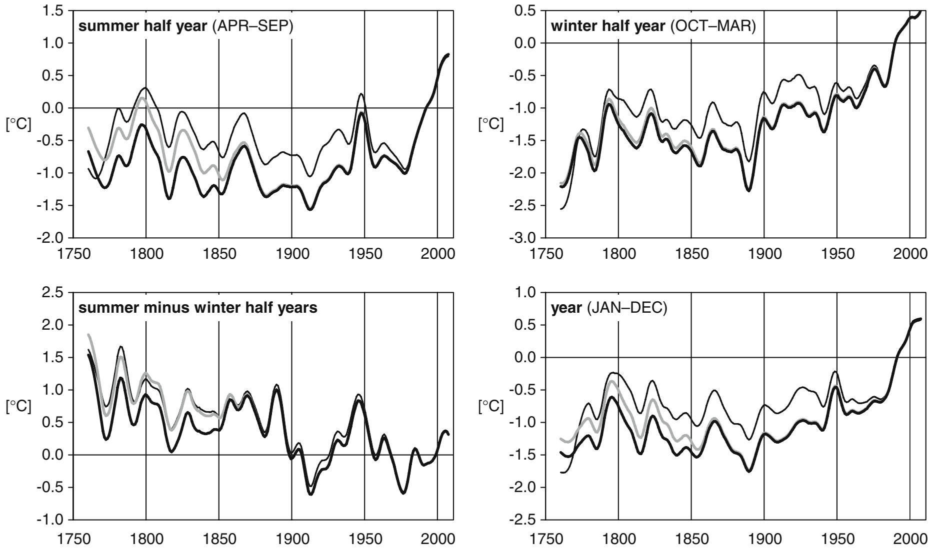


Fig. 13 The way from original (*thin black*) to homogenised (LSS-2007, *bold grey*) and to EIP-corrected (LSS-2008, *bold black*) long-term temperature series in central Europe: 20 years smoothed mean GAR-series 1760 to 2007 (1760/61 to 2007/08) as anomalies with respect to the recent 30 years for summer- and winter half years (*upper graphs*), annual range (*lower*, *left*) and annual mean (*lower*, *right*). Data are long series subset (LSS) of 32 temperature records in the greater Alpine region of central Europe (compare Fig. 1)

Comparing "original" (the thin black lines) with LSS-2007 (bold grey lines) we realize that the adjustments applied earlier have already produced other systematic adjustments than the EIP-correction. The most recent one happened 1970/71 (change of evening observing time in Switzerland and Austria) and a second in the years of WW-II (frequent relocations from historic city centres to airfields and airports). Both adjustments cooled the respective earlier parts and together they caused an increase of the general regional warming trend from nineteenth to twentieth century by approximately 0.5°C. As these two systematic biases in the fully developed instrumental period show no significant seasonal differences (compare the upper two and the lower right graph of Fig. 13) the annual range of temperature (AMJJAS minus ONDJFM, lower left) was not affected by the 2007-homogenization. In addition to some decadal-scale variations, the annual range of temperature in general was high in the late eighteenth and the entire nineteenth century, followed by a sharp reduction near 1900 to a lower level in the 20th. The stronger annual cycle in the earlier part of the instrumental period goes along with similar and more long-term findings based on indirect climate information (e.g. Jones and Moberg 2003), but the strength of the signal raises doubts. The bold lines in Fig. 13 illustrate the change from the 2007- to the 2008-version of the HISTALP dataset. The upper row of graphs show the expected consequence of the corrections of Fig. 12 applied to the EIP-subperiods shown in Fig. 11. Incipient in the 1860s, the regional mean EIP-series of the summer half-year was cooled by another approximately 0.4°C, the winter half-year by less than 0.1°C. This seasonal asymmetry caused a significant reduction of the EIP-annual range, which now is more in line with the findings elsewhere in Europe (references in the caption of Fig. 13).

According to our arguments at the end of the previous section we believe that the EIP-corrections applied to the regional central European HISTALP dataset are a significant step towards the determination of the true course of climate change over this period. But we are also aware of the still existing uncertainties of climate reconstruction in general even if it is based on instrumental evidence. In particular the early period of direct measurements may still bear some hidden and not yet detected and quantified biases.

Figure 14 serves to assess our result in the frame of the existing state of the art of instrumentally based EIP-temperature reconstruction. The figure compares many results in the region and from other parts of Europe. Regionally nearest to ours (LSS-2007 in bold-grey and LSS-2008 in bold-black) are results from national Italian efforts of the CNR-ISAC institute, Bologna (thin red) covering seven series also present in the southern part of the GAR. This Italian subset was not subject to a specific EI-correction, but was homogenized in a slightly different way. Only Italian series were used for homogeneity testing and adjusting, the basis being minimum and maximum temperature series. Moreover the homogenization was, on one side, supported by a larger metadata availability and, on the other, at each step, it was verified by

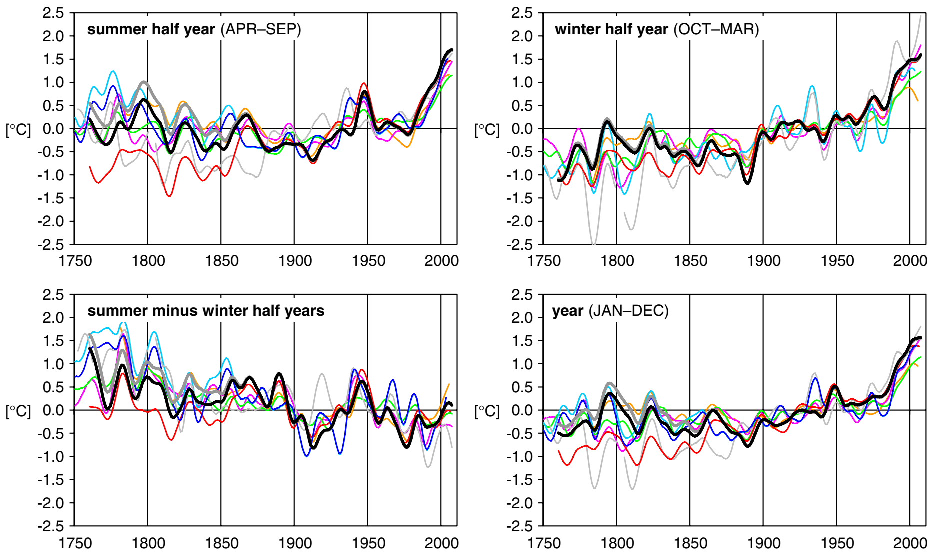


Fig. 14 HISTALP-LSS regional mean temperature series (*bold*) compared to other series from central and other parts of Europe. All series are anomalies to a common reference 1851–2000 and are 20 years smoothed (Gaussian lowpass filter), *bold black* HISTALP-LSS-Tm-2008, EI-corrected (this paper), *bold grey* HISTALP-LSS-Tm-2007, not EI-corrected (Auer et al. 2007), *thin red* ISAC-homogenized, mean of seven N-Italian series (Brunetti et al. 2006b), *thin pink* central European mean of CRUtem2v gridboxes 40–50 N, 10–20 E (Trenberth and Jones 2007), *thin light blue* Uppsala-Stockholm mean, not EI-corrected (Moberg et al. 2002; Bergström and Moberg 2002), *thin dark blue* Uppsala-Stockholm mean, EI-corrected (Moberg et al. 2003, 2005), *thin green* central England series (Manley 1974; Parker et al. 1992), *thin violet* de Bilt series (van Engelen and Nellestijn 1995), *thin grey* St. Petersburg series (Jones and Lister 2002)

checking its effect on daily temperature range series. Such daily temperature range series turned out to be very useful in order to minimize the risk of applying non-necessary adjustments. The ISAC-version is significantly colder even than the LSS-2008 in the early period. The mean additional cold bias with respect to LSS-2008 is approximately 1°C in pre 1870-summers and near to 0.5°C in pre-1840-winters. The reason for this is not yet clear.

The second existing instrumental regional EIP-information is the (green) central European mean series published as Fig. 2 of box 3.6 of the recent WG-1 IPCC report. It is the average of the respective gridboxes of the CRUTEM2v dataset, covering quite precisely the area of the GAR and shows only minor deviations from LSS-2008. The longest period with systematic deviations is the winter-halfyears from 1790 to 1820 which are more than 0.5°C colder in the CRUTEM2v.

The most interesting comparative series of the more remote group are the two Uppsala-Stockholm means shown in thin blue. They have also been subject to an EIP-correction of similar magnitude to ours. The (dark-blue) corrected summer-half-years of the EIP are near to HISTALP-LSS-2008 back to 1790 but significantly warmer before. Other deviations like the warm Swedish winters in the 1930s are likely real regional variations of climate.

The remaining two remote series from De Bilt and St. Petersburg tend to be cooler than HISTALP-LSS-2008 in the EIP. In summer they remain between HISTALP and the Italian ISAC-series, in winter they are even colder sometimes than ISAC. It is unclear to what extent this reflects real regional differences and/or remaining uncertainties of EIP-climate reconstruction. However, as such differences are also present in the late-nineteenth and in the twentieth century, this makes the former (real climate) more likely than the latter (artefacts of insufficient data).

The comparison with other available early instrumental temperature information in general supports what has been said already. The new EIP-corrected HISTALP-LSS-2008 version should represent a significant step towards a truer depiction of real climate change in the GAR over the last 250 years. It is in accordance with the majority of other instrumental EIP-information with one exception. The Italian ISAC-series hint at a possibly still existing need to apply even stronger EIP-corrections, but their own strong differences of the original and the homogenized versions of up to 1.3°C in summer and 0.7°C in winter, along with the much smaller sample of EIP-series poses a question mark against the ISAC-EIP-solution, particularly for the winter-reduction which cannot be explained by insufficient radiation screens.

To come to a decision on this remaining problem, new "third party evidence" would be helpful. As the respective EIP data potential seems to be exploited already, there are three feasible ways for respective future studies. The best of all would be to establish several other "Kremsmünsters"—multi-annual comparative historic versus modern measurements at still existing EIP-sites. This of course takes time and special efforts but would provide real new information to reduce uncertainties on climate change during the past 250 years. The second best would be further efforts to obtain additional metadata information on EIP-measurements. We are not optimistic for this possibility because the efforts described in this paper seem to have exhausted the existing metadata potential already. The third possibility, which we have in mind for a follow-up study is a comparison with documentary and natural climate proxies in the region. A number of new reconstructions have been developed recently—particularly for the GAR which could prove helpful. We mentioned a number of them in the introduction. Although we have already argued why indirect climate information should not be blended with direct measurements, it may well serve to estimate which of the existing instrumental solutions of the EIP-problem is more likely to represent the true course of climate change over this important period.

For the time being, we want to present the new HISTALP LSS-2008 versions of long-term temperature variability in the GAR. Figure 15 shows the regional averages of single years (half-years) temperatures from 1760 (1760/61) to 2007 (2007/08) along with the annual range (summer minus winter half-years) of temperature. We see a general 2°C annual temperature increase from the late nineteenth to the early twenty-first century in two steps which followed a weaker decrease of 1°C from 1790 to 1890. The stepwise warming of the twentieth century was more accentuated in summer than in winter. Winters do not show the accentuated summer cooling phase from the 1950s to the 1970s which was nearly 1°C in magnitude. Interannual variability in the region is higher in the cold season, but not stable in all subregions. In the Mediterranean part (not shown) winter and summer half-years have equal variance.

The annual range of temperature is represented here by the summer- minus winter-half-year differences in the lower left graph of Fig. 15. As already mentioned, this range was reduced in the early instrumental period by the asymmetric EIP-corrections. Nevertheless there still is a significant change from a stronger annual cycle before 1900 to a weaker one in the twentieth century. The smallest summer-winter differences occurred in the 1910s and in the 1960s and 1970s. These two (oceanic) phases typically went along with the last two glacier advances in the Alps, which were triggered by cool summers with higher albedo due to more frequent snow

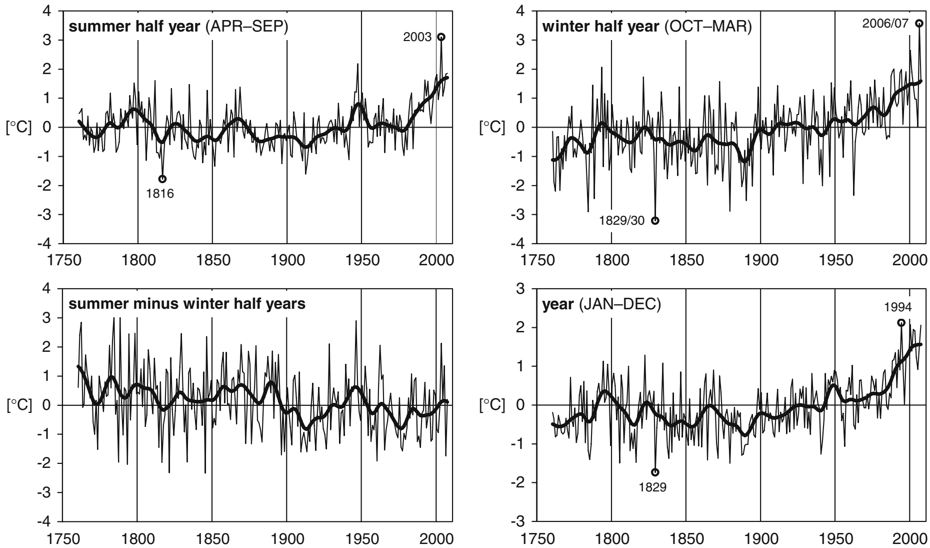


Fig. 15 Single years and 20 years smoothed mean GAR-series 1760 to 2007 (1760/61 to 2007/08) all relative to 1851–2000 average, summer- and winter halfyears (*upper graphs*), annual range (*lower left*) and annual mean (*lower right*) database: long series subset (LSS-2008) of 32 long-term temperature records in the GAR (compare Fig. 1)

cover on the glacier surface. During the last 25 years, winters and summers have simultaneously warmed at comparable rates: non-typical features for the regional climate evolution of the past 250 years. This has caused the extraordinary warming of the annual means by 1.2°C/25 years (lower right graph) which is unprecedented in the instrumental period.

The EIP corrections have re-ranked also the individual (seasonal) extremes. 1816 is now the coolest summer half year of the central European instrumental period (which it was not in the LSS-2007 version). 2003 is even more extraordinary compared to a series of warm summers in the early period. After EIP-correction 1811 (the second warmest) was surpassed by 1947—the latter now being second warmest. Winter half-years saw no changes in the ranks of extreme winters. 1829/30 is still the coldest of the past 250 years. Only the update to 2007/08 performed in this study brought a new record at the other end of the scale. The winter half-year of 2006/07 was +3.6°C above average (1851–2000) and 6.8°C warmer than the coldest of 1829/30 (−3.2°C). The range of the annual means is smaller. It spans only 3.8°C between the coldest year on record (1829, −1.7°C below 1851–2000 average) and the warmest (1994, +2.1°C above).

6 Conclusions

This paper has addressed the issue of potential biases in the EIP caused by the potentially poor exposure of thermometers before the necessary, but unfortunately mostly simultaneous, introduction of screens in the period from 1850–1870. The need for adjustments was justified based on evidence in documentary and proxy records across the GAR (Frank et al. 2007; Hiebl 2006). Using this information to develop adjustments is not practical, as it is often lower than monthly resolution and contains its own uncertainties, and would result in the loss of independence between the instrumental and the non-instrumental sources. The adjustment procedure thus relied upon simultaneous measurements taken at a site within the GAR (Kremsmünster). We would like to have used more such comparative series, but at present no others have been found. One recommendation from the study would be to carry out simultaneous measurements at the old and new exposures at more of the 32 LSS sites.

Using the eight years of simultaneous measurements at Kremsmünster, changes in the diurnal course due to the different exposures were developed. These were then expanded to include other north-facing orientations across the GAR. The effects are not the same for each location, and in fact depend not only upon the orientation towards north but also on the formulae used to calculate monthly means from the two or more observations taken per day at the LSS sites. Adjustment factors for the warm-bias were developed for all sites up to the time screens were introduced at most of the 32 sites. In all cases, there was at least one set (and normally many more) during the EIP period at each site. Averaged across the GAR, the warm bias was largest during June (between 0.21° and 0.93°C depending on site and formula) with a cold bias of up to 0.3°C in February. Overall, the revised GAR average cools the summer half year (April to September) by 0.4°C before about 1850.

Finally, we compared the new adjusted series (referred to HISTALP-LSS-2008) with some recent Italian work by ISAC (using a subset of stations amongst our 32).

This suggests the possibility of an even greater summer bias, and a non-negligible winter bias as well. We have also compared our results with instrumental records from further afield, northern Europe from England, the Netherlands, Sweden and St Petersburg (essentially all the other long instrumental records available in Europe). The results are not conclusive, due to the greater separations there are larger differences, but the results would tend to indicate better agreement in winter. This is suggestive of the cooler Italian option in winter as being incorrect, so casting doubt on their greater summer bias. The comparisons between the series from England, the Netherlands and Sweden indicate no greater departures in decadal-scale temperature variability in the EIP period compared to the 1850–2007 period.

Since March 2009 HISTALP data are available on the web. http://www.zamg.ac.at/histalp describes the history of HISTALP and the technical structure of the data, and it provides unrestricted access to all gridded HISTALP series and to most of the single station series. All temperature series (single station series as well as gridded products) are present there in the EIP-bias corrected version described in this paper.

Acknowledgements The study received funding from the Austrian Federal Ministry of Science and Research within WP-2 of project "HISTALP-2007". PDJ acknowledges support of the Office of Science (BER), US Dept. of Energy, Grant No. DE-FG02-98ER62601 and DF the EC-project Millennium (#017008). The basic idea emerged in former EU-FP-5 project ALP-IMP (EVK2-CT-2002-00148) and was further developed within the continuing informal cooperation of the HISTALP community, consisting of respective weather services and research institutes. We express once more our thanks to all data and metadata providers for the LSS-stations. We also want to thank a number of researchers from the climate proxy community for their valuable discussions, comments and hints, namely Jürg Luterbacher (Univ.-Bern), Karin Koinig, Roland Psenner, Kurt Nicolussi and Christoph Spötl (Univ.-Innsbruck), Dietmar Wagenbach and Pascal Bohleber (Univ.-Heidelberg), Ulf Büntgen and Jan Esper (WSL, Birmensdorf). Together with them, we hope to produce soon a wider follow-up of this instrumental based paper under the inclusion of their indirect climate information. Last but not least we want to appreciate the many known and unknown observers and data-processors who produced two and a half centuries of direct climate information in the GAR.

References

Aguilar E, Auer I, Brunet M, Peterson TC, Wieringa J (2003) Guidelines on climate metadata and homogenization. World Climate Programme Data and Monitoring WCDMP 53, WMO-TD 1186, WMO. Geneva

Andrighetti M, Rampanelli G, Zardi D (2007) Ricostruzione ed analisi climatologica delle serie di temperatura e precipitazione di Verona (1741–2006). In: Proceedings of the convegno nazionale di fisica della terra fluida, 11–15 Giugno 2007, Ischia

Annales de l'Institut de Physique du Globe (1890–1950) (before 1918: Elässische Jahrbücher)

Auer I, Böhm R, Schöner W (2001a) Austrian long-term climate 1767–2000—Multiple instrumental climate time series from Central Europe. Österr Beitr zu Meteorologie und Geophysik, 25 147 pages plus Data- and Metadata-CD

Auer I, Böhm R, Schöner W (2001b) Long climatic time series from Austria. In: Jones PD et al (eds) History and climate: memories of the future? Plenum, New York, pp 125–152

Auer I, Böhm R, Scheifinger H, Ungersböck M, Orlik A, Jurkovic A (2004) Metadata and their role in homogenizing. In: Proceedings of the fourth seminar for homogenization and quality control in climatological databases, Budapest, Hungary, 6–10 October 2003), WCDMP. 56, WMO-TD 1236: 17–23, WMO Geneva

Auer I, Böhm R, Jurkovic A, Orlik A, Potzmann R, Schöner W, Ungersböck M, Brunetti M, Nanni T, Maugeri M, Briffa K, Jones P, Efthymiadis D, Mestre O, Moisselin JM, Begert M, Brazdil R, Bochnicek O, Cegnar T, Gajic-Capka M, Zaninovic K, Majstorovic Z, Szalai S, Szentimrey T

(2005) A new instrumental precipitation dataset in the greater alpine region for the period 1800–2002. Int J Climatol 25:139–166

Auer I, Böhm R, Jurkovic A, Lipa W, Orlik A, Potzmann R, Schöner W, Ungersböck M, Matulla C, Briffa K, Jones PD, Efthymiadis D, Brunetti M, Nanni T, Maugeri M, Mercalli L, Mestre O, Moisselin J-M, Begert M, Müller-Westermeier G, Kveton V, Bochnicek O, Stastny P, Lapin M, Szalai S, Szentimrey T, Cegnar T, Dolinar M, Gajic-Capka M, Zaninovic K, Majstorovic Z, Nieplova E (2007) HISTALP—Historical instrumental climatological surface time series of the greater Alpine region 1760–2003. Int J Climatol 27:17–46

Austaller H (1988) Die temperaturreihe von Kremsmünster. PhD thesis, University of Vienna, 223 pp

Bergström H, Moberg A (2002) Daily air temperature and pressure series for Uppsala (1722–1998). Clim Change 53:213–252

Bider M (1964) Meteorologische beobachtungen und arbeiten in Basel. In: Cent ans de météorologie en Suisse 1864–1963. SMA, Zurich, pp 83–87

Bohleber P (2008) Age distribution and δ^{18}O variability in a low accumulation Alpine ice core: perspective for paleoclimate studies. Diploma thesis, IUP, University of Heidelberg, 146 pp

Böhm R, Auer I, Brunetti M, Maugeri M, Nanni T and Schöner W (2001) Regional temperature variability in the European Alps 1760–1998 from homogenized instrumental time series. Int J Climatol 21:1779–1801

Brohan P, Jennedy J, Harris I, Tett SFB, Jones PD (2006) Uncertainty estimates in regional and global observed temperature changes: a new dataset from 1850. J Geophys Res 111:D12106. doi:10.1029/2005JD006548

Brunet M, Saladié O, Jones P, Sigró J, Aguilar E, Moberg A, Lister D, Walther A, Lopez D, Almarza C (2006) The development of a new dataset of Spanish daily adjusted temperature series (SDATS) (1850–2003). Int J Climatol 26:1777–1802

Brunetti M, Buffoni L, Lo Vecchio G, Maugeri M, Nanni T (2001) Tre secoli di meteorologia a Bologna. Edizioni CUSL, Bologna

Brunetti M, Maugeri M, Nanni T, Auer I, Böhm R, Schöner W (2006a) Precipitation variability and changes in the greater alpine region over the 1800–2003 period. J Geophys Res 111. doi:10.1029/2005JD006674

Brunetti M, Maugeri M, Monti F, Nanni T (2006b) Temperature and precipitation variability in Italy in the last two centuries from homogenized instrumental time series. Int J Climatol 26:345–381

Buffoni L, Chlistovsky F, Maugeri M (1996) 1763–1996, 223 anni di rilevazioni termiche giornaliere a Milano-Brera. Edizioni CUSL, Milano

Büntgen U, Frank DC, Nievergelt D, Esper J (2006) Summer temperature variations in the European Alps: AD 755–2004. J Climate 19:5606–5623

Camuffo D (2002) History of the long series of daily air temperature in Padova (1725–1998). Clim Change 53:7–75

Camuffo D, Jones PD (eds) (2002) Improved understanding of past climatic variability from early daily European instrumental records. Clim Change 53 (special edition)

Carlini (1833) Sulla distribuzione e sull'uso delle osservazioni meteorologiche di Milano. Effemeridi astronomiche di Milano 1833

Chlistovsky V, Buffoni L, Maugeri M (1997) La temperature a Milano-Brera. Edizioni CUSL–Collata Scientifica, Milano, 192 pp

Della-Marta P, Wanner H (2006) A method of homogenizing the extremes and mean of daily temperature measurements. J Climate 19:4179–4197

Di Napoli G (1996) Tre secoli di clima a Torino: stato dei lavori. Nimbus 13–14:30–31

Di Napoli G, Mercalli L (2008) Il clima di Torino. 900 pp

Efthymiadis D, Jones PD, Briffa K, Böhm R, Maugeri M (2007) Influence of large-scale atmospheric circulation on climate variability in the Greater Alpine Region of Europe. J Geophys Res 112:D12104. doi:10.1029/2006JD008021

Frank D, Büntgen U, Böhm R, Maugeri M, Esper J (2007) Warmer early instrumental measurements versus colder reconstructed temperatures: shooting at a moving target. Quat Sci Rev 26:3298–3310

Geiger R, Aron RH, Todhunter P (1995) The climate near the ground. Vieweg, Braunschweig, 528 pp

Häfner R (1994) 175 Jahre Sternwarte Bogenhausen. http://www.usm.uni-muenchen.de/hist.html

Herrenschneider JLA (1815) Résumé des observations météorologiques faites a Strasbourg depuis le commencement de l'an 1801 jusqu'à la fin de 1810. Mémoires de la Société des Sciences de Strasbourg 1

Herrenschneider JLA (1825) Résumé des observations météorologiques faites a Strasbourg depuis le commencement de l'an 1811 jusqu'à la fin de 1820. Mémoires de la Société des Sciences de Strasbourg 2 46 pages plus 10 tables
Hiebl J (2006) The early instrumental climate period (1760–1860) in Europe. Evidence from the Alpine region and Southern Scandinavia. Diploma thesis, Geogr Inst, University of Vienna, 103 pp
Hormes A, Müller BU, Schlüchter C (2001) The Alps with little ice: evidence for eight Holocene phases of reduced glacier extent in the Central Swiss Alps. The Holocene 11:255–265
Jones PD (2001) Early European instrumental records. In: Jones PD et al (eds) History and climate: memories of the future? Plenum, New York, pp 55–77
Jones PD, Lister DH (2002) The daily temperature record for St. Petersburg, 1743 1996. Clim Change 53:253–258
Jones PD, Moberg A (2003) Hemispheric and large-scale surface air temperature variations: an extensive revision and an update to 2001. J Climate 16:206–223
Jones PD, New M, Parker DE, Martin S, Rigor IG (1999) Surface air temperature and its variations over the last 150 years. Rev Geophys 37:173–199
Jones PD, Briffa KR, Osborn TJ (2003) Changes in the Northern hemisphere annual cycle: implications for paleoclimatology? J Geophys Res 108(D18):4588. doi:10.10.1029/2003JD003695
Klemun M (1994) Aufbau und Organisation des meteorologischen Meßnetzes in Kärnten (19. Jh.). Carinthia II 184/104:97–114
Koinig KA, Kamenik C, Schmidt R, Agusti-Panareda A, Appleby PG, Lami A, Prazakova M, Rose N, Schnell OA, Tessadri R, Thompson R, Psenner R (2002) Environmental changes in an alpine lake (Gossenkollesee, Austria) over the last two centuries—the influence of air temperature on biological parameters. J Paleolimnol 28:147–160
Lang C (1882) Erläuterungen zu 67-jährigen Beobachtungen in München. Bavarian Meteorological Yearbooks 4:29–70
Lauscher F, Roller M, Wacha G, Weiss E, Frenzel J (1959) Witterung und Klima von Linz. ÖGM, 235 pp
Mangini A, Spötl C, Verdes P (2005) Reconstruction of temperature in the Central Alps during the past 2000 years from a δ^{18}O stalagmite record. Earth Planet Sci Lett 235:741–751
Manley G (1974) Central England temperatures: monthly means 1659 to 1973. Q J Royal Meteorol Soc 100:389–405
Maugeri M, Buffoni L, Chlistovsky F (2002) Daily Milan temperature and pressure series (1763–1998): history of the observations and data and metadata recovery. Clim Change 53:101–149
Maurer J, Billwiller Jr, Heß C (1909) Das Klima der Schweiz 1864–1900, vols. 1 and 2, 302, 217 pp
Meier N, Rutishauser T, Pfister C, Wanner H, Luterbacher J (2007) Grape harvest dates as a proxy for Swiss April to August temperature reconstructions back to AD 1480. Geophys Res Lett 34:L20705. doi:10.1029/2007GL031381
Mercalli L, Cat Berro D, Montuschi S, Castellano C, Ratti M, Di Napoli G, Mortara G, Guindani N (2003) Atlante climatico della Valle d'Aosta. Soc Met Subalpina, Torino, 405 pp
Moberg A, Alexandersson H (1997) Homogenization of Swedish temperature data. Part II: homogenized gridded air temperature compared with a subset of global air temperature since 1861. Int J Climatol 17:35–54
Moberg A, Bergström H (1997) Homogenization of Swedish temperature data. Part III: the long temperature records from Stockholm and Uppsala. Int J Climatol 17:667–699
Moberg A, Bergström H, Ruiz Krigsman J, Svanered O (2002) Daily air temperature and pressure series for Stockholm (1756–1998). Clim Change 53:171–212
Moberg A, Alexandersson H, Bergström H, Jones PD (2003) Were southern Swedish temperatures before 1860 as warm as measured? Int J Climatol 23:1495–1521
Moberg A, Tuomenvirta H, Nordli PØ (2005) Recent climatic trends. In: Seppälä H (ed) The physical geography of Fennoscandia. Oxford University Press, Oxford
Müller-Westermeier (1992) Untersuchungen langer deutscher Temperaturreihen. Meteorologische Zeitschrift NF 1:155–171
Nordli PØ (2001) Spring and summer temperatures in south eastern Norway (1749–2000). DNMI reports 01/01 Klima. Norwegian Meteorological Institute, Oslo
Parker DE (1994) Effects of changing exposure of thermometers at land stations. Int J Climatol 14:1–31
Parker DE, Legg TP, Folland CK (1992) A new daily Central England temperature series, 1772–1991. Int J Climatol 12:317–342
Peppler A (1922) Die badische Landeswetterwarte Karlsruhe. Braun'sche Hofbuchdruckerei

Peterson TC, Easterling DR, Karl TR, Groisman P, Auer I, Böhm R, Plummer N, Nicholis N, Torok S, Vincent L, Tuomenvirta H, Salinger J, Förland EJ, Hanssen-Bauer I, Alexandersson H, Jones PD, Parker D (1998) Homogeneity adjustments of in situ climate data: a review. Int J Climatol 18:1493–1517
Pfister C (1975) Agrarkonjunktur und Witterungsverlauf im Westlichen Schweizer Mittelland 1755–1797. Geographica Bernensia G2. Bern
Plantamour E (1863) Du climat de Genève. Henri Georg, Éditeur, Genève
Plantamour E (1876) Nouveles études sur le climat de Genève. Henri Georg, Éditeur, Genève
Polli S (1950) Valori medi ed estremi del clima di Trieste. Istituto Talassografico Pubbl., N. 257, 15 pp
Prettner J (1865) Klima und Witterung von Klagenfurt. Jb d Museums VII
Riggenbach A (1892) Geschichte der meteorologischen Beobachtungen in Basel
Stravisi F (2006) La meteorologia a Trieste. In: La variabilità del clima locale relazionata ai fenomeni di camobiamento climatico globale. Studi regionali a monografici 37:245–288
Trenberth KE, Jones PD (coord. lead authors) (2007) Observations: surface and atmospheric climate change. In: Climate change 2007: the physical science basis. Contribution of WG 1 to the 4th assessment report of the IPCC. Cambridge Univ. Press, Cambridge, UK and New York
Trepinska J (ed) (1997) Wahania klimatu w Krakowie 1792–1995 (Fluctuations of climate in Cracow 1792–1992). Institute of Geograophy of Jagellonian University, Cracow, 198 pp
van Engelen AFV, Nellestijn JW (1995) Monthly, seasonal and annual means of the air temperature in tenths of centigrades in De Bilt, Netherlands, 1706–1995. KNMI (Dutch Met. Service) Report, Climatological Services Division
Venerio G (1851) Osservazioni meteorologiche fatte in Udine nel Friuli pel quarantennio 1803–1842
Vincent C, Le Meur E, Six D, Funk M (2005) Solving the paradox of the end of the Little Ice Age in the Alps. Geophys Res Lett 32:L09706. doi:10.1029/2005GL022552
Vinther BM, Andersen KK, Jones PD, Briffa KR, Cappelen J (2006) Extending Greenland temperature records into the late 18th century. J Geophys Res 111:D11105. doi:10.1029/2005JD006810
von Rudloff H (1967) Die Schwankungen und Pendelungen des Klimas in Europa seit dem Beginn der regelmäßigen Instrumenten-Beobachtungen (1670). Vieweg, Braunschweig, 370 pp
von Schmöger (1835) Resultate der meteorologischen Beobachtungen zu Regensburg von 1774–1834
von Schoder (1882) Fünfzigjährige Ergebnisse der meteorologischen Beobachtungen in Stuttgart. Württembergisches Meteorologisches Jahrbuch 1878–1879
von Gunten L, Heiri O, Bigler C, van Leeuwen J, Casty C, Lotter F, Sturm M (2007) Seasonal temperatures for the past ~400 years reconstructed from diatom and chironomid assemblages in a high-altitude lake (Lej da la Tscheppa, Switzerland). J Paleolimnol 39:283–299. doi:10.1007/s10933-007-9103-4
Vose RS, Schmoyer RL, Steurer PM, Peterson TC, Heim R, Karl TR, Eischeid J (1992) The global historical climatology network: long-term monthly temperature, precipitation, sea level pressure, and station pressure data. ORNL/CDIAC-53, NDP-041. Carbon Dioxide Information Analysis Center. Oak Ridge National Laboratory, Oak Ridge
Wild (1879) Aufstellung der Thermometer zur Bestimmung der wahren Lufttemperatur. In: Repetitorium für meteorologie, T. VI, No. 9, St. Petersburg
Winkler P (2006) Hohenpeißenberg 1781–2006—das älteste Bergobservatorium der Welt. Deutscher Wetterdienst, Offenbach am Main, 174 pp
Zallinger F (1833) Innsbrucker meteorologische Beobachtungen von 50 Jahren. Ferdinandeum, Wagnersche Schriften, 107 pp
Zemp M (2006) Glaciers and climate change. Spatio-temporal analysis of glacier fluctuations in the European Alps after 1850. Schriftenreihe Physische Geographie, Glaziologie und Geomorphodynamik 49. PhD theses series, University of Zurich