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Climatology

Revisiting the early instrumental temperature records of Basel and Geneva

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Abstract

Basel and Geneva have two of the longest meteorological records in Switzerland, covering more than two and a half centuries. The respective monthly temperature series were published over 60 years ago and are part of todays main global temperature data sets. After digitizing the raw sub-daily measurements, we rebuilt the early instrumental part (i.e., before 1864) of the two series at daily resolution using modern methods and additional data sources that were not considered in previous efforts. A comparison with the old series and with other existing recontructions show a generally good agreement only for the last 30 years. Before the 1830s a few systematic differences appear, particularly in summer, suggesting that both new and old versions contain residual inhomogeneities. We use the new series together with other reconstructions to analyze the periods 1791–1807 and 1808–1824, which have been described, respectively, as a warm and cold period in summer in previous studies. Our results suggest that most existing instrumental data sets tend to overestimate summer temperature in Switzerland during the former period, confirming previous results based on proxy records. The overestimation is particularly large (almost 1 °C) in the old Geneva series. On the other hand, we find a probable systematic underestimation of summer temperature in our Basel series. Before the 1780s the agreement between existing reconstructions is poor, so that it is hardly possible to make confident statements about climate variability for the first few decades covered by the series. Nevertheless, the daily resolution of the data allows an insight into individual meteorological events such as cold spells and heat waves.

Keywords: temperature, Switzerland, homogenization, pre-industrial climate, data rescue

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1 Introduction

The 18th and 19th century constituted a period of large climate variability in Central Europe and, at the same time, a period characterized by a rapid development of meteorological instruments and a related increase in the availability of instrumental measurements (Brönnimann et al., 2019b). The lack of centralized networks and standards before the mid-19th century, however, means that considerable resources are necessary to collect and process those measurements.

When a central meteorological office – precursor of the Swiss national weather service MeteoSwiss – was created in 1863 to coordinate the newly formed national measurement network (Hupfer, 2019), the collection and reduction of large amounts of early instrumental measurements was immediately one of the priorities of its director, the astronomer Johann Rudolf Wolf, and resulted in the publication of hundreds of station years of data over the course of the following decades. At the same time, individual scientists from other Swiss institutions also contributed to this effort (e.g., Plantamour, 1876; Strub, 1910), paving the way for the publication of 200-year-long homogenized monthly temperature series for Basel (Bider et al., 1958, hereafter B58) and Geneva (Schüepp, 1958, hereafter S58), the two longest temperature series in Switzerland and among the longest worldwide. In the early 2000s MeteoSwiss undertook a new homogenization of the series (Begert et al., 2005), but the data before 1864 were simply reduced to the modern-day station location.

Even though several other long temperature series for Central Europe reaching back to the 18th century have been published in the past (see Lundstad et al., 2023, for a recent overview), only two of them (Hohenpeissenberg and Prague) are available with daily resolution in public data sets (e.g., Klein Tank et al., 2002). New efforts to collect and digitize Swiss early instrumental meteorological records took place during the last decade at the University of Bern, resulting in the publication of several millions data points (Brugnara et al., 2020; Brönnimann, 2022) as well as the digitization of the original documents (Pfister et al., 2019). This allowed us to create two new long daily temperature series for Bern and Zurich (Brugnara et al., 2022b).

In the present work we re-elaborate the data from Basel and Geneva to produce two new temperature series at daily resolution for the early instrumental period, taking advantage of the many additional Swiss records that are now available. We then compare the new series with existing monthly temperature reconstructions for Switzerland and try to describe the climate variability in the region between mid-18th and mid-19th century.

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Previous work has shown that the early 19th century was characterized by a very cold period, which culminated with the Year Without a Summer 1816 (Luterbacher and Pfister, 2015). According to some authors (e.g., Casty et al., 2005; Böhm et al., 2010), this was preceded by a period of unusually warm summer seasons, with the hot summer of 1807 as its highlight. The warm period, however, is not seen in proxy-based reconstructions (e.g., in tree rings), raising the question of whether we can trust early instrumental measurements (Frank et al., 2007). In this work, we will also try to answer this question by quantifying possible biases in the most commonly used instrumental data sets and dig into their causes – with a focus on Switzerland.

The paper is structured as follows: in Section 2 we describe the data sources and briefly summarize the history of the early instrumental meteorological measurements in Basel and Geneva; in Section 3 we explain the methods for the calculation of daily means, the homogenization, the merging of the different segments, and the data filling, and we compare them with the methods of B58 and S58; in Section 4 we analyze the new Basel and Geneva series, compare them with the old MeteoSwiss versions as well as with other temperature reconstructions, and use them to illustrate two case studies; finally, we summarize our conclusions in Section 5.

2 Data

The individual records that we used to build the daily temperature series for Basel and Geneva are briefly described in this section. For consistency we only used sub-daily instantaneuos measurements, even though regular daily maximum and minimum temperature measurements are available from the late 1820s onward. The data were digitized through single manual keying performed by undergraduate students at the University of Bern. The quality control procedure included visual inspections and automatic tests provided in the R package dataresqc (Brunet et al., 2020). Many of the resulting suspicious values were keying errors and could be corrected, the others (about 500 values or 0.15 % of the total number of measurements) were excluded from the calculation of the daily and monthly means. The raw measurements and the quality flags are available in Brugnara (2022b).

Metadata availability is variable but almost always includes the exact location (i.e., the address) and the observing times, although the latter can be rather uncertain. In the early years at most three measurements per day were taken, then increasing to five or more by the mid-19th century. As for most manual meteorological measurements of any period, nighttime is strongly underrepresented. Information on the instruments and their exposure is usually limited, if not missing altogether. However, instrumental changes can sometimes be inferred from the reporting resolution or from data gaps. Early instrumental temperature measurements were typically performed outside a north-facing window, if possible (see Böhm et al., 2010). In Switzerland (with the exception of Geneva, which joined the Swiss Confederation only in 1814) the "universal" spirit thermometer invented by Jacques-Barthélemy Micheli du Crest was the most popular thermometer among observers between the 1750s and the 1770s, with some employing it until the early 19th century. Mercury thermometers (initially with Réamur scale) became dominant only from the 1780s onward (see also Brugnara et al., 2020). More details on the metadata of each record are given in Brönnimann (2022).

We used 50 additional records from Brugnara (2022b) as reference series for the homogenization. To evaluate the homogenized series, we compared them with those available from MeteoSwiss (based on B58 and S58) and with several other temperature reconstructions for Switzerland based on instrumental and/or proxy records (Table 1). In particular, we used the global paleo-reanalysis EKF400 (Valler et al., 2022), in which both instrumental and proxy records are assimilated into an ensemble of general circulation model simulations to provide physically consistent fields at monthly resolution as well as their uncertainty. We also used modern (1981–2010) sub-hourly temperature data from the MeteoSwiss stations of Basel-Binningen and Geneva-Cointrin to correct the early instrumental daily means, which are generally warm-biased due to the lack of nighttime observations.

2.1 Basel

Basel is located at the northwestern edge of Switzerland (Figure 1), at the border with Germany and France. For centuries it has been an important cultural hub and is home to Switzerland's oldest university, of which most authors of the early meteorological records were influential members. In fact, the early instrumental temperature series of Basel is mainly built on the records by Johann Jakob d'Annone (1728–1804) and Peter Merian (1795–1883), both multiple times rectors of the University. Their records contribute nearly 80 % of the series (Figure 2).

Merian's observations cover 49 years between 1826–1874, although we use them only until 1863. Beside the instruments in his different apartments (he moved twice, in 1833 and 1837; see Figure 2), Merian set up several auxiliary stations that he used to check and complete his own measurements (see also Brönnimann and Brugnara, 2021). Among the observers appointed by Merian for these auxiliary stations are Johann Jakob Fürstenberger (Merian's stepbrother) between 1826–1829, Andreas Schneider between 1832–1855, and Franz Kaufmann between 1856–1874. Strub (1910) also mentions a record by lithographer Adolf Huber starting in 1853 that was used as additional reference. Most of these records were

Table 1: Temperature reconstructions used in this study

Name	Region	Type	Reference
Basel new	Basel	Instrumental	This work
Basel MeteoSwiss	Basel	Instrumental	BIDER et al. (1958)
Geneva new	Geneva	Instrumental	This work
Geneva MeteoSwiss	Geneva	Instrumental	SCHÜEPP (1958)
Bern	Bern	Instrumental	BRUGNARA et al. (2022b)
HISTALP	Gridded	Instrumental	BÖHM et al. (2010)
BEST	Gridded	Instrumental	ROHDE and HAUSFATHER (2020)
Casty	Gridded	Instrumental	CASTY et al. (2005)
EKF400v2	Gridded	Mixed	VALLER et al. (2022)
Luterbacher	Gridded	Tree rings	LUTERBACHER et al. (2016)
Trachsel	Switzerland	Multiproxy (mean)	TRACHSEL et al. (2012)
Wetter	Northern Switzerland	Grape harvest dates	WETTER and PFISTER (2013)
Pfister	Switzerland	Documentary	PFISTER et al. (1994)

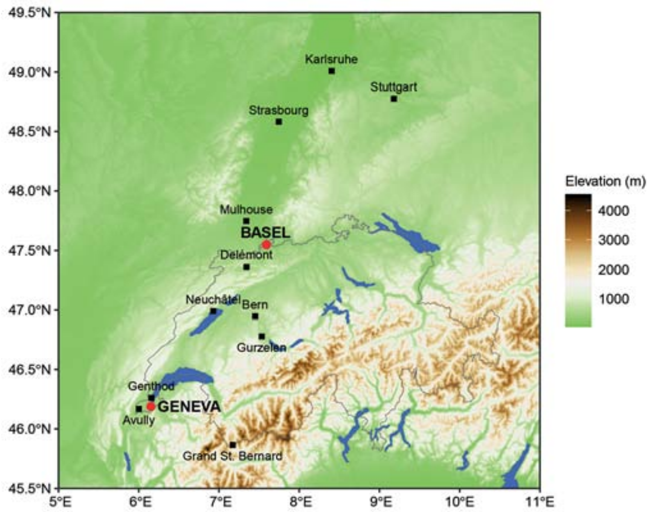

Figure 1: Map of the western Alpine region with topography, political borders of modern-day Switzerland, and position of the locations mentioned in the text. Digital Elevation Model from JARVIS et al. (2008).

not available to us if not for short segments (see Figure 2). We did, however, digitize all the observations by FÜRSTENBERGER, which were initially more regular and complete than those by MERIAN. We used them as our main source between April 1826 and December 1827. The data used by B58 has probably also a large contribution from FÜRSTENBERGER's record in that period. Even if we did not explicitly use SCHNEIDER's and KAUFMANN's records to build our series (we do use them as reference series), they contributed in minor part to MERIAN's record as they were used by MERIAN himself to fill gaps in his measurements.

The 50-year record by D'ANNONE (BRÖNNIMANN and BRUGNARA, 2020) has occasional gaps related to brief stays (up to two months) in the outskirts of Basel. During these periods D'ANNONE brought the instruments with him and continued to measure. Unlike B58, we removed those measurements from the record on account of the inhomogeneity that they would introduce, or replaced some of them with homogenized measurements made by D'ANNONE's young colleague DANIEL WOLLEB (1757–1822). For this reason the new series has 68 missing days between 1760–1765. It is also worth mentioning that the first five months of 1755 were actually measured at another location by FRIEDRICH ZWINGER (1707–1776), the dean of the medical Faculty, and then copied by D'ANNONE in his register.

Unfortunately, a 21-year gap (September 1804 to March 1826) remains between the records of D'ANNONE and MERIAN. We could fill part of this gap with two newly digitized records by DANIEL HUBER (1768–1829), the director of the University library, and J. RUDOLF BURCKHARDT. HUBER's record is very incomplete and follows irregular observing times, making it virtually unusable for scientists preceding the Computer Age if not for small segments (see also BRUGNARA and BRÖNNIMANN, 2022). The main difference between the old and new Basel series in terms of data sources is, therefore, the integration of HUBER's record in the latter. However, given the record's incompleteness, we also use data from the nearby locations of Delémont and Mulhouse (BRUGNARA and BRÖNNIMANN, 2022,). Note that B58 used some data from DANIEL HUBER to complete the year 1826, together with data from a station located on the Middle Bridge on the Rhine. These data were taken from yearbooks published by the central meteorological office (SNG, 1867) and are based on a single daily measurement at 9:00 local time (LT).

2.2 Geneva

Geneva lies in southwestern Switzerland, next to the border with France (Figure 1). It is the birthplace of many prominent scientists who made significant contributions to the field of meteorology and, in particular, to the development of meteorological instruments – such as JACQUES-BARTHÉLEMY MICHELI DU CREST, JEAN-ANDRÉ DELUC, and HORACE BÉNÉDICT DE SAUSSURE.

The early instrumental temperature series of Geneva can be divided into two parts: the first part (starting

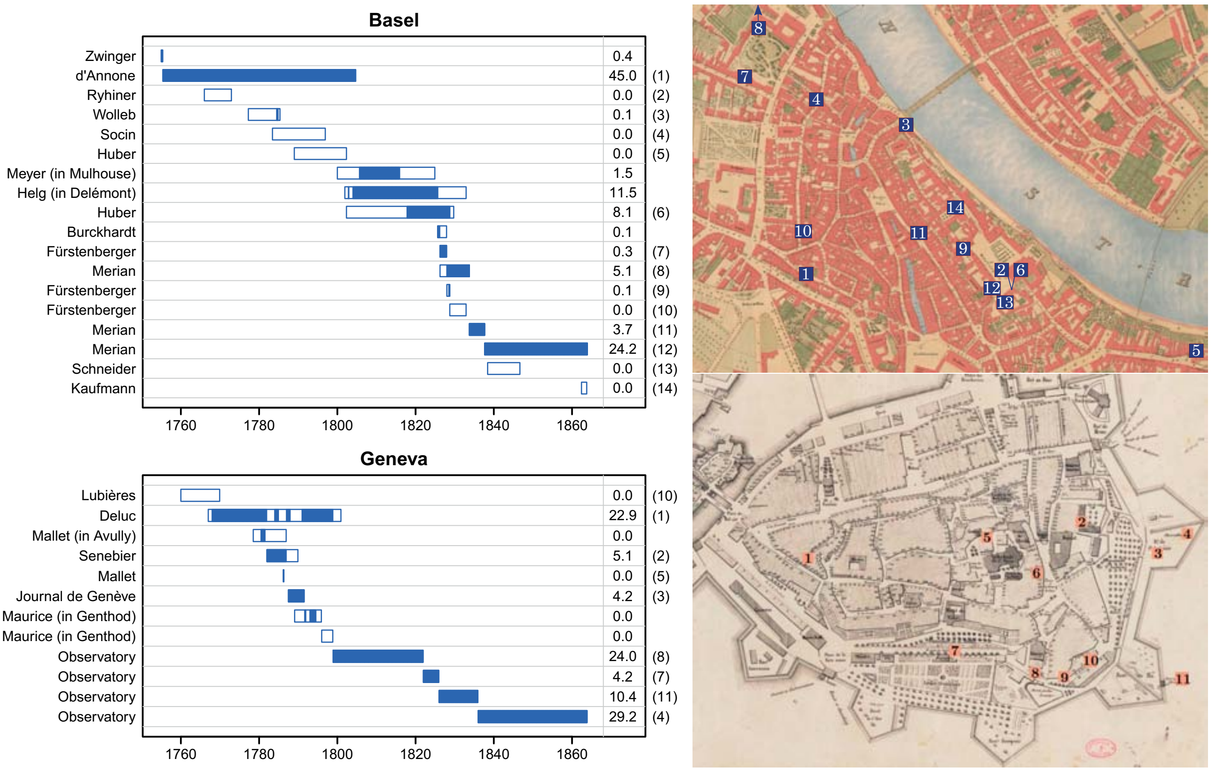

Figure 2: Left panels: Records used to build the early instrumental temperature series of Basel and Geneva (each row indicates a different location). The filled fractions represent the data that contributed to the merged series. The second column indicates the contribution of each record to the merged series in percentage. Right panels: Nineteenth century maps of Basel (top) and Geneva (bottom) with early instrumental measurement sites (adapted from Brönnimann, 2022). The numbers in parenthesis link the rows in the left panels to the respective map.

in 1768) is a combination of numerous records kept independently by individual scientists; the second part begins in December 1798 (year in which Geneva was annexed to revolutionary France) with the institution of an “official” meteorological observatory run by personnel of the Academy of Geneva (the future University). Generally speaking, the measurements at the observatory are of better quality than those made in the 18th century (more frequent and reliable observing times, more accurate instruments, etc.). However, there were multiple relocations (in 1822, 1826, and 1836) affecting their homogenity (Figure 2).

By far the longest and most relevant record in the 18th century is the one by Guillaume-Antoine Deluc (1729–1812; brother of Jean-André), which covers 33 years between 1768–1800. Even though the record is rather complete (only 1.3 % of days have no observations), it is of limited quality because it is based on only one daily measurement. Therefore, we integrated it with shorter records (as did B58), in particular those by Jean Senebier (who measured for the Palatine Society; see Pappert et al., 2021) and by an unknown observer (the data were published on a local newspaper, the *Journal de Genève*). Nevertheless, Deluc’s record remains the main data source and our only one before 1782. We also used two records from the nearby villages of Avully and Genthod (home to the family estates of Genevan scientists Jacques-André Mallet and Frédéric-Guillaume Maurice, respectively) to fill a few short gaps in Deluc’s record. An additional record by Charles de Lubières, starting in 1760, was deemed of insufficient quality to be used. Note that additional data exist for 1770–1789 (by Lubières) and 1774–1787 (by Marc-Auguste Pictet); they are not included in Figure 2 because not available to us in digital form (Pictet’s measurement sites are indicated by the numbers 6 and 9 in the right panel of Figure 2).

S58 extended the series back to 1753 using data from Neuchâtel and Bern, both located over 100 km from Geneva. Given the large distance we considered those data unsuitable to build a daily temperature series for Geneva.

3 Methods

3.1 Calculation of daily means

The data processing is identical to the one followed in Brugnara et al. (2022b). After the sub-daily measurements went through statistical and visual quality checks (Brunet et al., 2020) and the times were converted to UTC, we calculated daily means using a multiple linear regression (MLR) model trained on modern-day data at 10-minute resolution:

$$T_m = a_0 + \sum_{i=1}^{n+2} a_i x_i + \epsilon \tag{3.1}$$

where the predictors x_i are the elements of the vector

$$\vec{x} = \left[\sin\left(\frac{2\pi j}{366}\right), \cos\left(\frac{2\pi j}{366}\right), T_1, \ldots, T_n\right], \qquad (3.2)$$

T_m is the mean daily temperature anomaly (i.e., the predictand), j is the Julian day, n is the number of measurements, T_i are the differences of the 10-minute values at the observing times from the daily climatology on the analyzed day, a_i are the regression parameters, and ϵ is the residual error. The daily climatology is smoothed through a trigonometric fitting (see Brugnara et al., 2022b, for more detail). The first two elements of $\vec{x}$ are added to capture the seasonal variability of the diurnal cycle. Different regression parameters are calculated for each existing combination of day of year and observing times.

By applying the resulting parameters to the early instrumental measurements (from which the modern-day daily climatology is also subtracted) we obtained the daily means. We then calculated monthly means from the daily means according to the rules by WMO (2008).

3.2 Standard errors

We estimated standard errors for the daily means based on the characteristics of the raw measurements (Brugnara et al., 2022b). We considered five types of error related to: 1) instrumental resolution (e_1); 2) number of measurements on a day (e_2); 3) time uncertainty (e_3); 4) exposure (e_4); and 5) climate (e_5). The total standard error for daily means is then given by:

$$E_d = \sqrt{\sum_{i=1}^{5} e_i^2}. \qquad (3.3)$$

The standard error for monthly means is:

$$E_m = \frac{1}{N}\sqrt{\sum_{i=1}^{N} E_{d(i)}^2}, \qquad (3.4)$$

where N is the number of valid daily means in the month.

The instrumental resolution (used to derive e_1) was either one degree or half a degree in nearly all records, even though the readings were commonly performed at a higher resolution through visual extrapolation. One degree translates to 1.1 or 1.25 °C, depending on the employed scale (Micheli du Crest or Réaumur, respectively). The only exception is at the Observatory in Geneva from 1826 onward, when the Celsius scale was adopted at a resolution of 0.25 °C.

The error e_2 related to the number of measurements on a day is particularly large when only one measurement on a day is available. It is given by the standard deviation of ϵ (Eq. 3.1).

The time uncertainty e_3 arises from the lack of reliable metadata about the exact times when the measurements were made. It is considered to be 90 minutes for those records in which the observing times are educated guesses, 30 minutes otherwise (15 minutes after 1848, year of the introduction of a common national time).

For the exposure error e_4 – related to the impact of radiation on the measurements – we use a periodic function with maximum in summer and minimum in winter, consistent with the available results in the literature (see Brugnara et al., 2022b):

$$e_4 = \frac{1}{\sqrt{n}}\left(a + b \sin\frac{2\pi(j-81)}{N}\right) \qquad (3.5)$$

where $a = 0.8\,°\mathrm{C}$ (average error), $b = 0.4\,°\mathrm{C}$ (amplitude), n is the number of observations on a day, and N is the number of days in the year.

The climate error e_5 affects only the records of Delémont and Avully, and takes into account differences in the local climate with respect to Basel and Geneva, respectively, as estimated from the MeteoSwiss stations of Delémont and La Plaine. Since we could not find suitable modern-day data for Mulhouse, the climate error is not applied to that record.

3.3 Homogenization, merging, and gap filling

For the homogenization process we used the same reference series as in Brugnara et al. (2022b): they all consist of raw data series from Switzerland (except for one in France) and guarantee full independence from existing homogenized data sets. The reference series were split into homogeneous segments beforehand. We detected the inhomogeneities (breakpoints) visually through a Craddock test (Craddock, 1979), taking into account metadata. The detected breakpoints in the Basel and Geneva records are listed in Table 2. In addition, the beginning and the end of each record were also considered breakpoints (including relocations as represented in Figure 2).

The homogenization was performed backward starting from the most recent record. The most recent homogeneous sub-period in that record was left unchanged, the rest of the data – including all previous records – was adjusted sequentially. Monthly adjustments estimated from the available reference series were transformed to daily adjustments using a trigonometric fit (see also Brugnara et al., 2022b).

After homogenization, the single records were merged together to form a long daily series. Overlapping records were merged according to a subjective priority ranking: as a general rule, the record with the lowest error was preferred, although knowledge from metadata and the observer's location influenced the ranking. Figure 2 shows which fraction of each record was used to build the merged series. Note that more than one record can contribute to a given monthly mean, because gaps in the record with the highest priority were filled with lower-priority records. On the other hand, a daily mean and its error were always calculated from one and the same record.

Table 2: Breakpoints detected with the Craddock test

Series	Record	Date	Cause
Basel	D'ANNONE	31.03.1770	Observing times (B58)
	D'ANNONE	24.02.1779	Observing times (B58)
	HUBER	20.09.1790	Thermometer relocation
	D'ANNONE	31.12.1797	Unknown
	HUBER	31.10.1798	Unknown
	HUBER	04.02.1806	Thermometer relocation
	Delémont	31.05.1808	Unknown (data gap)
	HUBER	18.08.1811	Thermometer relocation
	Delémont	31.05.1818	Unknown (data gap)
	Mulhouse	31.12.1818	Unknown
	HUBER	16.08.1823	Thermometer relocation
	Delémont	30.09.1824	Unknown
	HUBER	16.08.1826	Thermometer relocation
	MERIAN	31.12.1849	Unknown
Geneva	DELUC	30.09.1775	Unknown
	DELUC	29.06.1781	Unknown (data gap)
	SENEBIER	31.12.1783	Unknown
	DELUC	31.12.1786	Unknown
	DELUC	16.03.1794	Unknown (data gap)
	Observatory	31.12.1806	Unknown
	Observatory	31.12.1811	Unknown
	Observatory	31.12.1847	Unknown

Finally, remaining isolated data gaps in the monthly series (four months in each series) were reconstructed from nearby stations using a weighted average, where the squared Pearson correlation coefficients are the weights (ALEXANDERSSON and MOBERG, 1997). Residual gaps in the daily series (78 days for Basel, 116 days for Geneva) were not filled.

3.4 MeteoSwiss series

It is worth describing here the adjustments that B58 and S58 applied to their monthly homogenized series in order to better understand the differences with our series. One general difference that applies to all records arises from the calculation of daily means: B58 and S58 reduced the daily means using the climatological diurnal cycle from the city center, while we had to resort to the sub-hourly data from the MeteoSwiss stations in Binningen (ca. 2 km from the center of Basel) and Cointrin airport (ca. 5 km from the center of Geneva) – both located in more rural settings – to train our MLR model. A comparison between the urban and rural diurnal cycle for Geneva is provided in BRUGNARA et al. (2022a), showing a slightly larger diurnal range and a faster cooling in the evening at the rural station in summer. This might result in a small positive bias in our series when an evening measurement was performed.

3.4.1 Basel

MERIAN's record was carefully elaborated and homogenized by STRUB (1910), who constitutes the data source of B58 from April 1826 onward. Methodological differences between our work and B58 are particularly relevant for the period before 1826. B58 reconstructed the period 1805–1825 by taking the average of seven previously adjusted reference series: Stuttgart, Karlsruhe, Strasbourg, Mulhouse, Delémont, Bern, and Geneva. The first three, all located to the north of Basel (see Figure 1), are the most important because they are the only ones that were considered homogeneous and provided a long overlap with MERIAN's record, so that they could be used to adjust all other reference series.

To homogenize the record by D'ANNONE (1755–1804) B58 applied several corrections, including a radiative bias correction proportional to the number of clear sky days in a month. They also singled out and corrected an apparent positive temperature drift of 0.6 °C in 15 years between 1790–1804, for which they speculated a gradual change in the zero of the thermometer as the cause. Eighteen century thermometers were indeed often affected by drifts caused by the gradual compression of the glass tube; however, this usually happened in the first few years after the thermometer was built and affected mainly mercury thermometers (KNOWLES MIDDLETON, 1966; WINKLER, 2009). D'ANNONE used a spirit thermometer and there is no real indication that he acquired a new thermometer around 1790. While we did detect an inhomogeneity in 1797, we treated it as a standard step-like change.

B58 used the daily means of D'ANNONE published by the national weather service in the late 19th century. They were supposedly converted from the Micheli du Crest to the Celsius scale following a table published in VAN SWINDEN (1778), while we used the equations from BRUGNARA et al. (2020). This results in differences that reach a maximum of 0.5 K at around 18 °C (Figure 3). By following VAN SWINDEN (1778) we actually obtained a maximum difference of 0.2 K for values larger than 0 °C, therefore we cannot fully explain the observed differences with the information at our disposal. An additional contribution (not considered in Figure 3) might come from the fact that we converted the data before calculating the daily means, while the daily means used by B58 were arguably calculated in Micheli du Crest units and then converted (note that the conversion formula is not linear). In extreme cases this could add another 0.1 K to the differences.

3.4.2 Geneva

The description of the Geneva series was not published in a peer-review journal and is less detailed than that of Basel. For the period 1826–1863, S58 probably started from the monthly means published by PLANTAMOUR (1876) but then combined it with an unpublished version of the same series that was developed in the same year (1958) by ERNST AMBÜHL in Bern. To adjust the period 1798–1825 he used the previously homogenized Basel series and again combined the results with those of AMBÜHL, who used the series of Grand St. Bernard as

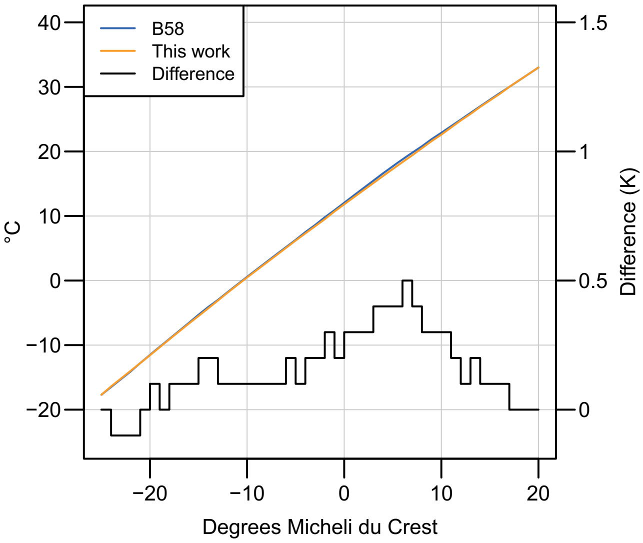

Figure 3: Differences between the conversion formulas from the Micheli di Crest to the Celsius scales used for the MeteoSwiss version of the Basel series and for ours, including the effect of rounding to the nearest 0.1 °C.

reference. Critically, S58 did not apply any correction for the station relocation of 1836.

The period 1768–1798 was created from the average of several of the records mentioned in Section 2.2 plus the reduced records of Bern and Gurzelen (the latter with a lower weight). There is no mention of further corrections, aside from the reduction of the daily averages to the true daily means. Judging from the description of the methods alone, it is to be expected that the quality of the MeteoSwiss series of Geneva is inferior to that of Basel, particularly in the 18th century.

4 Results and discussion

4.1 Comparison with existing reconstructions

Early instrumental measurements typically require negative adjustments to correct for radiative biases, poor ventilation, and heat exchange with buildings (Böhm et al., 2010). This is predominantly the case for the series of Basel and Geneva (Figure 4). Particularly large adjustments were necessary for Deluc's record in Geneva, explained by the exposure of the thermometer (see Brugnara et al., 2022a). The record by d'Annone in Basel, on the other hand, required comparatively small corrections. Note, however, that we reduced the data to the latest early instrumental measurements, which probably still require substantial adjustments to be comparable with modern-day data.

We show a visual comparison of the homogenized annual and seasonal series with those by MeteoSwiss in Figure 5 for Basel and Figure 6 for Geneva. In addition, we also plotted the temperature (ensemble mean) from the nearest grid point in EKF400 – which can be thought as a best estimate based on the current scientific knowledge – and its confidence range given by the ensemble spread.

For both series the agreement between the two versions is highest in winter and lowest in summer, which is expected given the much lower potential for errors in winter climate. There is very good agreement in all seasons from 1828 onward in Basel and from 1836 in Geneva: during these periods, the average absolute difference with the MeteoSwiss series in the monthly mean anomalies is of only 0.2 K for both cities, with a Pearson's correlation coefficient above 0.98.

For Basel, the substantial differences in methodology and data sources used to build the period 1805–1827 led inevitably to differences between the two versions before 1827. The annual means, however, remain remarkably similar until the early 1800s, with the exception of a few years (in particular 1825–1827, which are colder in our series). The largest differences are found in summer, when our series has systematically lower anomalies. This systematic difference persists for the rest of the series and becomes evident also in spring and in the annual means before 1800. EKF400 remains mostly inbetween the two instrumental series but agrees better with our series in the early years and with the MeteoSwiss series later on, particularly in summer.

The most recent relevant divergence with the MeteoSwiss series of Geneva occurs for the station relocation at the beginning of 1836, which was not corrected by S58. This introduces a warm bias of ca. 0.5 K (annual average, see also Figure 4) in the MeteoSwiss series before that year. The bias is temporarily reduced between 1806–1811 due to another inhomogeneity with opposite sign not corrected by S58, then it grows again until a peak is reached in the 1790s. At that point, the MeteoSwiss series is about 0.8 K warmer than both our series and EKF400 (Figure 6). Before ca. 1785 the difference between the two instrumental series becomes small (except in summer); however, both are warmer than EKF400.

In summer, a large fraction of the MeteoSwiss series of Geneva lies outside the ensemble spread of EKF400, further suggesting a warm bias. The same is true for Basel before 1780. On the other hand, our Basel series is probably too cold at times. To explore this further, we calculated difference series between our two series and several other reconstructions for summer (Figure 7, left panels).

Between 1780–1820 our Basel series is indeed colder than any other summer reconstruction. The most likely explanation is the large number of inhomogeneities that had to be corrected between 1806–1826, leaving insufficient homogeneous data for the calculation of the adjustments. It is hard to tell, however, how large this cold bias actually is: the series by MeteoSwiss (and the instrumental reconstructions that depend on it) might well be too warm. As already noted in S58, 1826 is a particularly unfortunate year for Swiss climatologists because all the main Swiss temperature series (i.e., Basel, Bern,

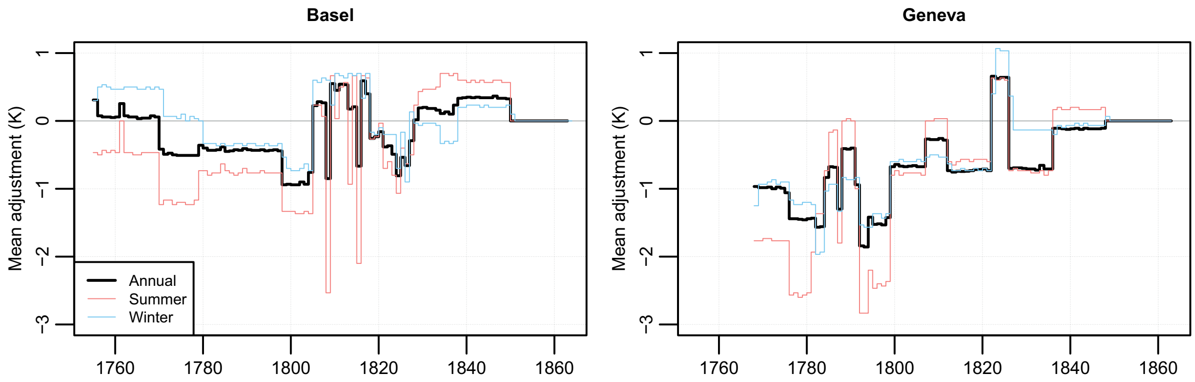

Figure 4: Time evolution of annual and seasonal mean adjustments in the merged series.

Geneva, Zurich) suffer from a station relocation around that time. Even the newly digitized record by Daniel Huber in Basel is affected by a thermometer relocation in 1826.

Our summer temperature series for Geneva compares better with the other reconstructions and in particular with proxy-based reconstructions. The MeteoSwiss series is warmer than any other reconstruction before 1800. Note again that most of the instrumental series (except for Bern) are probably not independent from the MeteoSwiss series, which might explain why they are generally warmer than the proxy reconstructions. In fact, few of the reconstructions are fully independent from each other and a good agreement between some of them does not guarantee that they represent a true signal. Before 1780 the spread among the different reconstructions increases to a level that makes the evaluation of the quality of any of the series hardly possible, at least for summer.

In Figure 7 we also show, for comparison, the difference series for winter (right panels). Clearly, the homogenization of winter temperatures is less problematic because the required adjustments are usually smaller (see Figure 4). In fact, the agreement between our series and the MeteoSwiss series is generally good over the whole period, even though differences of more than 1 K are possible for individual seasons. One notable exception is the period 1780–1800 for Geneva, which probably has a cold bias in our series. Again, the likely explanation is the large fragmentation of sources and the frequent inhomogeneities during that period.

4.2 Uncertainties

The main contributor to the standard errors of daily means in the Basel series is the exposure error (Figure 8), which we assumed to be identical for all records. During the period 1805–1820, however, the lack of measurements made in Basel introduces an additional climate error. Moreover, the record by Huber has sometime only one or two measurements on a day, implying an occasionally large e_2 in the 1820s.

In Geneva (Figure 9), Deluc also measured only once per day, causing the errors to be particularly large during the first 14 years and in the 1790s. Note that the summertime errors are slightly lower during the latter period because the observing time changed from 7:00 to 8:00 LT.

The errors have an obvious seasonal cycle affecting most of the components, with much larger errors in summer with respect to winter in the total errors. The reasons are the higher diurnal temperature range (affecting e_2 and e_3) and the higher solar radiation (affecting e_4). The only exception is e_5, which has larger values in winter due to a larger spatial variability of the daily mean temperature in that season.

The majority of the errors in both series are between 1 and 2 °C. For Basel only 0.2 % is larger than 2 °C, while for Geneva it is 7.6 %. The standard error of the monthly means is on average 0.2 °C and is never larger than 0.5 °C (not shown).

4.3 Climate variability between late 18th and early 19th century

The largest climatic anomaly in the analyzed period is certainly the long sequence of cold summers between 1808–1824 (all but two below the 1831–1860 average), which has been attributed mainly to volcanic activity (e.g., Wagner and Zorita, 2005; Brönnimann et al., 2019a; Schurer et al., 2019). Given the magnitude of the anomaly, this period represents an ideal testbed for temperature reconstructions.

In Table 3 we show the mean summer temperature anomaly for the period 1808–1824 and for the coldest year (1816) for each reconstruction, as well as the mean summer temperature index by Pfister et al. (1994) based on documentary evidence. Despite the large range given by the different reconstructions, all agree on a negative anomaly. There is little doubt that 1816 was indeed the coldest summer in Switzerland since the mid 18th century.

The decade preceding the cold spell has sometimes been described as a period with rather warm summer

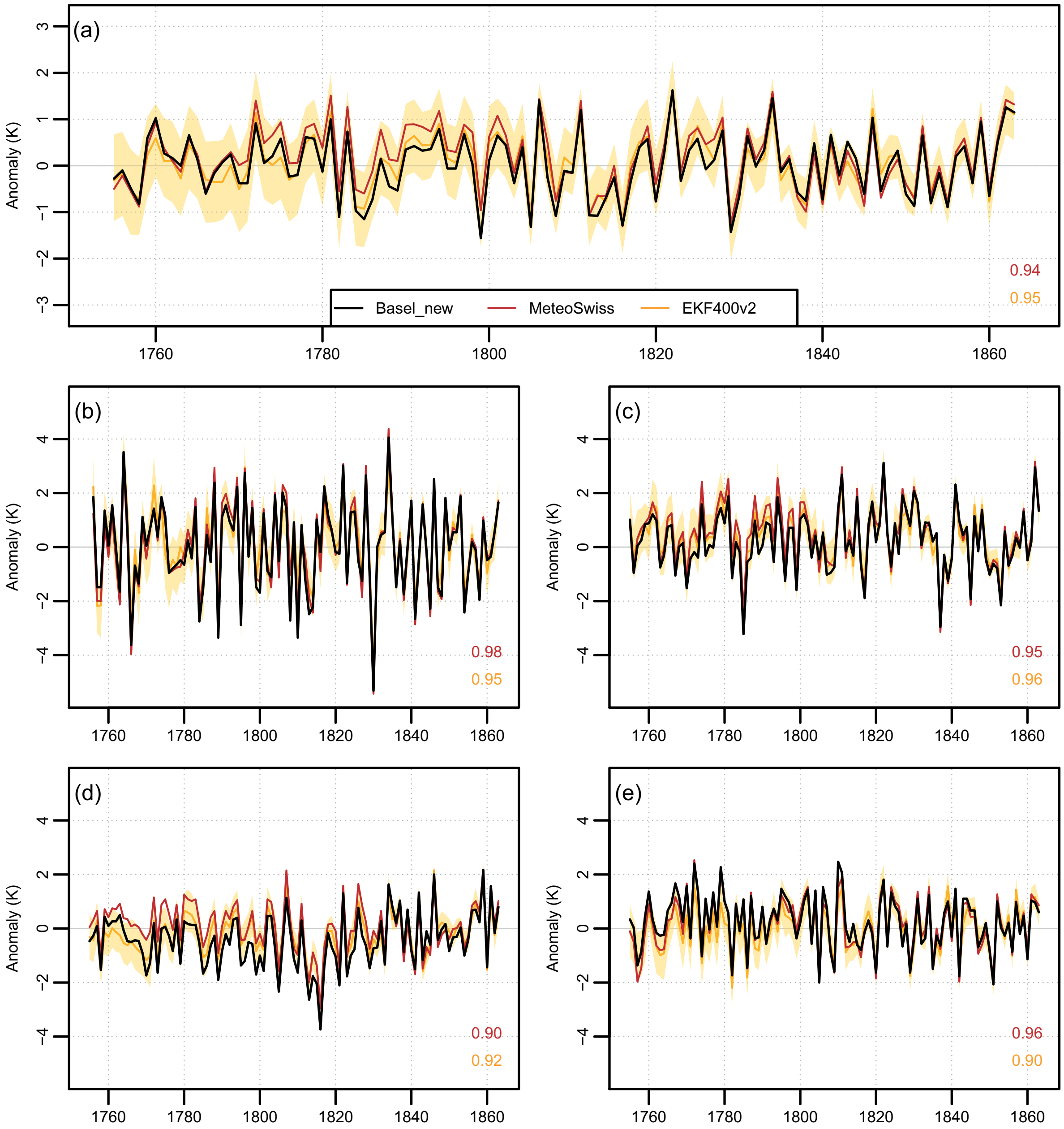

Figure 5: (a) Annual temperature series for Basel and the nearest grid point of the EKF400 data set, expressed as anomalies with respect to the period 1831–1860. The shading represents the ensemble spread in EKF400. The same is also shown for (b) December–February, (c) March–April, (d) June–August, and (e) September–November. Pearson correlation coefficients with the new Basel series are also given.

seasons in Central Europe, possibly warmer than during any similar period of the 19th century (e.g., Casty et al., 2005; Dobrovolný et al., 2010). To our best knowledge, a possible cause has not been suggested. The spread among the reconstructions shown in Table 3 does not actually allow a confident statement even about the sign of the anomaly for the period 1791–1807 (chosen to have the same length of the cold period). While there might have been a small positive anomaly, it was probably within the range of the expected noise and similar to the anomaly measured in winter (ca. 0.3 K), for which the agreement among instrumental data sets is much better than for summer (Table 3). Nevertheless, the warmest summer in that period (1807) was about 2 K above the 1831–1860 average and possibly the warmest summer of the analyzed period, although well below the anomalies of modern-day extreme summers (see e.g., Brugnara et al., 2022b).

A large positive summer temperature anomaly at the turn of the century would be at odd with numerous temperature proxies. For instance, while Swiss glaciers were in a shrinking phase in the late 18th century, the trend slowed down to near zero already in the 1790s, before a growth phase started in the 1810s (Brönnimann et al., 2019a). Moreover, a recent reconstruction of snow cover duration in the southern European Alps based on ring-

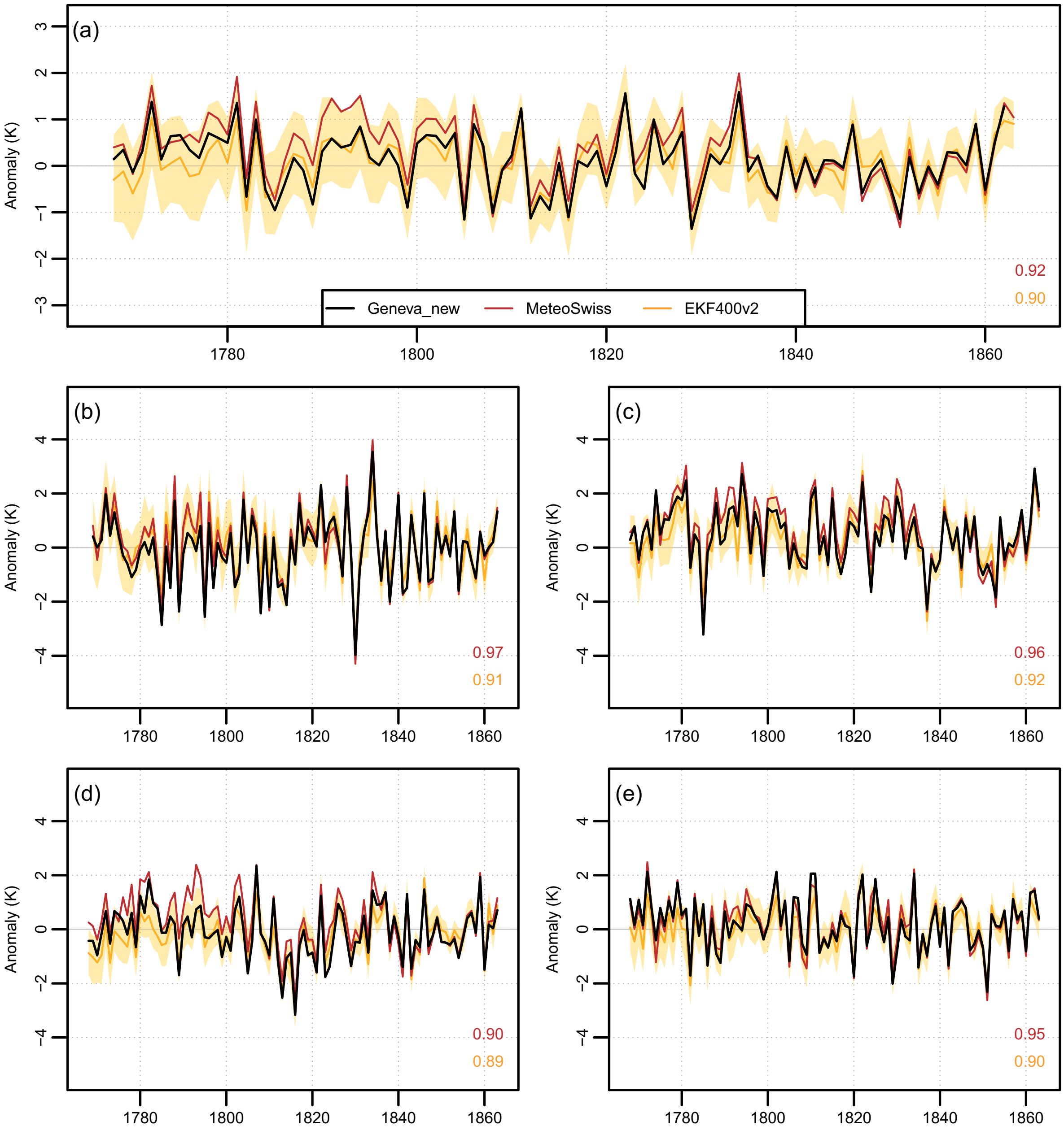

Figure 6: (a) Annual temperature series for Geneva and the nearest grid point of the EKF400 data set, expressed as anomalies with respect to the period 1831–1860. The shading represents the ensemble spread in EKF400. The same is also shown for (b) December–February, (c) March–April, (d) June–August, and (e) September–November. Pearson correlation coefficients with the new Geneva series are also given.

width series from a prostrate shrub found that the period 1780–1800 had the longest average duration of any 20-year period in the last six centuries (Carrer et al., 2023). Reconstructed weather types for Central Europe (Schwander et al., 2017) show a lower frequency of favorable circulation patterns for heat waves in the 1790s and 1800s with respect to the 1780s and, finally, there is weak documentary evidence for hot summers as shown by the index by Pfister et al. (1994).

It appears therefore unlikely that the period at the turn of the century could have had a summer mean temperature well above the 1831–1860 average in Switzerland, as suggested by the MeteoSwiss series of Geneva and other data sets based on that series. At the same time, a large negative anomaly as given by our Basel series appears equally unlikely.

4.4 Case studies: the extreme winters of 1830 and 1834

Aside from the summer of 1816, which was described in detail in previous studies (e.g., Brugnara et al., 2015; Brönnimann, 2020), the most outstanding seasonal anomalies in the analyzed period are the extremely cold winter of 1829/30 and the extremely mild winter of 1833/34 (Table 3), which are also found in

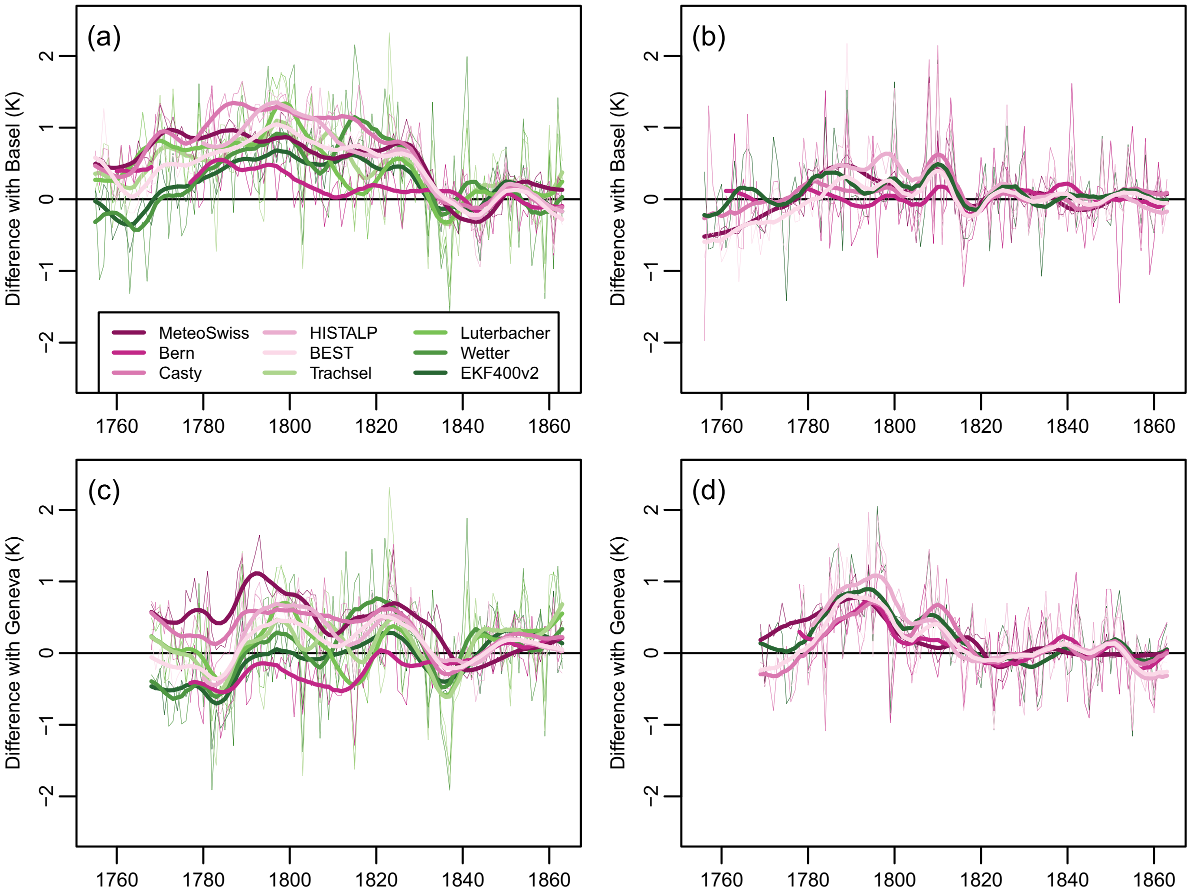

Figure 7: Difference between the early instrumental mean summer (a, c) and winter (b, d) temperature anomalies of Basel (a, b) and Geneva (c, d) and various other temperature reconstructions for various locations in Switzerland (or for the nearest grid point in the case of gridded data sets), including the Basel and Geneva instrumental series by MeteoSwiss. The smoothed lines are produced using a Gaussian filter with σ = 3 years. The reference period used to calculate the anomalies is 1831–1860.

Table 3: Seasonal temperature anomalies with respect to 1831–1860 in various temperature reconstructions for northwestern Switzerland, for relevant periods and extreme years (for winter, the year refers to when the season ends). Units are K except for Pfister (dimensionless), which is not considered for the average and standard deviation

		Winter (DJF)				Summer (JJA)			
Data set	Type	1791–1807	1808–1824	1830	1834	1791–1807	1808–1824	1807	1816
Basel new	Instr.	0.4	−0.2	−5.3	4.0	−0.6	−1.2	1.1	−3.7
Basel MeteoSwiss	Instr.	0.6	0.0	−5.4	4.4	0.2	−0.6	2.1	−3.0
Geneva new	Instr.	−0.1	−0.2	−4.0	3.5	0.1	−0.9	2.3	−3.2
Geneva MeteoSwiss	Instr.	0.4	−0.1	−4.3	4.0	1.0	−0.4	2.4	−2.7
Bern	Instr.	0.3	−0.2	−4.3	4.1	−0.2	−1.1	1.7	−3.4
HISTALP (7E 47N)	Instr.	0.6	0.0	−5.3	3.8	0.7	−0.6	2.7	−3.0
BEST (7.5E 47.5N)	Instr.	0.3	−0.1	−4.8	3.5	0.4	−0.6	2.1	−2.8
Casty (7.25E 47.25N)	Instr.	0.3	0.1	−4.7	3.5	0.6	−0.2	2.2	−2.2
EKF400v2 (7.5E 47.5N)	Mixed	0.3	0.0	−4.6	3.0	0.0	−0.7	1.7	−2.9
Luterbacher (7.5E 47.5N)	Proxy	—	—	—	—	0.4	−0.9	2.0	−3.3
Trachsel	Proxy	—	—	—	—	0.0	−0.6	1.6	−2.9
Pfister (index)	*Proxy*	—	—	—	—	*0.3*	*−0.7*	*1.0*	*−3.0*
Average		0.3	−0.1	−4.7	3.8	0.2	−0.7	2.0	−3.0
Standard deviation		0.2	0.1	0.5	0.4	0.5	0.3	0.4	0.4

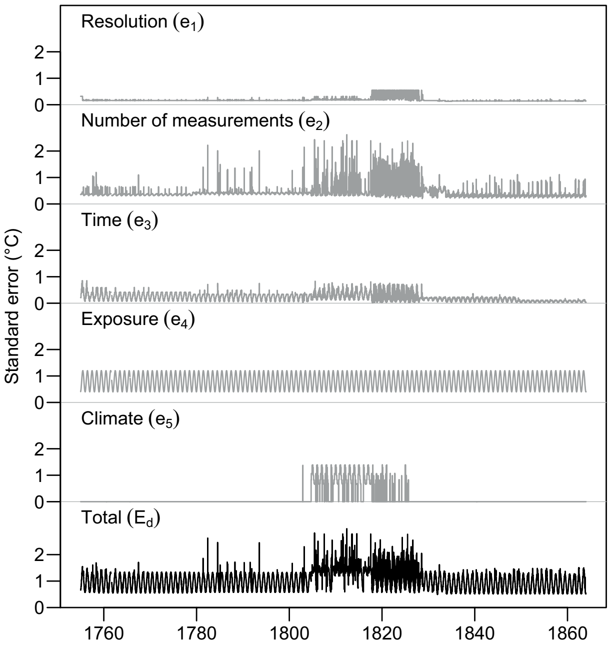

Figure 8: Time evolution of the daily standard error and its components for the merged Basel series.

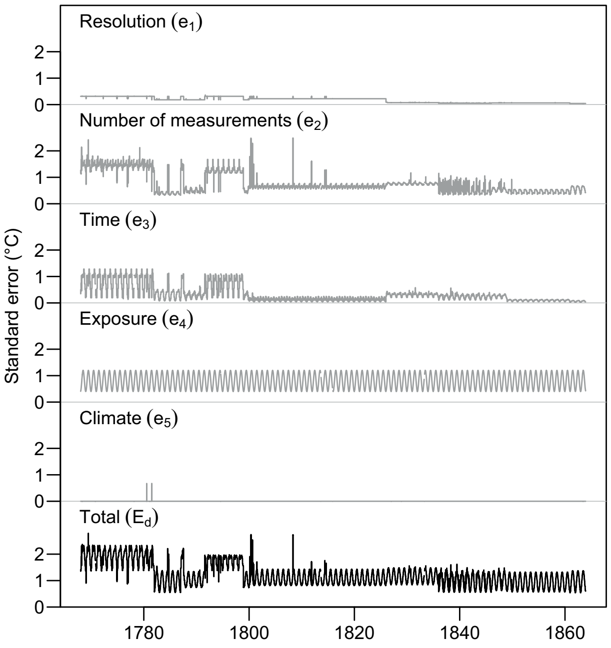

Figure 9: Time evolution of the daily standard error and its components for the merged Geneva series.

many other Central European records (e.g., Dobrovolný et al., 2010; Kunz et al., 2022). Figure 10 shows the daily mean temperature values in Basel and Geneva in the two seasons.

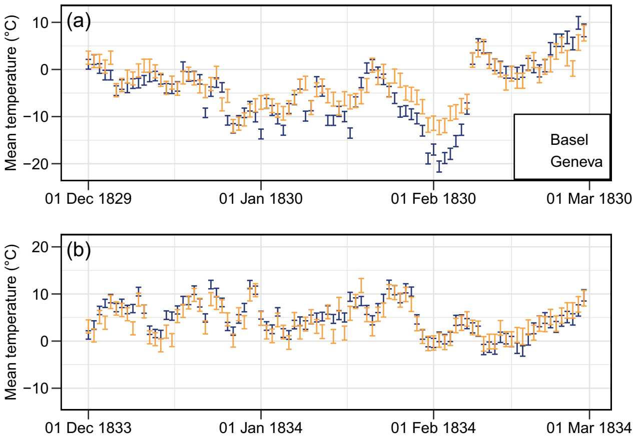

Figure 10: Daily mean temperatures for (a) the winter of 1829/30 and (b) the winter of 1833/34 with 90 % confidence intervals.

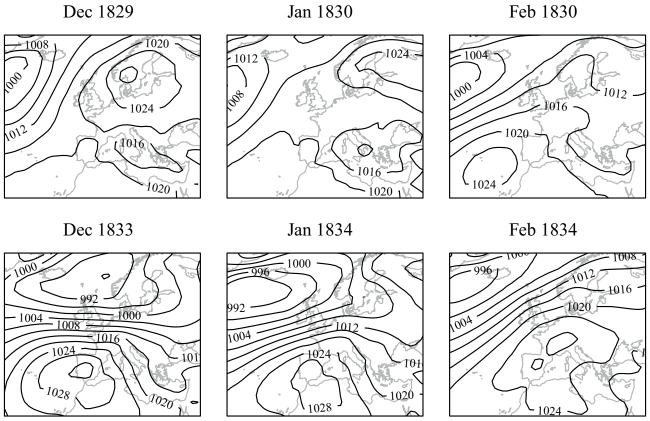

Figure 11: Monthly mean sea level pressure maps for Europe for the winter of 1829/30 and 1833/34 from EKF400v2 (contour lines are drawn every 4 hPa).

The winter of 1829/30 featured over two months of nearly uninterrupted negative temperature anomalies, reaching the coldest point at the beginning of February with a rare daily mean temperature below −20 °C in Basel on 2 February. The cause was a blocking pattern that effectively cut off Central Europe from the direct influence of the Atlantic Ocean for most of the winter (Figure 11), until a sudden change in the atmospheric circulation happened on 8 February. In Geneva the temperature values were not as low in absolute terms, possibly because of the influence of Lake Geneva. Similarly large differences (up to 12 K) between the two cities can be found during the extreme cold spell of December 1788 (Pappert et al., 2022).

In 1833/34 the circulation pattern was characteristic of a highly positive North Atlantic Oscillation, with strong pressure gradients and westerly flow over northern France and England particularly during December and January (Figure 11). In both Basel and Geneva over 90 % of days had a positive mean temperature, although extreme values were never reached. January 1834 and December 1833 have the two largest monthly temperature anomalies overall in the series of Basel (respectively the 1st and 6th largest in Geneva), which speaks for the unusual persistance of the atmospheric pattern.

5 Conclusions

We compiled two new long instrumental temperature series at daily resolution for Basel and Geneva, covering the period preceding the start of official measurements in Switzerland (1755–1863). The respective monthly temperature series were published over 60 years ago by the Swiss national weather service (MeteoSwiss). We provide alternative series obtained with modern methods and based on additional sources. Given the large heterogeneity and uncertainty of the underlying data, we also attached error estimates to each daily and monthly average. The new series complement the recently published series for Bern and Zurich (Brugnara et al., 2022b).

The data are homogenized taking advantage of the large number of early instrumental Swiss series that were digitized recently and making use of detailed metadata where available. Nevertheless, the fragmentation of the data sources in certain periods made the homogenization particularly challenging. Since we focused on the daily resolution rather than monthly, our series are not necessarily better than the MeteoSwiss ones in terms of long-term homogeneity, although they allowed us to point out residual inhomogeneities particularly in the Geneva series.

The series have the highest quality and homogeneity after ca. 1830, when both cities had well maintained meteorological observatories and instruments had reached a high level of standardization. For Geneva the quality remains relatively good back to 1798, although the MeteoSwiss version has probably a warm bias before 1836. For Basel, on the other hand, the period 1805–1825 is notoriously problematic due to the lack of measurements within the city, which are in large part filled in with measurements from nearby towns. The recovery of a new record from that period improved the situation only marginally due to its modest quality and could not avoid the introduction of a probable cold bias in our series. Homogeneity in the 18th century becomes increasingly hard to attain given the lack of reliable reference series so that the study of decadal climate variability remains challenging particularly before 1780.

A comparison with existing temperature reconstructions for Switzerland showed general agreement on the cold anomaly of the early 19th century, although with some distinctions on the magnitude. On the other hand, we found limited evidence of a warm period at the turn of the century. This was probably exaggerated in previous reconstructions based on instrumental data, in part as a consequence of the bias in the Geneva series.

The main advantage of the new series is the daily resolution, which is rarely available for early instrumental series. Together with the previously published series of Bern and Zurich, they constitute a considerable addition to the data available for the study of pre-industrial weather and climate in Central Europe. For example, we showed how they can help analyzing extreme events such as the winters of 1829/30 and 1833/34. More in general, they are suitable to be used for statistical weather reconstructions (e.g., Imfeld et al., 2022) as well as for data assimilation, while caution is needed when looking at long-term trends and decadal variability.

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Data availability

The daily early instrumental temperature series for Basel and Geneva are available through the Bern Open Repository and Information System (BORIS) (Brugnara, 2022a). The raw sub-daily data and the reference series used for the homogenization are available through PANGAEA (Brugnara, 2022b). The modern-day reference data are available through the MeteoSwiss data portal IDAWEB (https://gate.meteoswiss.ch/idaweb).

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