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A method to reconstruct long precipitation series using systematic descriptive observations in weather diaries: the example of the precipitation series for Bern, Switzerland (1760–2003)

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With 4 Figures

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Summary

In contrast to barometric and thermometric records, early instrumental precipitation series are quite rare. Based on systematic descriptive daily records, a quantitative monthly precipitation series for Bern (Switzerland) was reconstructed back to the year 1760 (reconstruction based on documentary evidence). Since every observer had his own personal style to fill out his diary, the main focus was to avoid observer-specific bias in the reconstruction. An independent statistical monthly precipitation reconstruction was performed using instrumental data from European sites. Over most periods the reconstruction based on documentary evidence lies inside the 2 standard errors of the statistical estimates. The comparison between these two approaches enables an independent verification and a reliable error estimate.

The analysis points to below normal rainfall totals in all seasons during the late 18th century and in the 1820s and 1830s. Increased precipitation occurred in the early 1850s and the late 1870s, particularly from spring to autumn. The annual precipitation totals generally tend to be higher in the 20th century than in the late 18th and 19th century. Precipitation changes are discussed in the context of socioeconomic impacts and Alpine glacier dynamics. The conceptual design of the reconstruction procedure is aimed at application for similar descriptive precipitation series, which are known to be abundant from the mid-18th century in Europe and the U.S.

1. Introduction

Precipitation and temperature are the most important climatic elements affecting human economies and terrestrial ecosystems. Extreme precipitation events and its potential consequences such as floods and droughts have an essential influence on human life (Cook et al., 1999; Wanner et al., 2004; Xoplaki et al., 2001, 2004; Touchan et al., 2005). As precipitation is far more spatially variable than temperature, a greater density of stations is needed to assess precipitation patterns. However, most precipitation stations were only set up in the twentieth century. Even in Europe and the U.S. only a few long series go back prior to 1850 (Wales-Smith, 1971; Craddock, 1977; Lewis, 1977; Pfister, 1977; Baron et al., 1980; Tabony, 1981; Camuffo, 1984; Wigley et al., 1984; Katsoulis, 1989; Brázdil, 1990; Camuffo et al., 1991; Schüepp, 1991; Vose et al., 1992; Tarand, 1993; Jones and Conway, 1997; Rodrigo et al., 1999, 2001; Auer et al., 2001, 2005; Garcia et al., 2002; Slonosky, 2002; Rodrigo, 2002). This shortage may be connected to the fact that rain-gauges – unlike thermometers and barometers – were not standardized and manufactured in large quantities in the eighteenth and early nineteenth century. They still had to be designed by local craftsmen as it is known for the Economic Society of Bern (Pfister, 1975). This fact agrees well with the observation that rain-gauges are rarely found in collections of ancient meteorological instruments in museums. In consequence of this scarcity of continuous measurements of precipitation in the early instrumental period, the EU project IMPROVE (Improved Understanding of Past Climatic Variability from Early Daily European Instrumental Sources) which aimed at improving past climatic variability from early daily instrumental sources just focussed on air-pressure and air-temperature. It did not include early instrumental series of precipitation (Camuffo and Jones, 2002). In sum, little is known about precipitation patterns in the "Little Ice Age" or even in the period prior to a substantial anthropogenic forcing in the twentieth century (Bradley and Jones, 1993; Lean et al., 1995; Mann et al., 1998).

Apart from studies dealing with local to regional precipitation variability based on station information, there are numerous studies using natural proxy information (e.g. tree-ring or dendroclimatic data) and documentary proxy evidence to reconstruct past variations of precipitation. Till and Guiot (1990) published a 900-year dendroclimatic reconstruction of October–September precipitation for different areas in Morocco. In a similar way, Touchan et al. (1999) developed a reconstruction of October–May precipitation for southern Jordan back to 1600. D'Arrigo and Cullen (2001) presented a 350-year dendroclimatic reconstruction of February–August precipitation for central Turkey. Akkemik et al. (2005) used oak trees to reconstruct March–June precipitation in the western Black Sea region of Turkey. Akkemik and Aras (2005) reconstructed April–August precipitation (1689–1994) for the southern part of central Turkey region by using tree-rings. Touchan et al. (2003) used tree-ring data from south-western Turkey to reconstruct May–June precipitation several centuries back in time. Touchan et al. (2005) recently published a several hundred years old May–August precipitation series for the southeastern Mediterranean area. Saz (2004) reconstructed seasonal precipitation for northwestern Spain using tree-ring information. Masson-Delmotte et al. (2005) describe the changes in European precipitation seasonality and in drought frequencies revealed by a four-century-long tree-ring isotopic record from western France. Based on fir tree-rings Brázdil et al. (2002) published a reconstruction of March–July precipitation for southern Moravia (Czech Republic) back to the 14th century. Wilson et al. (2005) presented a 500-year dendroclimatic reconstruction of March–August precipitation for the Bavarian Forest region (Germany). Pauling et al. (2005) and Luterbacher et al. (2006) review the available precipitation reconstructions based on natural proxies for Europe and the Mediterranean, respectively.

Brázdil (1996) presented a quantitative interpretation of decadal precipitation in the Czech Lands based on precipitation indices. A similar approach for the 16th century in Central Europe was published by Pfister and Brázdil (1999). Pfister (1999) presented monthly and seasonal precipitation indices for Switzerland for a couple of centuries. Precipitation indices for Germany were developed by Glaser (2001). Using documentary and early instrumental data Brázdil et al. (2003) presented a precipitation reconstruction for the Czech Lands based on the number of precipitation days. Barriendos (1997) used rogation ceremony records for climatic reconstructions for Catalonia, north-eastern Spain. Rodrigo et al. (1999, 2001) reconstructed seasonal precipitation records for Andalusia (Spain) for several centuries using documentary evidence. Alcoforado et al. (2000) and Xoplaki et al. (2001) used a variety of different documentary proxy information to derive monthly precipitation indices for the period 1675–1715 for Portugal and Greece. Precipitation in the Canary Islands has been reconstructed through the use of agricultural records for the period 1595–1836 (García Herrera et al., 2003). Brázdil et al. (2005) revised the present knowledge and potential of documentary proxy data for past European climate reconstructions.

Systematic daily weather observations are known to be abundant from the mid-eighteenth century in Europe and the U.S., because such notes on the daily weather were usually made alongside with early instrumental observations. In order to examine long-term precipitation we depend on additional non-instrumental sources (e.g. Druckenbrod et al., 2003). Werner and Gerstengarbe (2003) showed from a twentieth century data-set that subjectively registered data such as the "type of precipitation" have a strong correlation with measured parameters. This articles uses and adapts their approach to set up a 240 year long precipitation series for Bern.

In Sect. 2 we present the documentary data and the reconstruction methods. The detailed description of the reconstruction procedures is on the focus of this paper in order to make it applicable to similar precipitation observation series. The seasonal precipitation series of Bern from 1760 to 2003 are represented in Sect. 3. The analysis of the seasonal low frequency precipitation patterns is linked with socioeconomic impacts and connections to glacier dynamics. Further we provide a critical interpretation of the results (Sect. 4). Finally we sum up the major findings and give an outlook on further possible investigations (Sect. 5).

2. Data and approach

2.1 Data description

Metadata are fundamental not only to correct, homogenise and interpret documentary and instrumental data, but also to distinguish variations in observation methodology from real climate changes (e.g. Schmith et al., 1997; Camuffo and Jones, 2002).

The Swiss Meteorological Institute started its continuous daily observations in Bern only in 1864. Fortunately, daily weather records were registered from different observers with several gaps from 1760 to 1863 (Fig. 1). The records include measurements of temperature and air pressure on

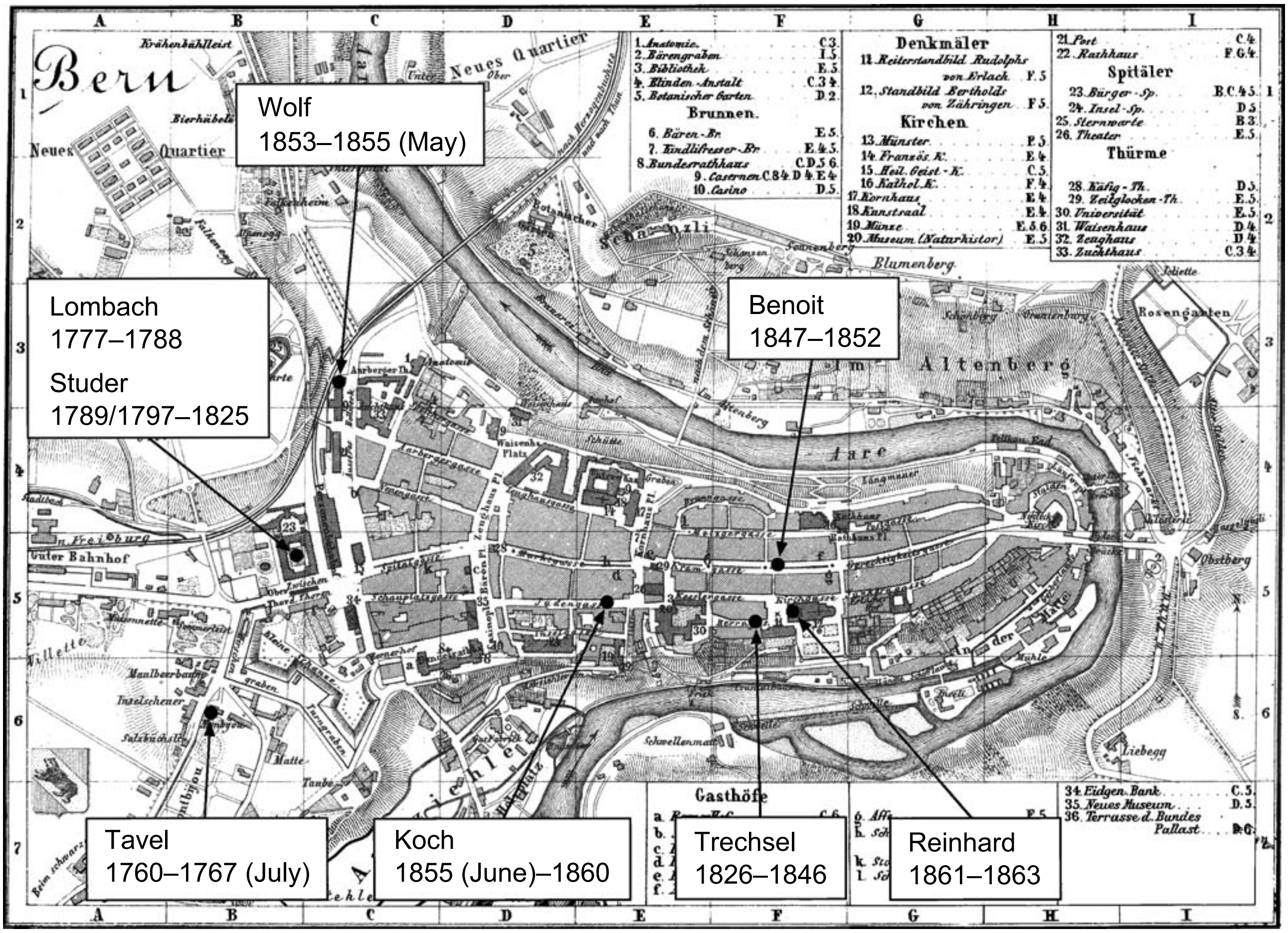


Fig. 1. Observation sites in Bern from 1760 to 1863 (Map source: Kartensammlung Geographisches Institut der Universität Bern)

the one hand and descriptive information about precipitation, wind and exceptional weather phenomena on the other hand. This work deals with the qualitative precipitation records.

In 1759 the Economic Society of Bern set up a regional climatic observation network. Six stations located mainly in western Switzerland measured barometric pressure, temperature and precipitation while two others just recorded temperature and barometric pressure. As far as we know this was the first network worldwide equipped with standardized instruments and taking standardized observations (Pfister, 1975). The observations were published in the ,,Abhandlungen und Beobachtungen der Ökonomischen Gesellschaft Bern'', which was the journal of the society.

Most members of the local nobility moved to their country estates in summer, which was unfavourable for making continuous weather registrations at the same place. The manor of Franz Jakob von Tavel (1725–1799) at Monbijou was opportune to this respect, because it was located only about 1.3 km SW of the Clocktower, which is the heart of the town. Von Tavel was unmarried and he remained on his estate all year long. He started his observations in January 1760. When the Economic Society was severely criticized by the authorities in summer 1766, von Tavel ceased to make his measurements. Later on, he became bankrupt and died in Paris (Pfister, 1975). Around 1770 the meteorological network of the society had almost collapsed.

Around 1776 the activities of the Society were relaunched. From the beginning of 1777 Karl Lombach, who was the secretary of the Town Hospital, began to take regular measurements of barometric pressure and temperature as well as precipitation observations. Like von Tavel he was unmarried. In 1789 Lombach ceased to make his measurements, as he had alienated from the Society (Pfister, 1975).

Samuel Studer (1757–1834) was perhaps the most enthusiastic meteorological observer. This is illustrated by the following episode: When he drove to his wedding he let the coach pause at the Town Hospital in order to make his observations (Häberli, 1959). In his observations he already distinguished different types of clouds and he made first attempts to realize synoptic reconstructions of atmospheric pressure and temperature. Studer started his observations in 1779. In 1789 he got the parish of Büren (about 22 km bee-line from Bern). In 1797 he returned to Bern and continued his records. Observation gaps above all in late summer and autumn were inevitable during his numerous expeditions in the Alps.

From 1826 to 1846 records were made by Johann Friedrich Trechsel (1770–1849) who was born as the youngest of 12 children of a butcher in the small town of Burgdorf. The young Trechsel made his living by giving lessons to individuals. Later on he became a parson, which at that time, was the only career a young intellectual could take. In 1805 he was elected Professor of mathematics of the "Hohe Schule" which was the forerunner of the University. He engaged himself in practical activities such as a trigonometrical survey of the Canton and in regularly taking meteorological observations (Sammlung, 1884). In 1834 he got a chair at the newly founded University in Bern (Dozenten, 1984). Trechsels assistant Gottlieb Benoit continued the observations from 1847 until 1852. From 1844 to 1863 the weather observations were established under the patronage of the 'Naturforschende Gesellschaft in Bern' (Graf, 1886) and were published in "Mittheilungen der Naturfoschenden Gesellschaft zu Bern" which was the journal of this society.

The next observer was Rudolf Wolf (1816–1893). In 1839 he got a position as a grammar school teacher for mathematics and physics in Bern. He became professor of astronomy there in 1844. 1847 he became a lecturer for mathematics and director of the observatory at the University of Bern. In 1855 he accepted a professorship of astronomy at both the University of Zürich and the Federal Technical University (ETH) in Zürich. He became world famous for discovering the relationship between the number of sunspots and geomagnetism. After his departure to Zürich his assistant Johann Rudolf Koch (1832–1891) took over Wolf's jobs as lecturer and the work at the observatory. Koch continued the weather observations from June 1855 until 1860.

The last part of the records was accomplished by Heinrich Reinhardt (1889), the guard of the cathedral's tower where the observation station took place from 1861 to 1863.

Gaps in the observation records (August 1766–1776, 1785 March to June and 1790–1796) were completed with the results of the statistical reconstruction. A critical assessment of the quality of the time series is given in Sect. 4.

All observations described above were published by Rudolf Wolf in the Schweizerische Meteorologische Beobachtungen (SMB, 1864–1880). Wolf used a scheme of abbreviations in order to save space using 11 abbreviation terms instead of the original wording. In doing so he expressed a weak or strong emphasis given by the observer with indices (0 and 2). In a sampled comparison between Wolf's publication and the original documents no essential loss of information was found. Therefore we adopt Wolf's abbreviations for the reconstruction approach. The detailed information about the precipitation character allows establishing 3 precipitation categories according to their estimated precipitation total (see Table 1).

Table 1. Abbreviation of precipitation events and creation of categories according to their expected precipitation total

Abbreviation	Meaning of abbreviation	Category
S^0	Snowfall (weak)	P0
R^0	Rain (weak)	
Rg	Rainy	
Rs	Drizzle	
R	Rain	P1
S	Snowfall	
Hg	Hail	
S^2	Snowfall (heavy)	P2
R^2	Rain (heavy)	
P	Cloudburst	
G	Thunderstorm	

Each observer had his personal style which is still evident in Wolf's publication of the records. However, some periods are consistent despite changing observers mainly because a new observer was instructed by his predecessor. This was the case in the observation series of the 'Naturforschende Gesellschaft in Bern'. Other changes of the observer lead to clear changes in the modality of the records. To avoid an observer-specific bias different observer-specific profiles were created. Altogether we differed five periods with consistent observations (Table 2).

2.2 Reconstruction procedures

The monthly precipitation totals of Bern were estimated with two different reconstruction techniques. The first approach relates directly to the data from the documentary sources described above (reconstruction based on documentary evidence). It was applied to the 1760–1863 period.

In an independent statistical reconstruction existing time-series of measured station precipitation, temperature and pressure from 174 neighbouring stations all over Europe were used (statistical reconstruction). The comparison between these two reconstructions enables an independent verification and an error estimate (see Sect. 4).

2.2.1 Reconstruction based on documentary evidence

For all observer-profiles we calculated the relative part of each precipitation category over all seasons. For that purpose the percentages of the days with observed precipitation for each category were determined. The results for the winter

Table 2. Classification of periods with observer-specific profiles

Profile	Period	Observers	Place	Altitude (m a.s.l.)
1	1760–1766 (July)	F. J. von Tavel	Manor Monbijou	520**
2	1777–1789	K. Lombach	Town Hospital	540**
3	1789, 1797–1825	S. Studer	Town Hospital	540**
4	1826–1846	J. F. Trechsel	House 317, 2nd floor	548
5*	1847–1852	G. Benoit	House 174, 2nd floor	542
	1853–1855 (May)	R. Wolf	Flat below the Observatory	551
	1855–1860 (June)	J. R. Koch	Observatory	546
	1861–1863 (November)	H. Reinhardt	Cathedral's tower	585

* Naturforschende Gesellschaft in Bern

** Altitude estimated

Table 3. Frequency of precipitation categories for the winter 1760–1863 in % (for profiles see Table 2)

	Profile 1	Profile 2	Profile 3	Profile 4	Profile 5
P0	7.4	14.1	8.5	13.4	12.9
P1	86.3	83.8	91.1	80.9	80.2
P2	6.3	2.1	0.4	5.7	6.9

Table 4. Precipitation categories and thresholds [mm] according to the observer profiles

	Profile 1	Profile 2	Profile 3	Profile 4	Profile 5
P0	0.3–0.4	0.3–0.6	0.3–0.5	0.3–0.6	0.3–0.6
P1	0.5–12.6	0.7–21.9	0.6–33.7	0.7–15.4	0.7–13.9
P2	>12.6	>21.9	>33.7	>15.4	>13.9

are given in Table 3, where we clearly recognize the considerable differences between the observer-profiles.

With regard to the following precipitation reconstruction the same categories for the calibration period (1864–2003) were created. The reconstruction models were calculated on the basis of a homogenised data set of daily precipitation totals from the actual station Bern-Liebefeld (46.5° N/07.25° E/565 m a.s.l.) (Begert et al., 2005). The probability density function of daily precipitation totals follows a gamma distribution (not shown). The data range is limited by zero. This limit was augmented to 0.3 mm because this limit is assumed to be the lowest possible precipitation total perceptible by a human observer. If we adopt the values given in Table 3 to the cumulative probability curve calculated from the data in the calibration period (1864–2003) we get thresholds of each precipitation category for each observer profile (Fig. 2). The threshold values in winter for all profiles are given in Table 4.

The reconstruction based on documentary evidence attempts to estimate the mean monthly precipitation totals from the descriptive *in situ* observations for Bern for the period 1760–1863. The observer-specific precipitation profiles (Table 4) play a decisive role in this context. In a multiple regression model (e.g. Luterbacher et al., 2002a, b; 2004) we used the three precipitation categories as predictors and the monthly precipitation total as predictand. Taking into account the five different profiles 60 different models were calculated. The models were derived in a calibration period (1864–2003) and applied to the reconstruction period (1760–1863). We renounced to apply the usual procedure with a subdivision in a calibration and verification period. The coefficient of determination (R^2) was calculated over the period 1864–2000 (not shown).

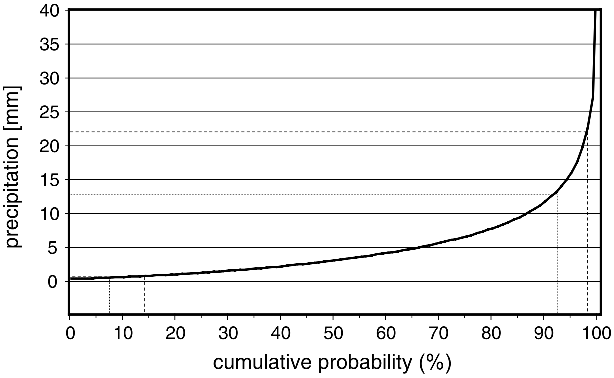


Fig. 2. Cumulative probability of daily precipitation totals in Bern for winter months (1864–2003). The pointed line indicates the determination of threshold values of the precipitation categories (P0, P1, P2) for the observer-profile 1 (Tavel). The dashed line shows the same for observer-profile 2 (Lombach)

2.2.2 Statistical reconstruction

In order to prove the reliability of the documentary based precipitation reconstruction a statistical estimate of monthly rainfall by using 174 stations with precipitation, temperature and pressure measurement (predictors), equally distributed over Europe was performed. This approach is an independent check of the monthly precipitation at Bern. Over the 1864–1995 calibration period, Empirical Orthogonal Functions (EOFs) explaining 90% of the predictor data (station data of precipitation, pressure and temperature; see Luterbacher et al. (2002a, b), Casty et al. (2005), Pauling et al. (2005) for information on the available station data and sources) variance for each season were regressed against the precipitation data from Bern. Seasonal models to estimate single monthly precipitation values within the respective seasons were also constructed. Due to the time-varying database of the monthly predictors, 335 regression models had to be developed. These regression equations from the 1864–1995 period were applied to the corresponding available predictor variables for the period 1760–1863 in order to derive monthly rainfall values for Bern.

For a detailed mathematical treatment of the reconstruction method, the reader is referred to Luterbacher et al. (2002a, b; 2004) and Pauling et al. (2005).

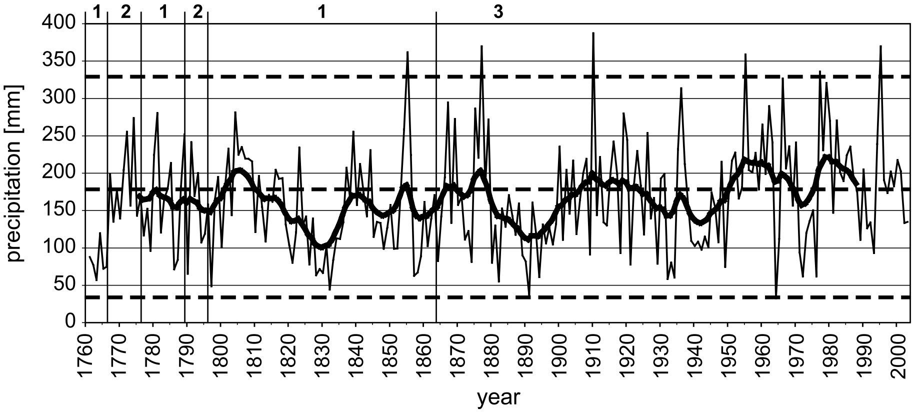
Uncertainty ranges for the predicted precipitation values were computed in terms of ±2 standard errors using statistics from the calibration period. SE quantifies the uncertainty in the regression coefficients and the residual variance that is not captured by the reconstructions (e.g. Mann et al., 1998; von Storch and Zwiers, 1999; Briffa et al., 2001, 2002; Jones et al., 2001; Luterbacher et al., 2002a, b; 2004; Xoplaki et al., 2005). Prediction for each model is obtained by fitting a regression model with the predictor data available for that particular month.

3. Results

The reconstruction based on documentary evidence results in a monthly precipitation series for Bern from 1760 to 1863. Completed with the existing measured climatological data from 1864 to date from the Swiss meteorological service, MeteoSwiss (Bantle, 1989; Begert et al., 2005), one of the most extended precipitation time series is obtained. This section presents the analysis of the seasonal low frequency precipitation dynamics with a focus on extreme periods (Fig. 3). Gaps in the observation records (August 1766–1776, 1785 March to June and 1790–1796) were completed with the results from the statistical reconstruction. A critical assessment of the quality of the time series is given in the Sect. 4.

Winter: The 1804 to 1809 winters show above normal (reference period 1901–2000) precipitation totals. Other wet winters were frequently noted in the late 1860s and the 1870s as well as in the 1950s and the 1960s. The enormous snowfalls in January and February 1951 led to disastrous avalanches with almost 100 causalities in the Swiss Alps (Laternser and Ammann, 2002). An extended very wet period occurred

a) Winter



b) Spring

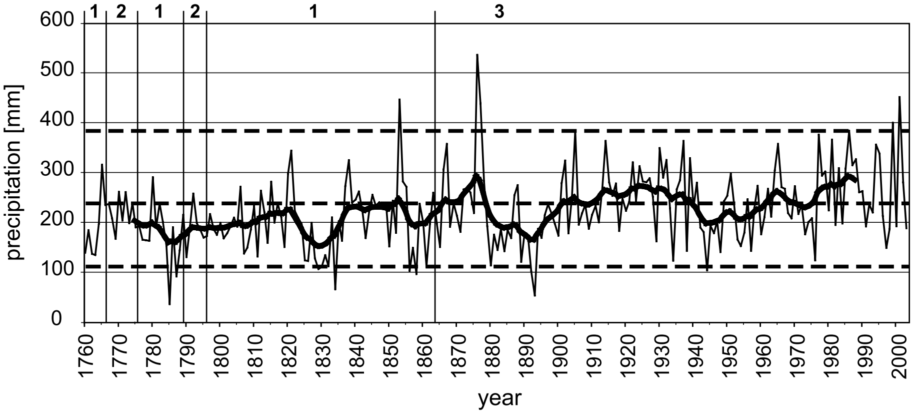
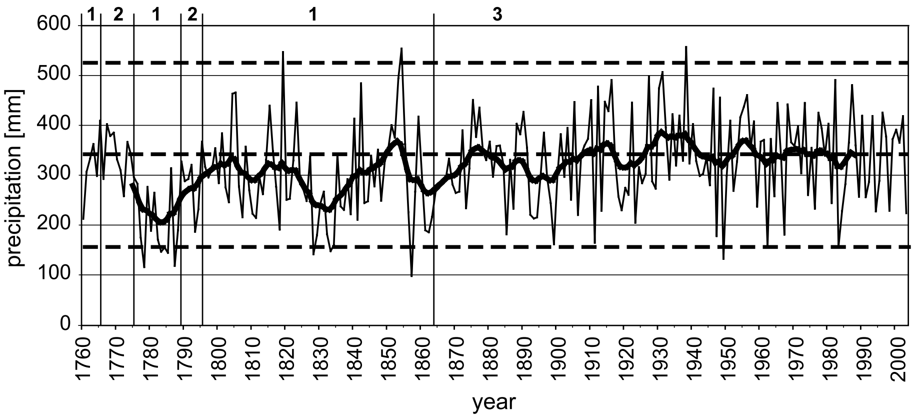
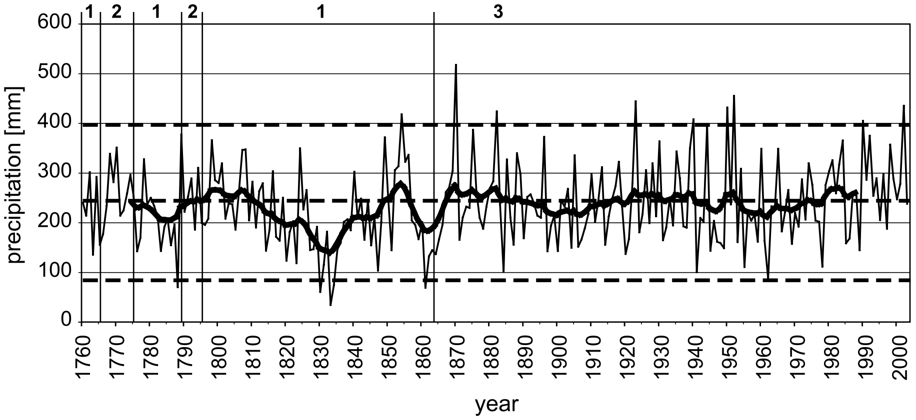


Fig. 3. Seasonal precipitation totals (calculated from monthly values) 1760–2003 (solid lines). The thick lines show the 30-year low pass (Gaussian) filtered values. Seasonal mean and the upper and lower 2 SD of the period 1901–2000 are indicated with dashed lines. Differences in the data quality are indicated at the top of the diagram (1: reconstruction based on documentary evidence, 2: statistical reconstruction, 3: measured data)

c) Summer



d) Autumn



e) Year

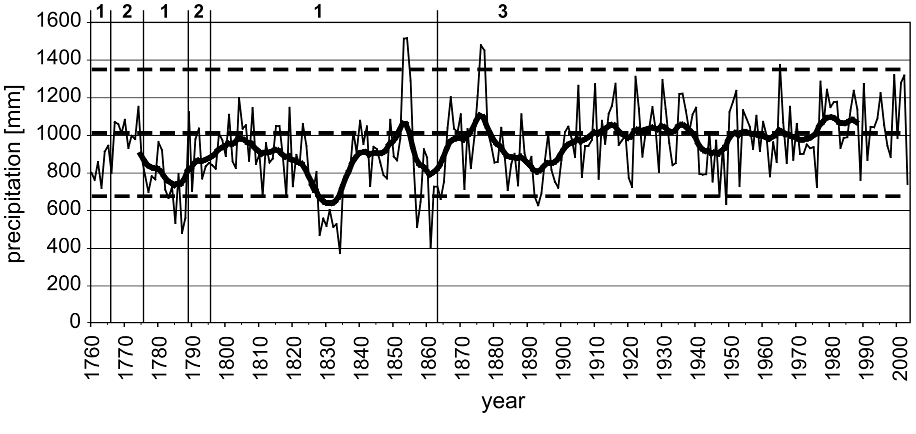


Fig. 3 (*continued*)

from the late 1970s to the end of the 1980s. The wettest winter over the whole period was 1910 with a precipitation total of around 390 mm, more than double of the 20th century mean (181 mm).

There is evidence of generally drier conditions in the first half of the 19th century. During the 1812–1836 period, the precipitation totals only slightly exceeded the 20th century mean in four winters. Another extended dry period occurred in the 1940s. The driest winter was 1964 with a precipitation total of only 32 mm.

Spring: The most extended wet period appeared from the late 1970s to 1990. Extremely wet springs occurred as well in two consecutive springs in the late 1870s (1876 and 1877). The precipitation surplus in spring 1876 (535 mm) connected with an extremely wet June led to disastrous floods in early summer (Pfister, 1999; Pfister and Schmid, 2000). There is evidence of wetter springs over the last around 60 years of the record.

Over the first around 120 years there is evidence of generally drier conditions. An exceptionally extended dry phase appeared from the mid 1780s to the mid 1830s. Shorter dry periods were identified from 1880 to the end of the century and from the early 1940 to the beginning of the 1960s. The driest spring occurred in 1893 with a precipitation total of 53 mm (average of the 20th century: 247 mm). In April 1893 absolutely no precipitation was measured.

Summer: After the two summer precipitation minima in the 18th and 19th century, there is a strong and significant upward trend of around +80 mm/decade (1776–1805 and 1826–1855, respectively). A short, but strongly distinctive wet period occurred in the first half of the 1850s. The late 1840s and the early 1850s are notorious for their high frequency of severe floods: Between 1849 und 1855 Lake Constance flooded its banks no less than four times. The communities situated at the shore of Lake Zürich made a lawsuit against the Canton. They argued that the high frequency of floods in the late 1840s and early 1850s needed to be blamed on an improper regulation of the sluices which had been installed at the entrance of the lake in 1842. A climatological expertise highlighted climatic variability as the effective cause (Wetli, 1885). Moreover it was demonstrated that agriculture was particularly suffering from the meteorological conditions in the early 1850. Grain prices soared (Pfister, 1988) what has triggered huge waves of overseas emigration in Switzerland and southern Germany (von Hippel, 1992; Ritzmann-Blickenstorfer, 1997). Wet conditions were registered from the late 1920s to 1940. The wettest summer of the whole period was noted in 1938 with 557 mm of rainfall.

Predominantly dry summers occurred from the mid 1770s to the 1790s and from 1820s to the end of the 1840s as well as from the late 1850s to 1870 and in the 1890s. The driest summer was recorded in 1857 with a precipitation total of 97 mm (average of the 20th century: 343 mm). As for winter, there is no significant trend within the entire 20th century.

Autumn: Exceptionally wet autumns occurred in the early 1850s. Taking into account a certain time-lag of glacier response, this shows a good accordance with the last glacier maximum in the late 1850s in the Swiss Alps (Zumbühl and Holzhauser, 1988), even more, if we take into consideration the frequently wet springs and summers in the early 1850s. Another wet phase appeared from 1870 to the mid 1880s. In the autumn of 1870, 517 mm of precipitation was measured (average of the 20th century: 243 mm).

The autumns of the 1806–1835 period became slightly drier. The driest autumn of the whole period was registered in 1833 with a precipitation total of 34 mm. Another period with frequently dry autumns appeared from the late 1850s to 1870. In the 20th century drier phases were observed from the mid 1950s to the mid 1960s.

Year (January to December): Extremely high precipitation totals were registered in two subsequent years in 1853 and 1854. 1853 was the wettest year of the whole period with a precipitation sum of 1514 mm (average of the 20th century: 1013 mm). The same phenomenon appeared again to a similar extend in 1876 and 1877. Increased precipitation totals were registered in the late 1970s and early 1980s.

From the mid 1770s to the end of the 1780s predominantly dry conditions were noted. The most striking feature is the decrease of the annual precipitation in the first decades of the 19th century reaching the driest decade in the 1830s. Mainly winter and autumn contribute to this trend towards drier conditions. 1834 was the driest year of the whole period with a precipitation total of around 370 mm. Other dry phases were noted from the late 1850s to the mid 1860s, in an extended period from the 1880s to the end of the century and in the 1940s. Generally, the average precipitation totals in the late 18th and the 19th century tend to be lower than in the 20th century (1760–1900: 876 mm, 1901–2000: 1013 mm).

4. Discussion

In order to check the reliability of the reconstruction based on documentary evidence a comparison with the statistical reconstruction was carried

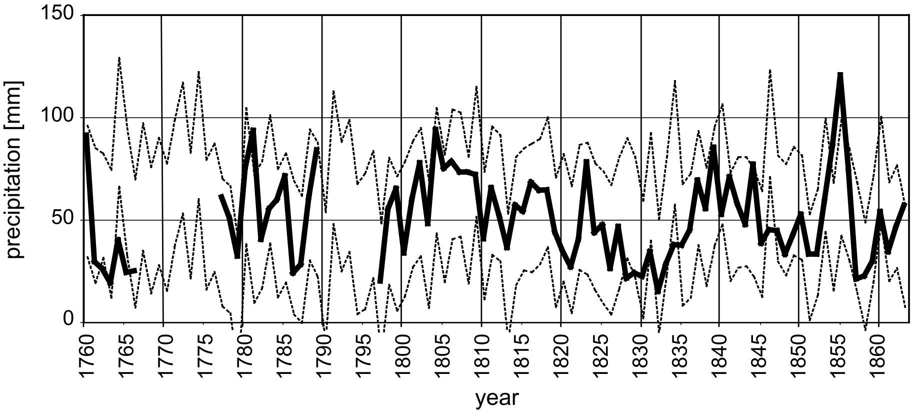
Table 5. Spearman correlations between reconstruction based on documentary evidence and statistical reconstruction for the periods 1864–1995 and 1760–1863 (sign. corr, $\alpha = 1\%$ are in bold). Latter periods include several gaps (1766–1776, 1790–1796)

	1760–1863	1864–1995
Winter (DJF)	**0.42**	**0.91**
Spring (MAM)	0.25	**0.86**
Summer (JJA)	**0.28**	**0.88**
Autumn (SON)	**0.32**	**0.89**

out. Table 5 shows the Spearman correlation coefficients between the two reconstructions over the 1760–1863 and 1864–1995 periods. Due to the improved quality of the statistical reconstruction as a result of maximum station availability, the correlations are stronger in the post-1864 period. In both periods the highest correlations were found in winter. In this season, large-scale advective weather patterns are relevant for the precipitation totals of Bern. In contrast, locally restricted convective precipitation events (e.g. thunderstorms) are dominant in summer.

The average seasonal precipitation totals of the reconstruction based on documentary evidence are represented in Fig. 4 together with the 2 standard errors (SE) from the statistical approach. The 2 SE of the statistical reconstruction were considered as the reference for the reliability of the reconstruction based on documentary evidence. The more station series are available the narrower is the spread of the 2 SE. Over most periods the reconstruction based on documentary evidence lies inside the confidence interval of the statistical reconstruction. In general we note the largest differences between the two reconstruction approaches in summer and spring (dominance of local convective precipitation events). The statistical approach is not able to take into account such spatial limited events as the reconstruction based on documentary evidence does. The direct reference to the simultaneous weather conditions is the main advantage of the recon-

a) Winter



b) Spring

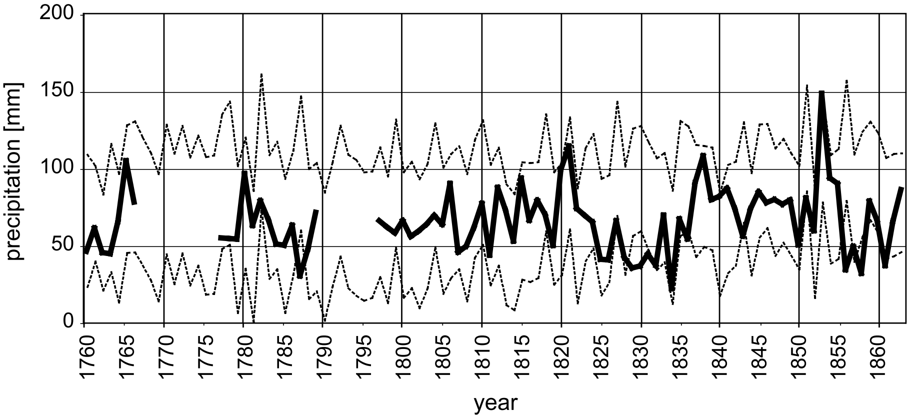
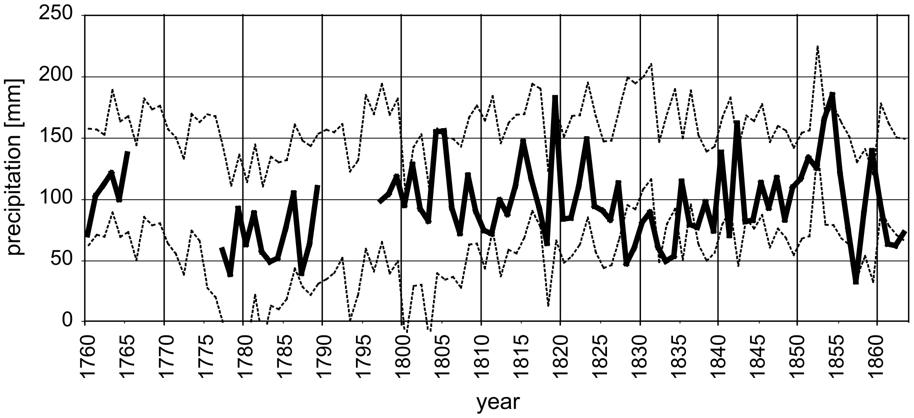


Fig. 4. Seasonal mean precipitation 1760–1863 (calculated from monthly values): reconstruction based on documentary evidence (solid line), 2 standard errors of the statistical reconstruction (dashed lines)

c) Summer



d) Autumn

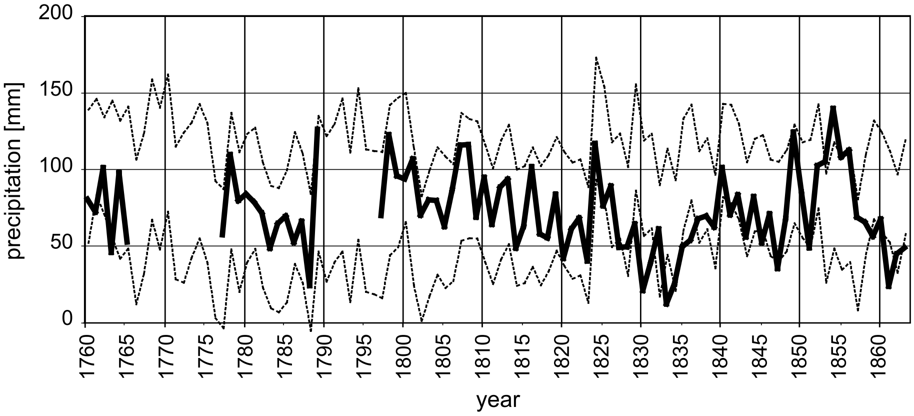


Fig. 4 (*continued*)

struction based on documentary evidence. The differences between the reconstructions in the observation period of Trechsel (1826–1846) are remarkable. In all seasons the precipitation total estimated by the reconstruction based on documentary evidence lies mainly near the lower 2 standard errors of the statistical reconstruction. We assume that the documentary approach with Trechsel's profile estimates systematically too low precipitation totals. The reason could be that Trechsel's observations do not have the same quality as the other records. On one hand this is surprising because Trechsel was the founder of the astronomical and meteorological observatory in Bern. On the other hand it is understandable because Trechsel had to cover the whole field of astronomy, mathematics and physics. This fact has to be taken into consideration with the interpretation of the results. Another problem of the reconstruction based on documentary evidence appears in the transitional months (March, April and October, November) because heavy rainfalls as well as heavy snowfalls occur. We assigned both events to the same category of precipitation intensity (see Sect. 2). However, heavy rain can produce much higher precipitation totals than heavy snowfall. As an extreme example the precipitation conditions in November 1854 have to be mentioned. Altogether, Wolf registered 18 days with precipitation, 7 of them with heavy snowfall, but not a single day with heavy rain. The reconstruction based on documentary evidence technique estimates a monthly precipitation total of 307 mm, which is likely strongly overestimated. The statistical reconstruction estimates a value some 200 mm lower. Hence, we have to be cautious in interpreting single wet months in early spring and late autumn.

It is often argued that eye observations are not complete because observers may have overlooked short rains or snow-falls during the night. However, this shortcoming should not be overestimated in the present context. It is assured that all observers regularly had noted heavy precipitation events (e.g. thunderstorms) even during the night. Nevertheless it can not be excluded that some specific events were not registered.

One of the main objectives of our work was to develop a method which is applicable to similar documentary data. For example, several records with the same characterization of precipitation observations exist in Wolf's compilation of weather records for Switzerland (SMB, 1864–1880).

5. Conclusions

A quantitative monthly precipitation series for Bern was reconstructed using a new technique based on systematic descriptive records from 1760 to 1863. The use of *in situ* observations enables to take into consideration the regional aspect of precipitation events. Every observer had his own personal style to fill out his diary. To avoid an observer-specific bias in the reconstructions observer-specific precipitation profiles were defined. The independence of the data allows the verification with a statistical reconstruction approach based on existing precipitation, temperature and pressure series from all over Europe. The comparison between these two approaches underpins the reliability of the reconstruction based on documentary evidence.

Completed with instrumental records from 1864 to date it was possible to analyse the precipitation conditions in Bern for the last 240 years. We find a period with below normal precipitation totals in all seasons in the last 20 years of the 18th century, in the 1820s and the 1830s. Considerably increased precipitation totals occurred in the early 1850s and late 1870s, above all in spring, summer and autumn. In general, the annual precipitation totals tend to be higher in the 20th century than in the late 18th and 19th century, which is possibly linked to warmer climate conditions and changes in atmospheric circulation patterns.

This reconstruction approach might be applied to other series of daily weather observations. In several parts of the world, in particular in Europe and in the US, an increasing total of detailed weather observations is known from the early eighteenth century. Mostly, such observations are found in instrumental diaries in which barometric and thermometric readings are recorded but which do not include measurements of precipitation. Three conditions must be met in order to make such an assessment of precipitation worthwhile:

1. The qualitative observations need to be sufficiently detailed in order to distinguish different degrees of rainfall duration and intensity.
2. The observations need to be sufficiently continuous.
3. Measurements of precipitation should be available from the same or a neighbouring station from a later date, in order to calibrate the qualitative observations and to get a long precipitation series as a final result.

Elaborating a number of long precipitation records for selected stations equally distributed over Europe would provide a better skill in reconstructing large-scale precipitation fields back in time (Pauling et al., 2005; Luterbacher et al., 2005). At the same time such series are needed to investigate historical floods and economic impacts of past climate in central Europe and in the Mediterranean (Pfister, 1988, 2005; Xoplaki et al., 2001; Thorndycraft et al., 2003; Brázdil et al., 2005).

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