Hydrological winter droughts over the last 450 years in the Upper Rhine basin: a methodological approach

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Abstract Processes involved in the generation of hydrological winter drought within the Upper Rhine basin are investigated. Extremely low water stages were mainly documented through hydrological measurements (since 1808) at Basel, Switzerland. The effect of water released from Alpine reservoirs for power generation was estimated in order to obtain a quasi-homogenous series of "natural flows". For the period prior to 1808, rocks emerging in rivers and lakes in the case of low water were used along with narrative evidence for assessing extreme events. 29 severe winter droughts are documented since 1540. Such events occurred after a succession of four months with below-average precipitation. A comparison with large-scale seasonal sea-level pressure (SLP) reconstructions revealed that they were often connected to persistent anticyclones centred over Western Europe. Severe winter droughts were relatively rare in the 20th century compared to the former period, which is due to increased winter temperature and precipitation.

Key words annual minimum flows; historical climatology; Little Ice Age; proxy data; sea-level pressure; socio-economic drought; Upper Rhine basin; winter drought

Approche méthodologique des sécheresses hydrologiques hivernales au cours des 450 dernières années dans le bassin supérieur du Rhin

Résumé Cet article étudie les processus impliqués dans la génération de la sécheresse hydrologique hivernale dans le bassin supérieur du Rhin. Les niveaux d'eau extrêmement bas ont été principalement documentés au moyen de mesures hydrologiques effectuées à Bâle (depuis 1808). Pour obtenir une série quasi homogène de « débits naturels », on a estimé l'effet de l'eau libérée à partir des réservoirs alpins pour la production d'électricité. Pour la période antérieure à 1808, on a utilisé des rochers émergeant dans les rivières, les lacs en période de basses eaux et des preuves narratives pour évaluer les événements extrêmes. Trente graves sécheresses hivernales sont décrites depuis 1540. De tels événements se sont produits après une succession de 4 mois de précipitations inférieures à la moyenne. Une comparaison avec des reconstitutions à grande échelle de la pression saisonnière au niveau de la mer (PNM) a révélé qu'ils étaient souvent liés à des anticyclones persistants centrés sur l'ouest de l'Europe. Par rapport à la période précédente, le 20e siècle a connu relativement peu de graves sécheresses hivernales, ce qui est dû à l'augmentation des températures et des précipitations en hiver.

Mots clefs débits annuels minimums; climatologie historique; Petit Age Glaciaire; données analogues; pression au niveau de la mer; sécheresse socio-économique; bassin supérieur du Rhin; sécheresse hivernale

INTRODUCTION

On 13 February 2006, the level of Lake Constance dropped to a stage close to the lowest mark ever recorded (February 1858) since the installation of a gauge in 1797 (Kobelt, 1926). The extremely low water level affected inland water navigation. The car ferries between Constance und Meersburg (Germany) and between Friedrichshafen (Germany) and Romanshorn (Switzerland) had to reduce their cargoes. Some of them did not load trains with trucks and/or tractors on board any more, whereas others accepted a lower number of trucks. The harbour of Rorschach (Switzerland) could no longer be reached and, temporarily, the island of Mainau (Germany) could be accessed on foot.

For the events of the winters of 2006 and 1858, the term of "hydrological drought" seems to be adequate. Hydrological drought is associated with the effects of periods of precipitation (including snowfall) shortfall on surface or subsurface water availability (i.e. streamflow, reservoir and lake levels, groundwater). The frequency and severity of hydrological drought is often defined on a watershed or river basin scale (NDMC, 2005). As several kinds of drought need to be distinguished, this term is discussed adopting the survey provided in the most recent academic textbook (Tallaksen & van Lanen, 2004). The primary cause of a drought is the lack of precipitation over a large area and for an extensive period of time (i.e. meteorological drought). This water deficit propagates through the hydrological cycle and gives rise to different types of droughts. Combined with high evaporation rates, it can cause a soil moisture drought to develop. The term agricultural drought is used when soil moisture is insufficient to support crops (Tallaksen & van Lanen, 2004). In the Upper Rhine basin, such a risk exists during the summer half-year (April–September). Due to the Alpine discharge regime, the only severe agricultural drought during the 20th century occurred in 1947 (Schorer, 1992; Schädler, 2003), whereas minor events are known from 1976 and 2003 (BUWAL, 2004). On the other hand, such situations develop more often during winter.

This paper sheds some light on the climatological processes involved in the generation of hydrological winter drought within a regional context. It proposes an approach to reconstruct and calibrate cases of severe hydrological drought over the last 450 years for the Upper Rhine basin, using low water marks and documentary evidence. The Upper Rhine basin was selected for two reasons. On the one hand, the gauge record of the Rhine at Basel – extending back to 1808 – is the longest known, uninterrupted discharge series of this kind in Central Europe (Ghezzi, 1915). Studies on low-stage events for the pre-instrumental period prior to 1800 have not been carried out to date, with the exception of the investigation by Liebscher (1983). The available observed flow records are generally insufficient for reliable frequency quantification of extreme low stage events (Smakhtin, 2001). On the other hand, a certain number of pre-instrumental low-water indicators are known for that region. Pointer rocks are known for the Rhine and Lake Constance. This lake serves as a secondary source of evidence. Its level is not altered by a weir; however, it is also affected by upstream power stations in the 20th century.

The methodologies worked out by historical climatology open up ways to reconstruct hydrological extreme events for several centuries beyond the availability of hydrological observations. Historical climatology is defined as a research field situated at the interface of climatology and (environmental) history, dealing mainly with documentary evidence, which is used to reconstruct weather, climate and its impacts on mankind. Documentary data are particularly suited to source extreme events. The more extreme an event, the more observations are available (e.g. Pfister *et al*., 2001; Brázdil *et al*., 2005b). Studies of "historical hydrology" in Central Europe for the period preceding the establishment of gauges have focused thus far upon the frequency and severity of floods (e.g. Brázdil *et al*., 1999; Sturm *et al*., 2001; Jacobeit *et al*., 2003a; Benito *et al*., 2003a,b; Barriendos & Coeur, 2004; Wanner *et al*., 2004; Brázdil *et al*., 2005a; Glaser *et al*., 2005; Glaser & Stangl, 2005; Ansell *et al*., 2006). In order to assess the magnitude of floods, many chroniclers referred to key terrain features such as bridges, town walls or buildings. From the early 16th century, flood marks on buildings, bridges and houses served as visual yardsticks to assess the severity of subsequent disasters. Moreover, the severity of floods is assessed from detailed reports about the kind and the amount of damage caused (Brázdil *et al*., 2005b). Cooperation between historians and hydrologists or geographers has been established within this field in several countries, such as Spain (Llasat & Puigcerver, 1994; Barriendos & Martín-Vide, 1998; Benito *et al*., 2003a,b; Barriendos & Coeur, 2004), France (e.g. Lang *et al*., 1998, 2002), Germany (e.g. Deutsch *et al*., 2004; Glaser & Stangl, 2005) and the Czech Republic (e.g. Brázdil *et al*., 2004, 2005a). “Flood hydroclimatology” (Hirschboeck, 1988) analyses floods within the context of longer-term varying climatic conditions and within a spatial framework of changing large-scale atmospheric circulation patterns. Investigations are linked to the concept of dynamics at these scales, which provide the ultimate framework from which the more immediate causes of flooding are generated (Hirschboeck, 1988; Jacobeit *et al*., 2003a).

Low water levels, on the other hand, belong to the category of creeping disasters (Böhret, 1990). Usually, they do not cause eye-catching damage and for this reason they were less often recorded in the past. Nevertheless, some people also preserved the memory of extreme low-stage events. They applied low-water marks as a counterpart to flood marks by chiselling the year of such events into rocks that emerged out of rivers and lakes in periods of hydrological drought. Obviously, they had a clear perception of a drought event. The abstract notion of drought was embodied in an environmental signal, which announced its beginning and disappeared at its end. Knowledge of such signals was a matter of local tradition.

Why did contemporaries attempt preserving the memory of events, which were neither spectacular nor destructive? Admittedly, pre-industrial economies and societies were affected by such events in several ways. People depended on water power for milling. When the mills stopped, bread became scarce and expensive. At the same time, the water supplies from local springs often dwindled. Weber (2005) has shown for the Rhine that shippers had to unload part of their cargoes to avoid becoming shipwrecked on rocks, which were usually lying deep in the water. Prices for hauling cargo went up as a consequence. In summer, low water tables always bore the risk of a major outbreak of dysentery, which mainly took the lives of small children. Tallaksen & van Lanen (2004) refer to such situations as “socio-economic drought”. On the other hand, many people used to celebrate such episodes in the same way as is known from the freezing of lakes, without giving reasons for it.

From a climatic change perspective, it is important to know how frequently such extremely low stages occurred in the period of “natural climate”. The event of 1858 occurred in the final phase of the so-called Little Ice Age (LIA), when most Alpine glacier snouts were close to the multi-secular maximum positions. The LIA was the most recent period during which glaciers maintained an expanded position on most parts of the globe, whereas their fronts oscillated in advanced positions (Holzhauser & Zumbühl, 1999; Ogilvie & Jonsson, 2001; Grove, 2004; Holzhauser *et al*., 2005, Steiner *et al*., 2005; Oerlemans, 2005). After the late 19th century, temperatures increased on regional, continental and global scales during the 20th century, connected to an overall retreat of most glaciers to approximately the position of the “Medieval Warm Period” and even further back (e.g. Brázdil *et al*., 2005b; Holzhauser *et al*., 2005). From a statistical reconstruction of monthly to seasonal temperature and precipitation patterns (Luterbacher *et al*., 2004, 2006; Xoplaki *et al*., 2005; Casty *et al*., 2005; Pauling *et al*., 2006) back to 1500, it was concluded that spells of cold advection and extended droughts in the winter half-year in Central Europe were more frequent, more persistent and more severe during the LIA than in the preceding "Medieval Warm Period" and the subsequent "warm 20th century" (Pfister, 2005). From the final decade of the 19th century, winter precipitation in Switzerland and in southwestern Germany significantly increased during the 20th century (Begert *et al*., 2005; Schmidli & Frei, 2005). It may be hypothesized that extreme low-stage events occurred more frequently and were more pronounced during the LIA than in the 20th century. In this context, the issue is raised as to how the climatic conditions leading to the recent extreme low-stage event compare to the situation in the winter of 1858 and to former episodes of this kind.

This paper is structured as follows: following a brief overview of the Rhine basin, the subsequent section is devoted to documentary sources from natural and manmade archives available for the Upper Rhine area related to drought conditions. Next, an analysis of the gauge readings and streamflow measurements of the Rhine at Basel is provided. The third section deals with the critical analysis of the historical evidence and provides a survey of extreme low-stage events since 1541 The results are discussed and interpreted in the fourth section. Conclusions are drawn in the last section.

THE EVIDENCE

The Rhine basin (183 000 km^2) can be divided into the Alpine area upstream from Basel (Switzerland), comprising approx. 36 000 km^2 with a mean elevation of approx. 1000 m a.s.l., and the middle and lowland parts, downstream of that town. In the Alpine area, the water is supplied by two main rivers, the Rhine and the Aare. These rivers flow together approximately 60 km upstream from Basel. Downstream from Basel, the Rhine is supplied by several large tributaries, such as the Neckar, the Main and the Mosel, and a considerable number of smaller tributaries (Fig. 1). Upstream from Basel, the river is governed by a snowmelt regime, with a maximum in early summer in combination with an early summer precipitation maximum, and a minimum during the winter. Downstream of Basel, a pluvial regime with a distinct winter maximum dominates. The long-term mean discharge of the Rhine at Basel already comprises half of the entire discharge of 2200 $m^3 s^{-1}$ measured at the German–Dutch border at Lobith (Viviroli & Weingartner, 2004).

One of the longest daily hydrological data series available in Europe concerns the River Rhine at Basel and covers the period 1808–2006. In 1808, a gauge was installed near the pier ("Schiffländte") and read once a day. For the period 1808–1868, daily gauge readings are available in manuscript form at the Swiss Environmental Agency in Ittigen (Bern). The original values are given in Baden feet (1 Baden foot is equivalent to 0.3 m) with decimal division. An engineer by the name of Ghezzi (1915) carefully analysed and homogenized the series for 1808–1913 in order to identify as accurately as possible the problems arising from the recording frequency (once a day up until 1869), the relationship between the water level and the discharge, and the lowering of the river bed. Thanks to the fact that digital values are available after 1869, comprehensive hydrological analyses can be carried out. The results of statistical tests based on daily runoff means show that the series for 1869–2006 is homogeneous.

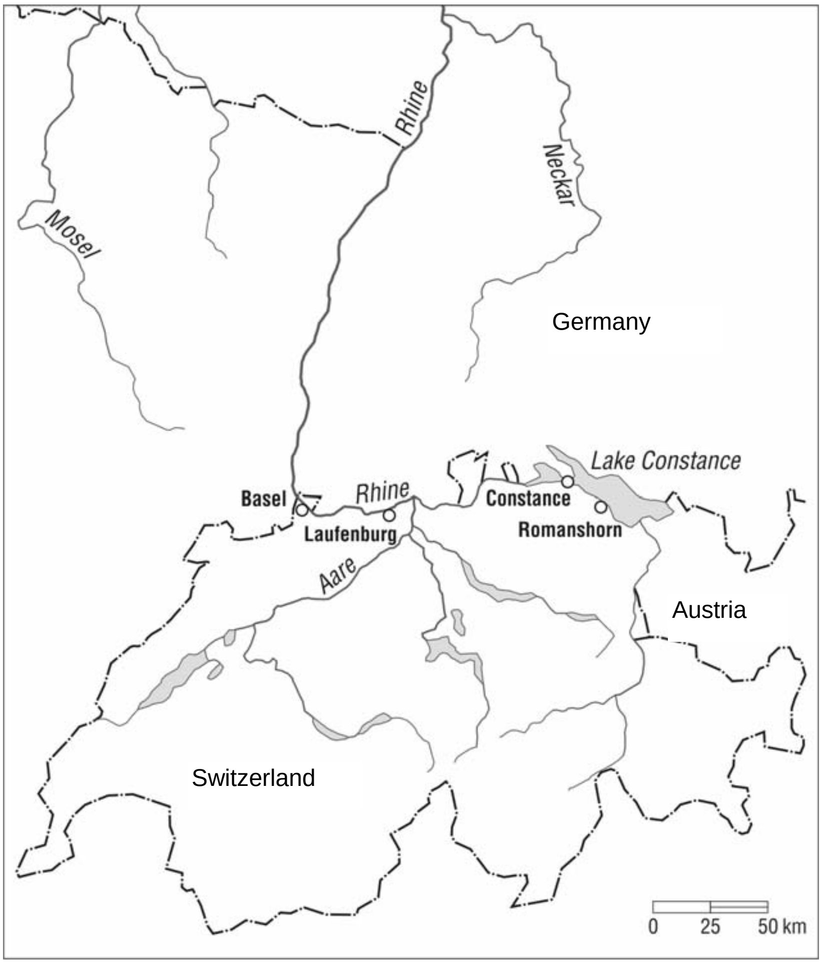


Fig. 1 The Rhine drainage basin.

For the period preceding the installation of the gauge, the stages have to be estimated from limited data. The best documented low-stage indicator was the so-called "Laufenstein". This is a rock situated about 100 m west of the old bridge in the small town of Laufenburg, situated east of Basel after the confluence of the Rhine with the Aare. The Laufenstein was blown up in 1908 or 1909 in conjunction with the building of the nearby power station (Anonymous, 1983). Fortunately, the memory of former extreme low-stage events chiselled into the rock was preserved by an engineer, who wrote his PhD on the "cataract" of Laufenburg, probably in view of the planned run-of-river power station. Walter (1901) included a detailed drawing of the marks chiselled into the rock (Fig. 2) in his dissertation, along with a photograph of the surroundings of the Laufenstein, which was probably taken during the low-stage event in February 1898 (Fig. 3). To conclude from Fig. 2, the number of documented cases for this period is limited.

Lake Constance receives the water of the Alpine Rhine and some small local tributaries. Therefore, it is not representative for the entire Upper Rhine basin. However, the lake offers additional low-water marks which complement those chiselled in the Laufenstein. Josef Wittman, a physician from Mainz (Germany), compiled evidence for extremely low levels of Lake Constance on the occasion of the low-stage episode

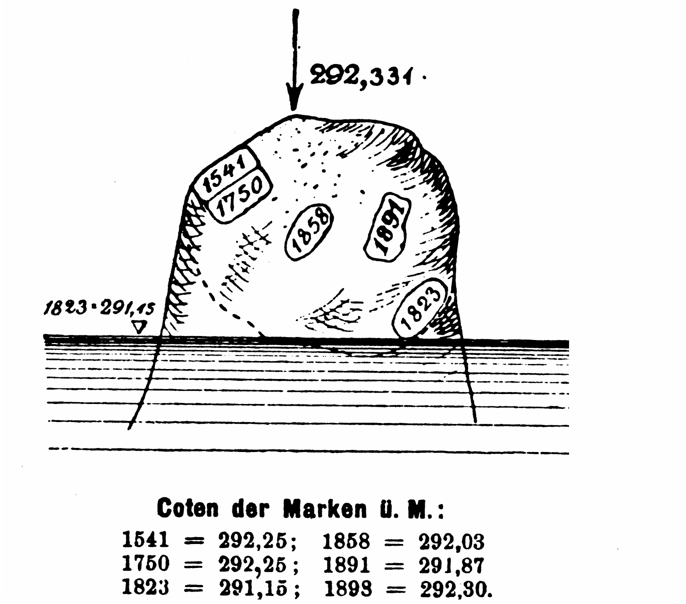


Fig. 2 Low-water marks on the Laufenstein (source: Walter, 1901).

Fig. 3 Surroundings of the Laufenstein (source: Walter, 1901).

of February 1858. This hydrological occurrence was also a unique opportunity for archaeological research. Many archaeological remains from the early modern, Roman and Neolithic periods - such as sunken ships, the foundations of bridges and pile-dwellings - were discovered in the nearly desiccated river bed of the Rhine. This event gave rise to many short articles in the German and Swiss press on the dimension and severity of the hydrological drought. Wittmann collected many of these reports and completed them by getting additional evidence from chronicles. The result is an uncritical compilation of known extreme low-stage events for the basin of the Rhine back to AD 70 (Wittmann, 1864). The compilation refers to many low-water marks that were destroyed during the last 150 years. For Lake Constance, it mentions two indicator rocks into which dates of extreme low-flow events were chiselled, namely an erratic block near Mannebach in the Untersee, which is an extension of Lake Constance, and the Devil's Table, located near the shore of Lake Constance between Wallhausen and Überlingen. In February 1858, when the Devil's Table stuck out of the water completely, it became a welcome place to celebrate carnival. Snack bars, gambling stands and even a carousel were set up on the Devil's Table. Festivities ended in early March, when the initiating snowmelt led the lake level to rise again (*Südkurier*, 8 July 1977). In March 1972, when the Devil's Table stood partly out of the water, a commemorative tag was affixed to the rock. Another commemorative tag was affixed in January 2006.

CRITICAL ANALYSIS, CROSS-CHECKING AND CALIBRATION OF THE EVIDENCE

The degree of knowledge and the level of precision that can be obtained in our estimates will always depend on the information contained in the observed data (Tallaksen & van Lanen, 2004). In particular, historical field evidence and documentary data often suffer from gaps in observations (Brázdil *et al.*, 2005b). In this section, the evidence presented in the section above is critically reviewed, cross-checked, calibrated and augmented with additional descriptive evidence. These operations comprise three different approaches.

The initial task involved evaluating discharge data series from 1808 to 2006 for the River Rhine at Basel. The annual minimum of the 7-day mean flow (AM_7) is taken as a standard to describe low-water conditions. The *n*-day mean flow is one of the most frequently applied low-flow indices. In contrast to the absolute minimum daily mean (AM_1), there is less likelihood of error if AM_7 is used, which is important precisely in relation to low water, an area where measuring errors can be relatively great. The hydrological year, i.e. from 1 October to 30 September, was used as a basis for low-water analyses. This time period was chosen because it takes into account the fact that the first discharge minimum often occurs in November or December, and a second occurs between January and March of the following calendar year, giving two interdependent values. By using the hydrological year, this sort of auto-correlation can be avoided. The results obtained from these data form a valuable basis for assessing historical records and, even, for quantifying individual low-flow events.

The second approach involves the application of the standardized methodology of historians for evaluating sources. In addition to proxy evidence, complementary narrative evidence is needed to provide the exact timing of the event and to point to its meteorological causes and economic impacts (Pfister *et al.*, 1996). Human evidence from the past cannot be regarded as reliable unless it can be shown either that the author lived close in time and space to the events he purports to describe, or that he recorded his observations within a short space of time after these events had taken place. If information was copied from other chronicles, which was the case with Wittman's (1864) compilation, misdating frequently occurred. Likewise, the dates chiselled into the Laufenstein and into the rocks near the shore of Lake Constance mentioned by Wittmann (1864) need to be reviewed, because they were probably difficult to decipher. All evidence for the period prior to 1808 needs to be compared with the verified narrative information on hydrological droughts (Pfister & Dietrich, 2006).

It was found that three dates on the Laufenstein (Fig. 2) are probably wrong by one digit: 1797 should be 1767 and 1764 should be 1714. The correct date for 1714 is confirmed by Wittmann (1864). The same author refers to a low-water mark on the Aare (near the town of Olten) in the extremely severe winter of 1767. For the 16th and 17th centuries, narrative descriptions in chronicles support the few available low-water marks. In March of 1672, an extended sandbank emerged in Lake Constance, on which a memorial shooting competition was held (Wittmann, 1864). Extremely low water levels are mentioned for February 1654 (Pfister & Dietrich, 2006). In February 1585, the River Rhine at Basel became a runnel, leaving large parts of the river bed completely dry - a memorial shooting competition was held on the desiccated part of the river, and the famous physician Felix Platter even wrote a few verses about the unusual aspect of the Rhine (Pfister & Dietrich, 2006). During the winter of 1541, the level of Lake Constance was so low that the town of Constance could tackle the construction of new fortifications, and the low level of the Rhine at Laufenburg is documented by a mark on the Laufenstein (Wittmann, 1864).

The summer half-year of 1540 is the warmest such period known from the documentary data of Central Europe. It also appears to have been considerably drier than any other year for which instrumental measurements are available, including 2003 (Pfister, 1999; Luterbacher *et al.*, 2004; Casty *et al.*, 2005; Pauling *et al.*, 2006). From mid-March to the end of September 1540, blocking anticyclonic situations were probably quasi-persistent over Central Europe (Jacobeit *et al.*, 1999; Luterbacher *et al.*, 2002). Many brooks and small rivers had completely dried out at that time. The level of the River Rhine was so low that it could be walked across at several locations (Pfister, 1999; Glaser *et al.*, 1999). Based on these descriptions, it seems very plausible that the runoff at Basel was at a minimum during the subsequent winter.

The third approach involves a calibration of the documented hydrological droughts with independent climatic evidence, which also serves as an additional cross-check. Measured precipitation data for several stations in the Upper Rhine basin are available from 1864 onwards (Begert *et al.*, 2005). For the time prior to that, one has to rely on proxy data that were obtained from documentary evidence (e.g. Pfister, 1999; Brázdil *et al.*, 2005b; Gimmi *et al.*, 2006).

Over the last 15 years, it became commonplace in the community of historical climatologists to express the degree of dryness and wetness of a month or a season in the pre-instrumental period in terms of an ordinal index. In most cases, reconstructions of climate involve two different kinds of documentary data, namely weather narratives and proxy data. Most observers were well aware that their descriptions were subjective. Therefore, they were looking for indicators in the environment that were known to be more objective to back-up their reports in cases of anomalies. These indicators are highly diverse, depending on the local traditions and environments. Among other things, the list includes the number of rainy days, the duration of a dry spell, and an advance or delay in the timing of vegetation or the freezing over of lakes and rivers. An appropriate statistical approach for quantifying both kinds of information jointly is not available. A rather robust solution to this problem consists of transforming all data available for a region and a given stage of the year into series of ordinal indices, referring to a rough range of temperature or precipitation rather than to exact values. The transformation requires broad source-specific, dynamical and statistical expertise (e.g. Pfister *et al*., 1999; Pauling *et al*., 2003; Brázdil *et al*., 2005b). Simple monthly indices use a three-term classification (temperature: 1 warm, 0 normal, –1 cold; precipitation: 1 wet, 0 normal, –1 dry). Weighted monthly temperature indices are based on a seven-term classification (3 extremely warm, 2 very warm, 1 warm, 0 normal, –1 cold, –2 very cold, –3 extremely cold), and a similar graduation for precipitation (3 extremely wet, 2 very wet, 1 wet, 0 normal, –1 dry, –2 very dry, –3 extremely dry). Months characterized by purely descriptive reports, e.g. "mainly dry" or "very cold" score +1 or –1, irrespective of the emphasis given by the observer, because such statements may include a subjective bias.

These indices are defined as percentages of the standard deviations of the respective series referred to within the instrumental period (Pfister, 1998, see Table 1). Evaluation of natural proxies and documentary evidence for precipitation fields in Europe and the Mediterranean area demonstrated that the most important single proxy (in terms of explained variance for each single proxy for specific areas, see Pauling *et al*., 2003 and Luterbacher *et al*., 2006 for further details) for winter precipitation are documentary-based precipitation indices (Luterbacher *et al*., 2006).

Table 1 Threshold values of the weighted precipitation index (after Pfister, 1998).

Index	Identification	σ %	Duodecile
–3	Extremely dry	–180%	<1st
–2	Dry	–130%	1st–3rd
–1	Below normal	– 65%	>3rd–5th
0	Normal		>5th–7th
1	Above normal	65%	>7th–9th
2	Wet	130%	>9th–11th
3	Extremely wet	180%	>11th

σ %: deviation in % of standard deviation from the mean, 1901–1960.

The reference period is 1901–1960. The selection of this time window has the advantage that most series do not yet show a warming trend. Series of intensity indices obtained from documentary evidence can be further interpreted in precipitation units (mm and %, respectively). In this case they should overlap the period of instrumental measurements, which is usually possible in a few cases and for specific periods (for details, see Pauling *et al.*, 2006; Gimmi *et al.*, 2006). The procedure for such reconstructions includes the following three steps: calibration, verification and reconstruction (Pfister & Brázdil, 1999).

It was hypothesized that hydrological droughts occur after several consecutive months of limited rainfall. In order to detect such situations in the record of monthly precipitation indices, moving averages for three to five consecutive months were computed for the entire period 1540–1807. The minima were matched with the periods of extremely low stages known from low-water marks and descriptive evidence. It was found that conditions in the four months preceding the event yielded the best fit. All verified low-water marks were found in good agreement with situations of limited rainfall for four consecutive months. Moreover, four additional periods of limited rainfall not documented with historical field evidence met this criterion, namely 1609 (March), 1653 (February), 1669 (December) and 1779 (March). These are cases which were not documented for the Upper Rhine basin. The result has important consequences for the interpretation of fragmentary descriptions of hydrological droughts in medieval chronicles. Inasmuch as such descriptions are contemporary and reliable, they allow one to conclude that rainfall during the preceding four months was limited.

HYDROLOGICAL AND CLIMATOLOGICAL DISCUSSION OF THE RESULTS

The discussion of the results comprises three steps. First, an interpretation of the low-flow conditions of the Rhine River at Basel since 1808 is offered. The second step involves a synoptic interpretation of selected cases of extreme hydrological drought in order to shed light on their spatial extent and their relationship to the atmospheric circulation. In the final step, the entire time series of extreme low-stage events is discussed with regard to climatic change.

Figure 4 shows the series of AM7 values for the Rhine at Basel consisting of two parts. From 1808 to 1869 the daily data are only available in the form of a manuscript (stored at the Swiss Federal Environmental Agency, Ittigen, Bern, Switzerland), which would make a full analysis extremely time-consuming. Because this article deals with extremely low flows, transcription just involved the appropriate winters known from Ghezzi (1915). From 1870 onward, digital daily discharge data are available. Two

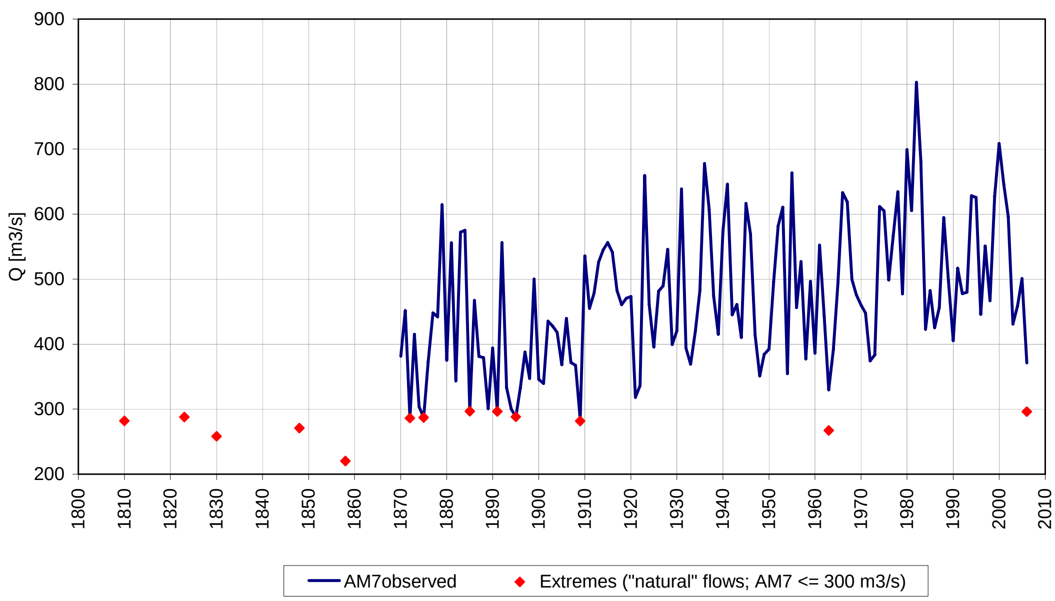


Fig. 4 Series of AM_7 values for the Rhine at Basel for 1870–2006 (hydrological years), including extremely low discharges from 1808 to 1869.

distinctive periods, namely 1870–1909 and 1910–2006, clearly emerge in the series from 1870. Trend analyses corroborate this observation and provide more details:

- The data series for 1870–2006 shows a significant positive trend, based principally on the "jump" around 1910. It might be inferred that the abrupt change in winter temperatures from 1910 on (Begert *et al*., 2005) is a main reason for this jump and not a change in the rating curve.
- No significant trend can be identified in the series for 1870–1909.
- Conditions during the period 1910–2006 are less clear: half of the 12 trend-test procedures used showed a significant trend.
- In addition, within the series for 1910–2006, there are significant positive trends for periods starting between 1945 and 1970 and ending in the 1980s.

These trends are confirmed by the 10-year AM_7 means shown in Fig. 5 (observed values). The reasons for this increase in annual minimum flows are as follows: In principle, the distinction needs to be made between direct manmade interference into the hydrosphere and the consequences of climatic change. Mainly since 1945, a considerable volume of water is stored in Alpine reservoirs within the Upper Rhine catchment basin (1945: approx. 0.5 km^3, today: 1.6 km^3). These reservoirs are usually filled up during the summer half-year.

During the winter half-year, they are gradually emptied for power generation (Swiss Federal Office of Energy, 2006), which increases discharge. At present, the estimated mean rise in winter discharge at Basel through water release from Alpine reservoirs is between 70 and 80 m^3 s^{-1}. Prior to World War II, the increase in winter discharge was correspondingly less. As can be seen from Fig. 5, a considerable proportion of the rise in the AM_7 value during the 20th century can be attributed to

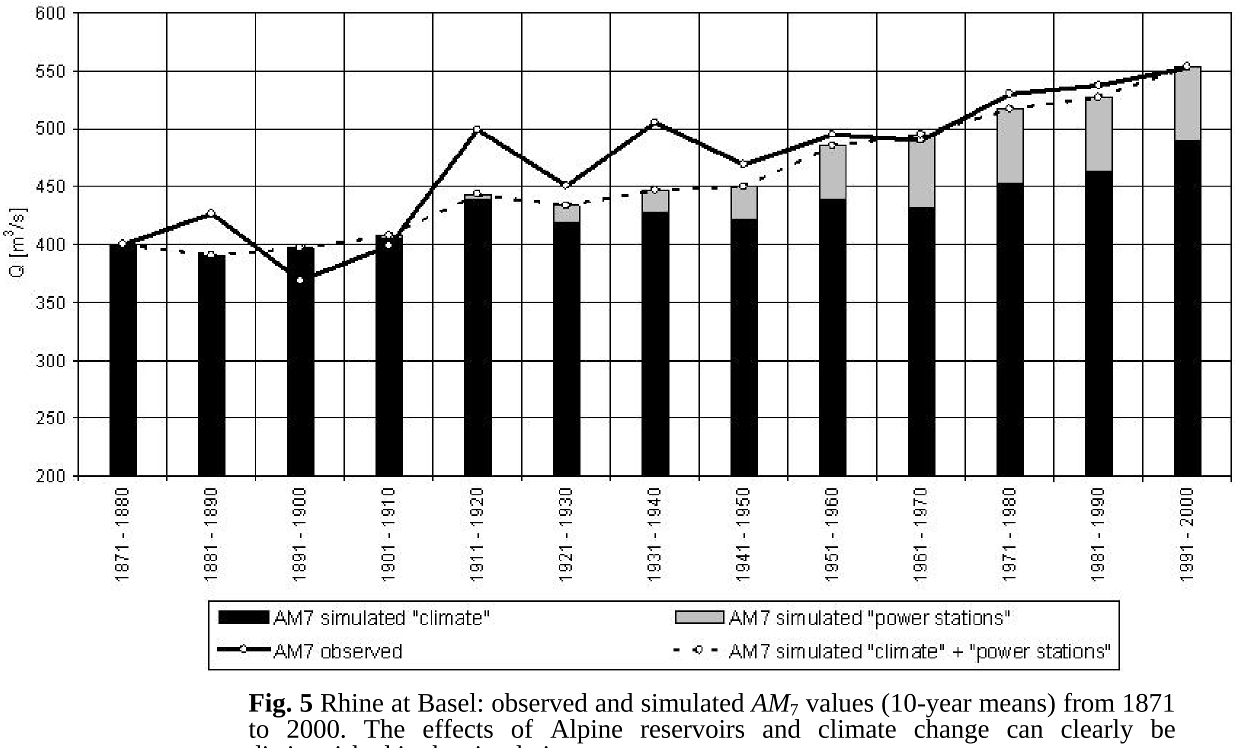


Fig. 5 Rhine at Basel: observed and simulated AM_7 values (10-year means) from 1871 to 2000. The effects of Alpine reservoirs and climate change can clearly be distinguished in the simulation.

hydropower generation. Other manmade factors (e.g. the correction of the Jura Waters, 1868–1991 and 1962–1973), which dropped the water levels of the three lakes in the western Swiss Mittelland to a lower common level (Vischer & Feldmann, 2005), may affect low water, but their influence was far less significant.

These considerations allowed the estimation of "natural" low-water discharge for the 20th century and the comparison of these figures to those for the 19th century. Likewise, quasi-homogenous low extremes (<300 $m^3 s^{-1}$) could be singled out for the entire 200-year period (Fig. 4). Only two extremes, namely 1963 and 2006, occurred after 1910, compared to 11 during the period 1808–1909. Furthermore, very extreme low flows were somewhat more frequent during the first half of the 19th century than during the second half. By far the lowest level during the past 200 years was observed in February 1858.

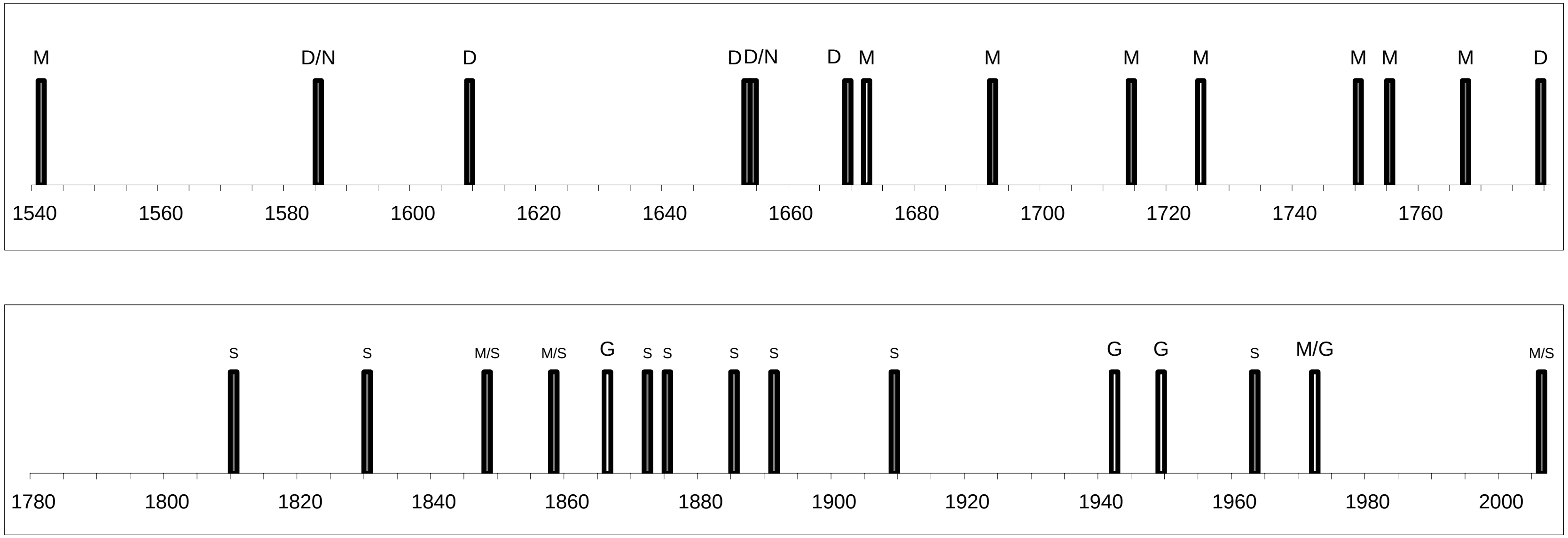
In order to determine the influence of climatic change on AM_7 values, a regression model was devised for the period 1869–1910, which was largely exempt from the influence of hydro-electric power stations, namely $AM_7 = f$ (mean winter temperature and winter precipitation for Zürich). The homogeneous data series for Zurich was used to infer the independent values (Begert *et al*., 2005). This model was then used for the period after 1910 and the 10-year mean was subsequently calculated (Fig. 5). The result suggests that climatic change, i.e. warmer and wetter winters, indeed promoted an increase in low water discharge, in particular during the second half of the 20th century (see Widmann & Schär, 1997; Begert *et al*., 2005).

Considering the number of extreme low-stage events per century, the following picture emerges (Fig. 6): on the whole, 29 extreme low-stage events are documented for the Upper Rhine basin. Within the last two centuries, differentiation is made between those events representative for the entire basin (Basel station) and those known only for Lake Constance. Taking into account an estimated minimum flow of <300 $m^3 s^{-1}$ at Basel, three events are known for the 20th century and ten for the 19th century. By further including the minima only known for Lake Constance, the number of severe winter droughts rises to six for the 20th century and remains the same for the 19th century. During both the 17th and 18th centuries, six winter droughts are known. The number of two reported events for the 60-year period 1540–1600 may considerably underestimate the number of real events.

Figure 7 shows that most extreme winter droughts between 1541 and 2006 occurred between January and March, with a maximum in March.

The mid-latitude atmospheric circulation is one of the dominant factors for the explanation of regional precipitation, drought and temperature patterns (e.g. Xoplaki *et al*., 2003, 2004; Jacobeit *et al*., 2001, 2003b; Slonosky & Yiou, 2002; Casty *et al*., 2005; Touchan *et al*., 2005; Pauling *et al*., 2006). The climatic interpretation of hydrological drought episodes draws on reconstructions of gridded seasonal sea-level pressure (SLP) fields back to 1500 for the eastern North Atlantic–European region (30°W–40°E; 30°–70°N) (Luterbacher *et al*., 2002) (Fig. 8).

Spatially and temporally high-resolution estimates of past natural climate variability are important to assess recent significant climate trends. The reconstructed SLP fields are presented as anomalies with respect to the 1901–1960 periods (seasonal SLP of a particular year, minus the corresponding seasonal 1901–1960 SLP average). Because extreme low-stage events are related to several consecutive months of limited precipitation, seasonal averages are the most adequate representation of SLP.



M	Low-water marks	N	Narrative evidence	D	Drought derived from precipitation indices	G	Gauge readings and streamflow measurements
■	Evidence from Basel (whole Upper Rhine catchment)		Evidence only for Lake Constance	S	Actual or estimated streamflow measurements for the Upper Rhine basin (series of Basel 1808–2006) AM_7 of <300 $m^3 s^{-1}$, homogenized		

Fig. 6 Frequency of severe hydrological drought in the Upper Rhine basin, 1541–2006.

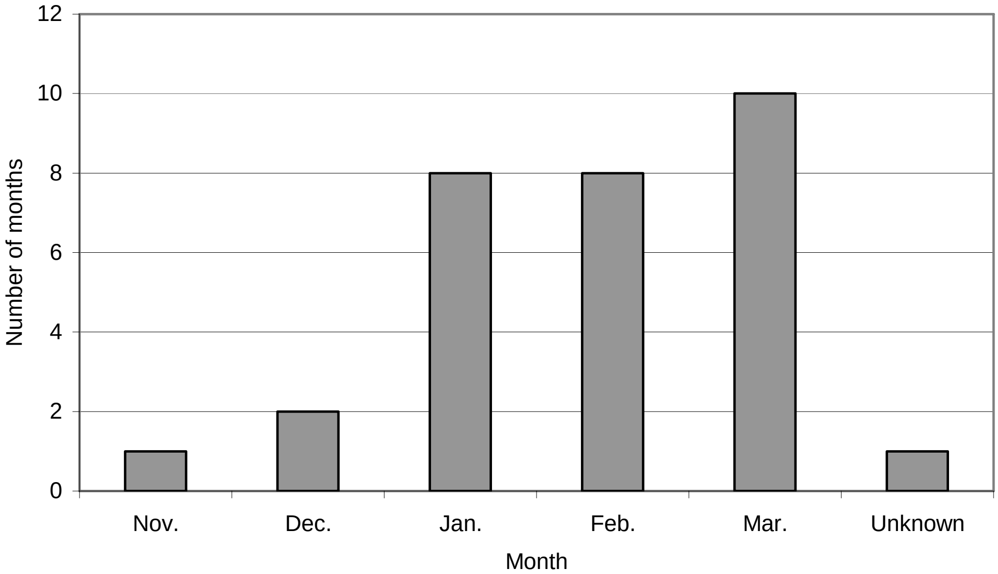


Fig. 7 Monthly distribution of extreme hydrological winter droughts in the Upper Rhine basin, 1541–2006.

Figure 8 presents a selected number of reconstructed SLP anomaly maps for typical cases of severe hydrological drought. The seasonal SLP anomaly maps shown in Fig. 8 feature strong positive pressure anomalies over the continent. In 1585, 1654, 1672, 1755, 1779, 1858 and 1909, the positive pressure anomalies were centred on the British Isles; in 2006 also over Scandinavia; in 1609 and 1669, they were situated in the northern Balkans; and in 1750 and 1949, throughout Central Europe. The latter two seasons were connected with widespread dry conditions over large parts of Europe (Pauling *et al*., 2006). Most of these winters further show a dipole pattern of anomalous temperature distribution with warmer than normal conditions in the north and cooler conditions in the south (Fig. 8; Luterbacher *et al*., 2004). The two severe winters of 1830 and 1963, in which Lake Constance was completely ice-bound (Pfister, 1999), represent extreme cases of a negative NAO (e.g. Luterbacher *et al*., 2002). The low discharge in these long and severe winters mainly reflects the fact that the bulk of precipitation was stored in the form of snow, which did not melt as long as the cold lasted. The overall coldness during the early 1940s was recently attributed to an ENSO influence (Brönnimann *et al*., 2004). A comparison of the known cases of extreme winter drought, with a sum of precipitation representative for the Swiss Mittelland (stations of Neuchâtel, Bern, Zürich and St. Gallen) (Pfister, 1998, updated to 2006) for the same year, reveals that most hydrological years with extremely low discharges are included in the driest years during the last 140 years (e.g. 1872, 1891, 1909, 1942, 1949, 1972, 2006), when taking into consideration the winter (DJF) or autumn (SON) and winter precipitation (data not shown here).

Disregarding the evidence available only for Lake Constance, situations of extreme winter drought were particularly rare in the 20th century compared to the preceding three centuries, for which adequate evidence is available. This conclusion agrees with the established result that winters in Central Europe prior to 1900 were generally drier than in the 20th century (Pfister, 1984, 1992; Wanner *et al*., 1995;

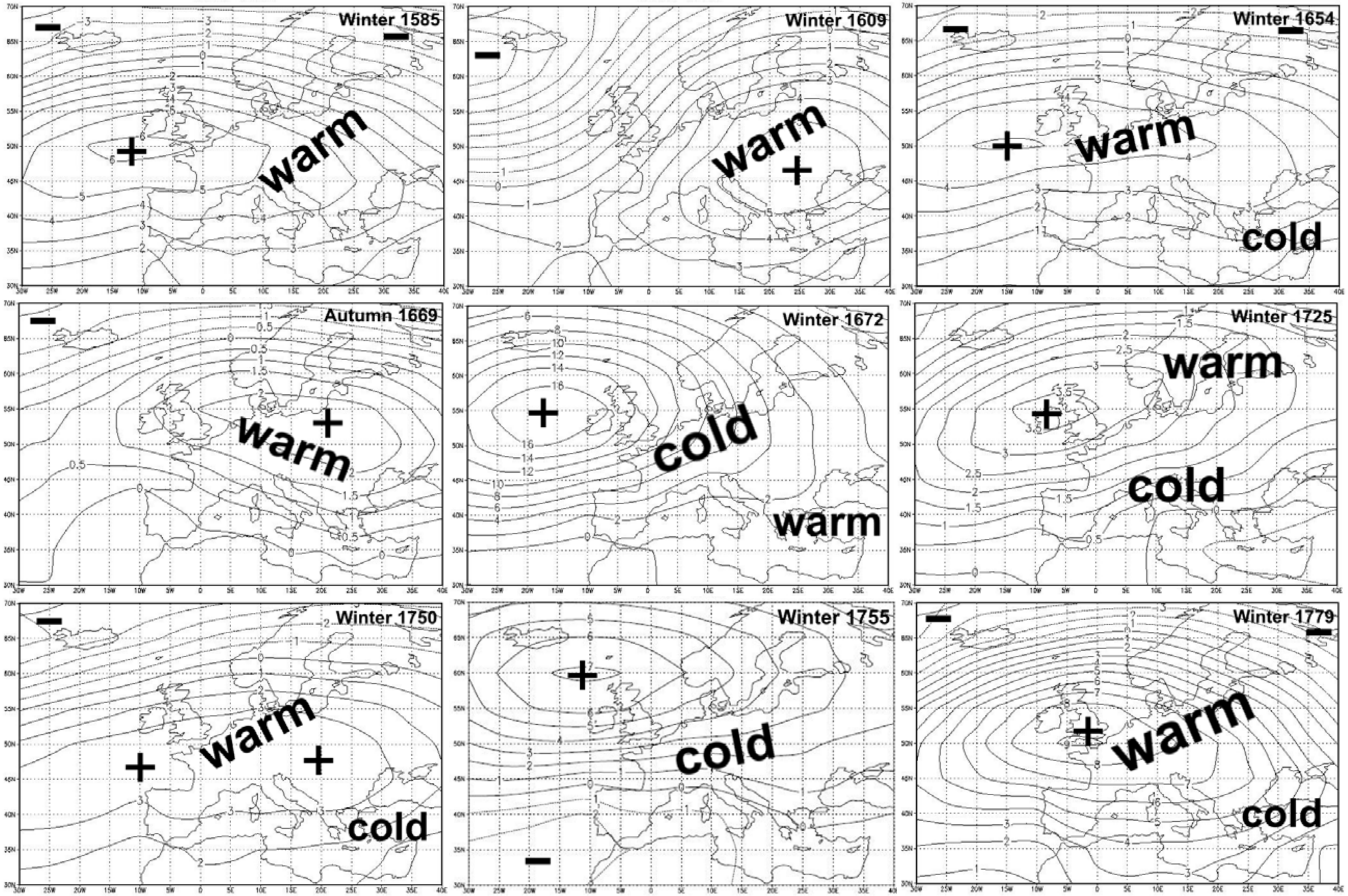


Fig. 8 (a) Seasonal sea-level pressure (SLP) over the Atlantic–European region for selected years of severe hydrological drought in the Upper Rhine area, 1585–1779. Anomalies from the average 1901–1960.

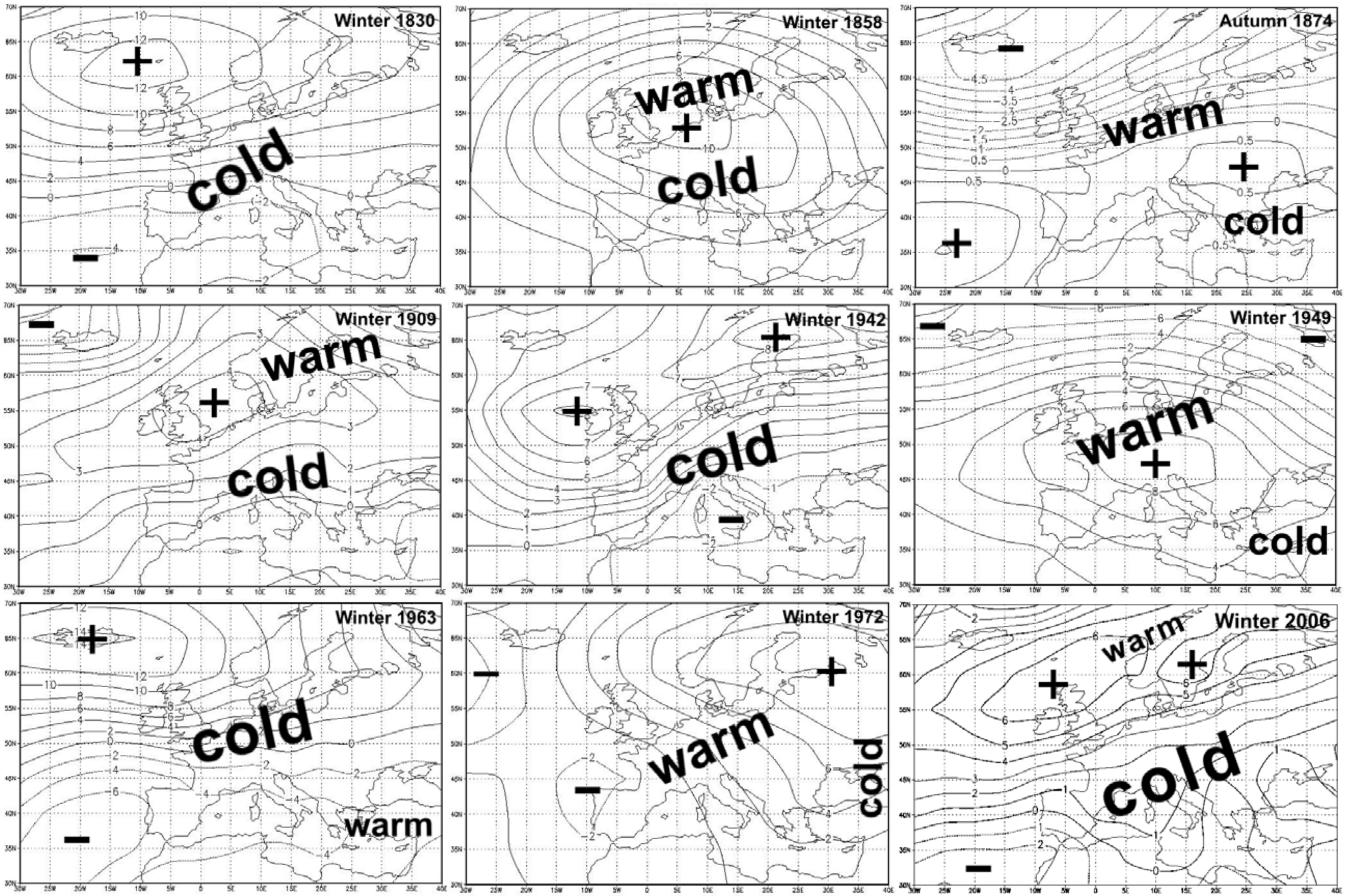


Fig. 8 (b) Seasonal sea-level pressure (SLP) over the Atlantic–European region for selected years of severe hydrological drought in the Upper Rhine area, 1830–2006. Anomalies from the average 1901–1960.

Luterbacher *et al*., 2001, 2004; Pauling *et al*., 2006). From the reconstructed SLP fields, it was demonstrated that the driest winters of the last 450 years, resulting from blocking anticyclones over the British Isles, or the western part of the continent, were not necessarily very severe.

Integrating the evidence for Lake Constance involves a shift in the ranking of the most severe winter droughts over the last 150 years. In particular, very low levels of this lake are known from the hydrological years 1942, 1949 and 1972, which are not included in the list of the extremely low flows at Basel, despite the fact that precipitation throughout the Swiss Mittelland was extremely low. A noteworthy difference also stands out in the severity of the hydrological drought in 2006. Using the example of Lake Constance, the level in February of this year was very close to the known minimum of February 1858. On the other hand, considering the streamflow measurements at Basel, the minimum registered in 2006 is only 12th in the ranking of the lowest AM_7 discharges since 1808 (Fig. 4). When comparing the evidence of the streamflow measurements at Basel and the level of Lake Constance with winter precipitation for the last 60 years, it is noticeable that Lake Constance seems to be a better indicator of meteorological winter drought in the Upper Rhine basin than the Rhine itself, despite the fact that the lake only represents part of it.

CONCLUSIONS

As is generally known, historical hydrology allows one to assess the magnitude of extreme floods for a period of two to three centuries preceding the establishment and systematic reading of water gauges in the 19th century. In this paper, it is demonstrated that the severity of extreme winter droughts can be assessed in a similar way using low-water marks, or low-lying rocks known to emerge in situations of extremely low water levels. The reconstruction of past extreme hydrological drought is useful with regard to its past and present socio-economic impacts and the interpretation of current winter-dry conditions.

The results of this study indicate that extreme winter droughts, covering around the last 450 years in the Upper Rhine basin, occurred after a succession of four months with below-average precipitation. It is found that, in most cases, droughts were not regionally limited and associated with persistent anticyclones centred over north-western/northern Europe (negative NAO mode).

The approach used requires co-operation between environmental historians, hydrologists and climatologists. The historian's job is the critical review and cross-checking of different kinds of evidence needed to provide a coherent and valid data structure. The hydrologist analyses and corrects the instrumental series leading from the past to the present. Moreover, he removes potential anthropogenic effects to ensure the homogeneity of the data. The climatologist's part entails reconstructing the large-scale atmospheric circulation and providing the synoptic interpretation for regional droughts.

Future research is needed to explore inconsistencies between extremely low levels of Lake Constance and the estimated "natural flow" of the Rhine at Basel, in particular for the last 70 years. Moreover, corresponding reconstructions of extreme low flows might be attempted for the northern part of Central Europe, where drought episodes usually occur in summer. Local pointer rocks, called hunger-stones ("Hungersteine") in the vernacular (Le Roy Ladurie, 2004; Stölben, 2004), are known for many rivers. It is hoped that future research in historical hydrology will notice the potential of this kind of *in situ* evidence for the reconstruction of extreme low-flow events.

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REFERENCES

Anonymous (1983) *75 Jahre Kraftwerke Laufenburg 1908–1983.* Sauerländer, Aarau, Switzerland.

Ansell, T., Jones, P. D., Allan, R. J., Lister, D., Parker, D. E., Brunet-India, M., Moberg, A., Jacobeit, J., Brohan, P., Rayner, N., Aguilar, E., Alexandersson, H., Barriendos, M., Brázdil, R., Brandsma, T., Cox, N., Della-Marta, P. M., Drebs, A., Founda, D., Gerstengarbe, F., Hickey, K., Jonsson, T., Luterbacher, J., Nordli, O., Oesterle, H., Rodwell, M., Saladie, O., Sigro, J., Slonosky, V. C., Srnec, L., Suarez, A., Tuomenvirta, H., Wang, X., Wanner, H., Werner, P. C., Wheeler, D. & Xoplaki, E. (2006) Daily mean sea level pressure reconstructions for the European–North Atlantic region for the period 1850–2003. J. Climate 19, 2717-2742.

Barriendos, M. & Coeur, D. (2004) Flood data reconstruction in historical times from non-instrumental sources in Spain and France. In: *Systematic, Palaeoflood and Historical Data for the Improvement of Flood Risk Estimation: Methodological Guidelines* (ed. by G. Benito & V. R. Thorndycraft), 29–42. Centro de Ciencias Medioambientales, Madrid, Spain.

Barriendos, M. & Martin-Vide, J. (1998) Secular climatic oscillations as indicated by catastrophic floods in the Spanish Mediterranean coastal area (14th–19th centuries). *Climatic Change* **38**(4), 473–491.

Begert, M., Schlegel, T. & Kirchhofer, W. (2005) Homogeneous temperature and precipitation series of Switzerland from 1864 to 2000. *Int. J. Climatol.* **25**, 65–80.

Benito, G., Díez-Herrero, A. & Fernández de Villalta, M. (2003a) Magnitude and frequency of flooding in the Tagus basin (central Spain) over the last millennium. *Climatic Change* **58**, 171–192.

Benito, G., Sopena, A., Sanchez-Moya, Y., Machado, M. J., Perez-Gonzalez, A. & Fernandez de Villalta, M. (2003b) Paleoflood record of the Tagus River (central Spain) during the late Pleistocene and Holocene. *Quart. Sci. Rev.* **22**, 1737–1756.

Böhret, C. (1990) *Folgen – Entwurf für eine aktive Politik gegen schleichende Katastrophen.* Leske + Budrich, Opladen (Germany).

Brázdil, R., Dobrovolný, P., Elleder, L., Kakos, V., Kotyza, O., Květoň, V., Macková, J., Müller, M., Štekl, J., Tolasz, R. & Valášek, H. (2005a) *Historical and Recent Floods in the Czech Republic.* Masaryk University and Czech Hydrometeorological Institute, Brno, Prague, Czech Republic.

Brázdil, R., Dobrovolný, P., Kakos, V. & Kotyza, O. (2004) Historical and recent floods in the Czech Republic: causes, seasonality, trends, impacts. In: *Flood Risk Management – Hazards, Vulnerability, Mitigation Measures* (Proc. NATO Advanced Research Workshop 6–10 October 2004), 35–46. Ostrov u Tisé, Czech Republic.

Brázdil, R., Glaser, R., Pfister, C., Antoine, J. M., Barriendos, M. Camuffo, D., Deutsch, M., Enzi, S., Guidoboni, E., Rodrigo, F. (1999) Flood events of selected rivers of Europe in the sixteenth century. In: *Climatic Variability in Sixteenth Century Europe and its Social Dimension* (ed. by C. Pfister, R. Brázdil & R. Glaser), Special issue of *Climatic Change* **43**(1), 239–285.

Brázdil, R., Pfister, C., Wanner, H., von Storch, H. & Luterbacher, J. (2005b) Historical climatology in Europe – the state of the art. *Climatic Change* **70**, 363–430.

Brönnimann, S., Luterbacher, J., Staehelin, J., Svendby, T. M., Hansen, G. & Svenoe, T. (2004) Extreme climate of the global troposphere and stratosphere 1940–1942 related to El Niño. *Nature* **431**, 971–974.

BUWAL (Bundesamt für Umwelt, Wald und Landschaft) in collaboration with Bundesamt für Gewässer und Hydrologie BWG und dem Bundesamt für Meteorologie und Klimatologie Meteoschweiz (2004) *Auswirkungen des Hitzesommers 2003 auf die Gewässer*. Schriftenreihe Umwelt vol. 369, Bern, Switzerland.

Casty, C., Wanner, H., Luterbacher, J., Esper, J. & Böhm, R. (2005) Temperature and precipitation variability in the European Alps since 1500. *Int. J. Climatol.* **25**, 1855–1880.

Deutsch, M., Böhner, J., Pörtge, K.-H. & Tilman Rost, K. (2004) Untersuchungen historischer Hochwasserereignisse in Thüringen – dargestellt am Beispiel der Werra. *Z. Geomorphol. Supplement* **135**, 11–32.

Ghezzi, C. (1915) *Die Abflussverhältnisse des Rheins in Basel*. Mitteilungen der Abteilung für Landeshydrographie vol. 8, Bern, Switzerland.

Gimmi, U., Luterbacher, J., Pfister, C. & Wanner, H. (2006) 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). *Theoret. Appl. Climatol*. doi:10.1007/s00704-005-0193-5.

Glaser, R. & Stangl, H. (2005) Climate and floods in Germany since AD 1000: Data, methods, results and consequences. *Surv. Geophys.* **25**(5/6), 485–510.

Glaser, R., Ammann, B., Brauer, A., Heiri, O., Jacobeit, J., Lotter, A. F., Luterbacher, J., Maisch, M., Magny, M., Pfister, C., Tinner, W., Veit, H. & Wanner, H. (2005) Paleoclimate within the River Rhine catchment during Holocene and historic times. *Erdkunde. Archiv für wissenschaftliche Geographie* **59**(3/4), 251–275.

Glaser, R., Brázdil, R., Pfister, C., Dobrovolný, P., Barriendos Vallve, M., Bokwa, A., Camuffo, D., Kotyza, O., Limanówka, D., Rácz, L. & Rodrigo, F. S. (1999) Seasonal temperature and precipitation fluctuations in selected parts of Europe during the sixteenth century. In: *Climatic Variability in Sixteenth Century Europe and its Social Dimension* (ed. by C. Pfister, R. Brázdil & R. Glaser), Special issue of *Climatic Change* **43**(1), 169–200.

Hirschboeck, K. K. (1988) Flood hydroclimatology. In: *Flood Geomorphology* (ed. by V. R. Baker, R. C. Kochel & P. C. Patton), 27–49. John Wiley & Sons Inc., New York, USA.

Holzhauser, H. & Zumbühl, H. (1999) Holocene glacial fluctuations. In: *Hydrological Atlas of Switzerland* (ed. by M. Spreafico, R. Weingartner & C. Leibundgut). No. 3.8, Bundesamt für Landestopographie, Bern, Switzerland.

Holzhauser, H. P., Magny, M. & Zumbühl, H. J. (2005) Glacier and lake-level variations in west-Central Europe over the last 3500 years. *Holocene* **15**(6), 789–801.

Jacobeit, J., Glaser, R., Luterbacher, J. & Wanner H. (2003a) Links between flood events in Central Europe since AD 1500 and large-scale atmospheric circulation modes. *Geophys. Res. Lett.* **30**(4), 1172.

Jacobeit, J., Wanner, H., Luterbacher, J., Beck, C., Philipp, A. & Sturm, K. (2003b) Atmospheric circulation variability in the North Atlantic–European area since the mid-seventeenth century. *Climate Dynamics* **20**, 341–352.

Kobelt, K. (1926): *Die Regulierung des Bodensees. Hochwasserschutz, Kraftnutzung und Schiffahrt*. Mitteilungen des Amtes für Wasserwirtschaft, vol. 20. Bern, Switzerland.

Lang, M., Coeur, D., Lallement, C. & Naulet, R. (1998) Valorisation de l'information historique pour la prédétermination du risque d'inondation: application au bassin du Guiers. *Ingénieries EAT* **16**, 3–13.

Lang, M., Naulet, R., Recking, A., Coeur, D. & Gigon, C. (2002) Etude de cas: l'analyse des pluies et crues extrêmes observées depuis 200 ans dans un bassin cévenol, l'Ardèche. *La Houille Blanche* **1**, 23–32.

Le Roy Ladurie, E. (2004) *Histoire humaine et comparée du climat. Canicules et Glaciers XIIIe–XVIIIe siècles.* Fayard, Paris, France.

Liebscher, H. J. (1983) The use of long-term river level and discharge records in the study of climatic variations in the Federal Republic of Germany. In: *Proc. Symp. on Variations in the Global Water Budget* (ed. by A. Street-Perotti). Reidel, Dordrecht, The Netherlands.

Llasat, M. C. & Puigcerver, M. (1994) Meteorological factors associated with floods in the north-eastern part of the Iberian Peninsula. *Natural Hazards* **9**, 81–93.

Luterbacher, J. & 48 co-authors (2006) Mediterranean climate variability over the last centuries: a review. In: *The Mediterranean Climate: an Overview of the Main Characteristics and Issues* (ed. P. Lionello, P. Malanotte-Rizzoli & R. Boscolo), 27–148. Elsevier, Amsterdam, The Netherlands.

Luterbacher, J., Dietrich, D., Xoplaki, E., Grosjean, M. & Wanner, H. (2004) European seasonal and annual temperature variability, trends and extremes since 1500. *Science* **303**, 1499–1503.

Luterbacher, J., Rickli, R., Xoplaki, E., Tinguely, C., Pfister, C. & Wanner, H. (2001): The Late Maunder Minimum (1675–1715) – a key period for studying decadal scale climatic change in Europe. *Climatic Change* **49**, 441–462.

Luterbacher, J., Xoplaki, E., Dietrich, D., Rickli, R., Jacobeit, J., Beck, C., Gyalistras, D., Schmutz, C. & Wanner, H. (2002) Reconstruction of Sea Level Pressure fields over the Eastern North Atlantic and Europe back to 1500. *Climate Dynamics* **18**, 545–561.

NDMC (National Drought Mitigation Center) (2005) What is drought? Understanding and defining drought: hydrological drought. University of Nebraska–Lincoln, available from: http://drought.unl.edu/whatis/concept.htm. (Accessed: 25 May 2006).

Oerlemans, J. H. (2005) Extracting a climate signal from 169 glacier records. *Science* **308**, 675–677.

Pauling, A., Luterbacher, J. & Wanner, H. (2003) Evaluation of proxies for European and North Atlantic temperature field reconstructions. *Geophys. Res. Lett.* **30**, 15. doi:10.1029/2003GL017589.

Pauling, A., Luterbacher, J., Casty, C. & Wanner, H. (2006) 500 years of gridded high-resolution precipitation reconstructions over Europe and the connection to large-scale circulation. *Climate Dynamics* **26**, 387–405.

Pfister, C. (1984) *Das Klima der Schweiz von 1525 bis 1860 und seine Bedeutung in der Geschichte von Bevölkerung und Landwirtschaft.* 2 vols. Academica Helvetica 5. Haupt, Bern, Switzerland.

Pfister, C. (1992) Monthly temperature and precipitation patterns in Central Europe from 1525 to the present. A methodology for quantifying man-made evidence on weather and climate. In: *Climate Since A.D. 1500* (ed. by R. S. Bradley & P. D. Jones), 118–142. Routledge, London, UK.

Pfister, C. (1998) *Raum-zeitliche Rekonstruktion von Witterungsanomalien und Naturkatastrophen 1496–1995.* Unter Mitarbeit von Daniel Brändli. Schlussbericht zum Projekt 4031-33198 des NFP 31. VdF, Zürich, Switzerland.

Pfister, C. (1999) *Wetternachhersage. 500 Jahre Klimavariationen und Naturkatastrophen 1496–1995*. Haupt, Bern, Switzerland.

Pfister, C. (2005) Weeping in the snow. The second period of Little Ice Age-type impacts, 1570–1630. In: *Kulturelle Konsequenzen der "Kleinen Eiszeit"* (ed. by W. Behringer, H. Lehmann & C. Pfister), 31–86. Vandenhoeck, Göttingen, Germany.

Pfister, C. & Brázdil, R. (1999) Climatic variability in sixteenth century Europe and its social dimension: a synthesis. In: *Climatic Variability in Sixteenth Century Europe and its Social Dimension* (ed. by C. Pfister, R. Brázdil & R. Glaser), Special issue of *Climatic Change* **43**(1), 5–53.

Pfister, C. & Dietrich, U. (eds) (2006) *Euro-Climhist*. A database on past weather and climate in Europe and its human dimension, Bern, Switzerland. http://www.euroclimhist.com.

Pfister, C., Brazdil, R., Obrebska-Starkel, B., Starkel, L. & von Storch, H. (2001) Strides made in reconstructing past weather and climate. *EOS Trans. Am. Geophys. Union* **82**(22), 248.

Pfister, C., Kleinlogel, G., Schwarz-Zanetti, G. & Wegmann, M. (1996) Winters in Europe: the fourteenth century. *Climatic Change* **34**(1), 91–108.

Schädler, B. (2003) Drought. In: *Extreme Events and Climate Change* (ed. by OcCC), 54–56. OcCC, Bern, Switzerland.

Schmidli, J. & Frei, C. (2005) Trends of heavy precipitation and wet and dry spells in Switzerland during the 20th century. *Int. J. Climatol.* **25**, 753–771.

Schorer, M. (1992) *Extreme Trockensommer in der Schweiz und ihre Folgen für Natur und Wirtschaft*. Geographica Bernensia vol. G40. Bernensia, Bern, Switzerland.

Smakhtin, V. U. (2001) Low flow hydrology: a review. *J. Hydrol.* **240**, 147–186.

Steiner, D., Walter, A. & Zumbühl, H. J. (2005) The application of a non-linear back-propagation neural network to study the mass balance of Grosse Aletschgletscher. *J. Glaciol.* **51**, 313–323.

Stölben, I. (2004) Der Hungerstein zu Pünderich. *Jahrbuch für den Kreis Cochem-Zell*, 2004, 90–91.

Sturm, K., Glaser, R., Jacobeit, J., Deutsch, M., Brázdil, R., Pfister, C., Luterbacher, J. & Wanner, H. (2001) Hochwasser in Mitteleuropa seit 1500 und ihre Beziehung zur atmosphärischen Zirkulation. *Petermanns Geographische Mitteilungen* **145**(6), 14–23.

Swiss Federal Office of Energy (2006) *Schweizerische Elektrizitätsstatistik 2006*. http://www.energieschweiz.ch. (Accessed: 20 May 2006).

Tallaksen, L. M. & van Lanen, H. A. J. (2004) *Hydrological Drought. Processes and Estimation Methods for Streamflow and Groundwater*. Developments in Water Science vol. 48. Elsevier, Amsterdam, The Netherlands.

Touchan, R., Xoplaki, E., Funkhouser, G., Luterbacher, J., Hughes, M. K., Erkan, N., Akkemik, Ü. & Stephan, J. (2005) Reconstructions of spring/summer precipitation for the eastern Mediterranean from tree-ring widths and its connection to large-scale atmospheric circulation. *Climate Dynamics* **25**, 75–98.

Vischer, D. & Feldmann, H. U. (2005) The first correction of the Jura waters, 1868–1891. *Cartographica Helvetica* **32**, 17–32.

Viviroli, D. & Weingartner, R. (2004) Hydrologische Bedeutung des europäischen Alpenraums. In: *Hydrologischer Atlas der Schweiz*, no. 6.4. Bundesamt für Landestopographie, Bern, Switzerland.

Walter, H. (1901) Über die Stromschnelle von Laufenburg. Diss. Phil. II, Zürich, Switzerland.

Wanner, H., Beck, C., Brázdil, R., Casty, C., Deutsch, M., Glaser, R., Jacobeit, J., Luterbacher, J., Pfister, C., Pohl, S., Sturm, K., Werner, P. C. & Xoplaki, E. (2004) Dynamic and socioeconomic aspects of historical floods in Central Europe. *Erdkunde* **58**, 1–16.

Weber, E. (2005) Untiefen, Flut und Flauten. Der Güterverkehr auf dem Rhein zwischen 1750 und 1850. Die Modernisierung der vorindustriellen Rheinschiffahrt aus einer wirtschafts-, sozial- und umwelthistorischen Perspektive. Diss. Phil. Hist., Historisches Institut der Universität Bern, Arth, Switzerland.

Widmann, M. & Schär, C. (1997) A principal component and long-term trend analysis of daily precipitation in Switzerland. *Int. J. Climatol.* **17**, 1333–1356.

Wittmann, J. (1864) Chronik der niedrigsten Wasserstände des Rheins vom Jahre 70 n. Chr. Geb. bis 1858 und Nachrichten über die im Jahre 1857/58 im Rheinbette von der Schweiz bis nach Holland zu Tage gekommenen Alterthümer und Merkwürdigkeiten. *Z. des Vereins zur Erforschung der Rheinischen Geschichte und Alterthümer in Mainz* 1864, 1–142.

Xoplaki, E., Gonzalez-Rouco, J. F., Luterbacher, J. & Wanner, H. (2003) Mediterranean summer air temperature variability and its connection to the large-scale atmospheric circulation and SSTs. *Climate Dynamics* **20**, 723–739.

Xoplaki, E., Gonzalez-Rouco, J. F., Luterbacher, J. & Wanner, H. (2004) Wet season Mediterranean precipitation variability: influence of large-scale dynamics and trends. *Climate Dynamics* **23**, 63-78.

Xoplaki, E., Luterbacher, J., Paeth, H., Dietrich, D., Steiner, N., Grosjean, M. & Wanner, H. (2005) European spring and autumn temperature variability and change of extremes over the last half millennium. *Geophys. Res. Lett.* **32**, L15713.

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