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Flood history of the Bavarian Alpine Foreland since the late Middle Ages in the context of internal and external climate forcing factors

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Abstract

This paper describes the flood history of the Bavarian part of the Alpine Foreland of Germany and addresses different questions concerning climate variability and flood frequencies from the 13th century until today. Will recent climatic change modify the flood frequencies within the Bavarian Alpine Foreland or are the flood frequencies varying due to altering climatic conditions since historical times? In the context of recent discussions whether man-made climate change will modify the present state of flood frequencies, a look back into the past is essential to understand the occurrence of floods in general and of recent floods in particular. In order to understand climatic variability and changes in a comprehensive way, it is necessary to review long time series. A perceived increase of summer floods in eastern Germany and Bavaria since 1997 requires examination of long time series to estimate changes in flood frequencies in a proper way. In view of the annual distribution of flood events within the Alpine Foreland of Germany, summer floods prove to be most important. Based on written historical sources, the flood history of the Alpine Foreland of Germany can be reconstructed back to the 14th century. One major result is the occurrence of "flood-rich" and "flood-poor" episodes in nearly cyclical sequences. Flood-rich periods were recorded in the periods 1300–1335, 1370–1450, 1470–1525, 1555–1590, 1615–1665, 1730–1780, 1820–1870, and 1910–1955 as well as in a 9th period beginning in 1980. The flood-rich periods are characterized by longer flood durations. Most of the flood-rich and flood-poor periods (in particular the beginning and the end of them) can be connected to changes in natural climate variability. These include changing sunspot numbers (as a measure of solar activity), so-called Little Ice Age Type Events (LIATEs) as well as changes in the North Atlantic Oscillation (NAO). Climate signals from external forcing factors, which could be used to explain the changing flood frequencies in the Bavarian Alpine Foreland, end in 1930. Relationships within the climate system such as the correlation of flood frequencies with the NAO have changed during the transition from the post Little Ice Age period to the Modern Climate Optimum around

1930. Natural climate variability might have been outperformed by anthropogenic climate change.

1 Introduction

Historical climatology, especially the branch addressing historical floods, has gained increasing interest during the last decades. Different parts of Central Europe have been investigated. For example, Schmoecker-Fackel and Naef (2010) and Pfister (1984, 1996, 1999) analysed the flood history of Switzerland, Brázdil et al. (2005) examined the flood history of the Czech Republic, Böhm and Wetzel (2006), Mudelsee et al. (2004), Deutsch and Pörtge (2001, 2002), Deutsch et al. (2004), and Glaser (2008) investigated different parts or catchment areas of Germany, while Rohr (2008) examined extreme natural events in Austria including floods. Sturm et al. (2001) and Glaser and Stangl (2003a, b) analysed different European flood histories with a focus on Central Europe. Nevertheless, the flood history of the entire Bavarian Alpine Foreland has not been analysed in a systematic way until now (cf. Böhm, 2011). Additionally, the Bavarian Alpine Foreland represents a region with a high sensitivity to climatic changes (cf. Auer et al., 2007).

The Bavarian part of the Alpine Foreland of Germany (hereafter termed Bavarian Foreland) has constantly experienced flood events, but the return periods e.g. for strong floods as well as for flood-rich or flood-poor periods cannot be derived by standard reference periods of 30 years. All of the recent major summer floods have been triggered by cyclones following a special pathway (cf. van Bebber, 1891). This so-called Vb cyclone track seems to be the main condition causing catastrophic flood events in the Bavarian Foreland, currently and also in the past (but not every Vb cyclone affects the investigation area in total). For the past, this can be seen from reconstructions of historic weather patterns (cf. Böhm, 2011). The recent period since 1997 has experienced numerous floods triggered by Vb-conditions during the summer months. The so-called “(River) Oder Flood 1997” and the “Pfingsthochwasser (Whitsun

Flood) 1999", both of which took place at the end of May, can be compared to the following summer floods of 2002 (Elbe/Danube Flood) and 2005 (Alps Flood). All these floods (despite their special naming) have affected the Bavarian Foreland.

To generate a long time series, it was necessary to integrate three different periods of flood documentation. The oldest information comes from the so-called descriptive period and has been obtained from historical writings such as chronicles and compilations. These written records can be analysed in a statistical way since the late Middle Ages as depicted in Glaser (2008). From the year 1826 onward, data are available from the so-called early instrumental period (EIP) (cf. Jacobeit et al., 1998). For at least one representative gauge station in the lower sections of every alpine river considered, recorded historic water level records can be evaluated. From the beginning of the 20th century up to the present, modern instrumental data (water level and discharge measurements) are available. The separately evaluated flood histories of the rivers Iller, Lech with tributary Wertach, Isar, Inn and its tributary Salzach have been merged for one overall time series. The timeline of the flood history of the Bavarian Foreland includes more than 550 individual flood events (see methods' section).

2 Investigation area

In this paper the Bavarian Foreland is defined by the lower sections of the catchment areas of the aforementioned rivers. From west to east the research area is bordered by the river Iller (in the west) and the rivers Inn and Salzach (in the east) as depicted in Fig. 1. The headwaters, however, are located in the Alps so that all of the rivers are northern-alpine mountain rivers (apart from river Wertach which should be regarded as a foreland river). The main rivers Iller, Lech, Isar and Inn are Alpine tributaries of the Danube river.

All the rivers coming from the Northern Limestone Alps traverse the Flysch Zone, enter the area of the faulted Molasse sediments and cross the belt of Pleistocene moraines and gravel fields. The substratum of the lower sections of the rivers is formed by sandy sediments of the Molasse trough. All traversed geological formations differ in their east-to-west extension. The geological formations of the outer alpine stream segments are of particular interest because of their texture. Due to the texture of the subsoil and anthropogenic encroachments after 1850, the riverbeds have deepened themselves. These circumstances affect hydrological interpretations concerning the EIP. To assure homogeneity in the comparison of flood events of individual time series, a high-pass-filter has been applied (see methods). The regional distribution of annual precipitation totals differs from around 600 mm a^{-1} in the region of the Danube river up to 2500 mm a^{-1} and more within the highest elevations of the investigation area. The share of alpine catchment is important for runoff from the headwaters into the Bavarian Foreland due to its function as temporary water storage reservoir and orographic barrier. In Table 1 the reference data of the relevant rivers are listed.

In the Bavarian Foreland we can differentiate spatial and chronological aspects of flood genesis as a function of hypsometric distribution and thereto linked snow retention into the individual catchments. We can observe a west-east gradient contrasting the chronological annual mean discharge maximum starting in the western part or the investigation area with a spring peak (rivers Iller and Wertach). The catchment areas of river Lech and Isar, located in the central part of the investigation area, are denoted by a distinctly marked summer peak followed to the eastern part with prolonged summer peaks (rivers Inn and Salzach). This spatial distribution is reflected by the seasonal distribution of the flood events indicated in Table 2.

Due to the spatial distribution of the catchment areas within the northern Limestone Alps and the Bavarian Foreland, the highest proportion of summer floods occurs in the eastern river sections of Inn (79 %) and Salzach (73 %), followed by Isar (58 %) and Lech (57 %). Due to the lower extent of alpine catchment area, the rivers Iller and Wertach only have about 40 % of floods during summer. In total a dominance of summer floods to the annual time series can be stated. Hereafter the use of annual information is owed to minimized data quality and information before the 16th century.

The flood-rich periods of the summer months and of the whole year correspond substantially to each other (cf. Figs. 5 and 7).

The investigation period 1300–2008 covers the Little Ice Age (1300–1850) and the transition period to the Modern Climate Optimum as found today. According to Wanner et al. (2000), it is advisable to differentiate the Little Ice Age into so-called Little Ice Age Type Events (LIATEs) addressing three major periods of extended glacier tongues. The periods, starting with LIATE3, are descripted for the years 1300 –1380, 1570–1640, and 1810–1850.

3 Database

The body of historical source material is due to the wide range of settlements along the northern alpine mountain rivers. All of the above-mentioned rivers host at least one notable historical site (among a multitude of other sites, e.g. Kempten (Iller), Augsburg (Lech/Wertach), Munich (Isar), Wasserburg (Inn), Burghausen (Salzach)). Within the framework of a DFG (German Research Foundation) funded research project, a database called IBT (Inundationes Bavariae Thesaurus) (cf. Böhm, 2011) was developed in cooperation with HISKLID (historical climatic database – cf. Glaser, 2008). The first investigation period was the descriptive period from the 14th century to the year 1880. The evaluated written evidences originated from handwritings and chronicles (e.g. the "Historische Kommission der Bayerischen Akademie der Wissenschaften/Historical Commission of the Bavarian Academy of Sciences" has published 37 volumes of city chronicles between 1862 and 1968), annuals, historical print media, compilations (e.g. Sonklar, 1883; Weikinn, 1958–1963; Alexandré, 1987; Fliri, 1998; Stahleder, 1995–2005; Börngen and Tetzlaff, 2000–2002; Brázdil, 2005), unedited historical leaflet database (Schorn, † 1937; Ferdinandeum Innsbruck Administration of Inheritance) and already existing databases (Militzer, 1998; Glaser, 2008) which were re-examined with a focus on the Bavarian Foreland. The early instrumental records in the Bavarian Foreland started with the year 1826. More than 20 historical gauge station records were examined. The data were analysed with respect to monthly maxima of water level. Due to physical structures and vertical erosion of gauge stations, the gauge datum has been changed in some cases (sometimes repeatedly). To homogenize the data, a high-pass filter was applied. In the present paper we choose one representative gauge station for each river, each with the longest coherent time series since 1826. They include the time series of Kempten (Iller), Landsberg am Lech (Lech), Landshut (Isar), Wasserburg (Inn) and Burghausen (Salzach). The EIP time series of the river Wertach was merged between overlapping periods, verified by a high Pearson correlation coefficient ($r = 0.86$) between the data from the gauge stations Ettringen and Augsburg/Oberhausen. From 1900 onwards data were available from the Bavarian Water Authority.

To merge the different data periods, we used the following approach. To compare flood events from written historical sources with flood events measured by water level or discharge during the instrumental period, we used an existing intensity classification of historical floods which was adapted to the instrumental period. According to the scheme of Sturm et al. (2001), the flood events were classified into three intensity levels. The classification is based on damage reports and weather descriptions. If flood events were mentioned only by rudimentary descriptive information or damage was only minor, the event was classified as a regional flood (intensity Level 1). If damage of water-related structures (e.g. bridges, weirs and mills) or buildings near the rivers was reported or if there were indicators for long-lasting flooding of farmland, Level 2 was assigned to the flood. Catastrophic floods, as a rule reported from different river systems, associated with severe damage or destruction of water-related structures, loss of lives, long-lasting flooding of wide areas and geomorphological changes in the fluvial system, were classified as Level 3. The selected instrumental data are based on the monthly maxima of water level or discharge. The mean values of these measurements plus one, two or three standard deviations define the thresholds for the classification of the instrumental data (in case of water level data high-pass filtered data were used, see methods). According to experience in working with historical flood information, all floods of the descriptive period from intensity Levels 1, 2 and 3 were considered, whereas Level 1 events from the instrumental period were disregarded. An overlapping period (1826–1880) between the descriptive and the instrumental periods suggested this procedure. Samples of rudimentary descriptive flood information have shown that the traditional of historical flood information through time are mainly based on strong events (cf. Böhm, 2011).

To create a wide data base as possible, the time series "flood frequency of the Bavarian Foreland" uses all flood events of the outer alpine river sections in the Bavarian Foreland which could be gathered during the descriptive period, with and without source-critical verification. This process minimizes the loss of historical flood information due to anthropogenic or natural calamities. To avoid the usual criticism to not varied historical records, we refer to a "non critical approach" (NCA), a methodical practice verified inter alia by cross-comparison with verified records, e.g. HISKLID (cf. Böhm, 2011). The NCA is a procedure especially designed for extraordinary hydrological events. Within the range of historical climatic data, flood information has an exceptional position. Common threads connecting all flood informations are damages which have led to burdens on former neighbors. The main argument for the NCA is based on the reasonable assumption that historical flood reports – due to the particular burdens – contain more objective information than other climatic descriptions. Therefore, floods can act as an indirect climatic indicator.

4 Methods

In Fig. 2 the monthly maxima of water levels of the example gauge Ettringen/Wertach (35 km south of Augsburg) before (a) and after (b) high-pass filtering are depicted. Figure 4a shows the deepening of the riverbed due to anthropogenic encroachment into the river system. The beginning of this deepening took place around 1860. Since the administration did not change the datum of the measuring device for a time, but instead extended the measuring sticks of the gauges into the negative range, a total riverbed incision of more than 6 m within 30 years can be documented. Furthermore, first counter-measures (like lateral water-buildings) obviously occurred around 1870. Around 1885 the incision seems to be stopped. After a short data gap around 1895, two datum changes can be identified. The high-pass filtering seems to be the most suitable method to address these different changes.

To better understand the long-term development of flood events in the Bavarian Foreland, normalized 31 year running flood frequencies have been calculated as in many earlier studies (e. g. Glaser, 2008). To reveal the flood history of the entire Bavarian Foreland, all flood events within this study area have been merged into one overall time series. To integrate different historical sources and locations which refer to one meteorological event, a time-window including a maximum number of seven days before and after a designated event has been introduced. Therewith the varying duration of hydro-meteorological sequences (from the genesis of synoptic disturbances to the termination of flood waves) as well as the blur of historical informations can be considered. For example, the summer flood of the year 1501 which was one of the biggest floods since the beginning of written records (quantitative evidence in terms of a flood mark is located at the “Fischmarkt” in Passau, Bavaria), has been recorded in the IBT more than 150 times. This event is counted only once in the 31 year running flood frequency of the Bavarian Foreland.

The determinations of flood-rich and flood-poor periods are based on a polynomial function of the 5th degree for the running flood frequencies (see red graph in Fig. 3). In general, the intervals above/below the function graph are defined as flood-rich/flood-poor periods. Due to the changing data basis over the entire time series, it was necessary to interpolate in some cases. Different databases and data densities (e.g. 14th/15th century – the period of the Renaissance – beginning of the instrumental period) were thus considered as well as possible.

4.1 Statistical significances

The time series for the Bavarian Foreland has been submitted to a two-sided t-test which can identify fracture points within the time series (cf. Glaser and Stangl, 2003b). The α level of 0.05 (solid line) is depicted in Fig. 4. Most of the detected fracture points coincide with changes in atmospheric conditions (see next section). The flood frequency time series of the Bavarian Foreland has additionally been correlated with reconstructed NAO index-values (cf. Luterbacher et al., 2002) as well as with moving mean sunspot numbers (data after Hoyt and Schatten, 1997). Significant correlations between these quantities include the consideration of inherent autocorrelations (cf. Werner, 2002).

5 Results

In Fig. 3 the flood history of the Bavarian Foreland between AD 1300 and 2010 is depicted. Based on a polynomial function of the 5th degree (see the red line), 9 flood-rich and 8 flood-poor periods can be identified. The polynomial function matches best in view of the different data density from early historical times until the present day. A rising data density after the mid-15th- century must be seen in a context of the invention of letterpress. Single flood-rich periods will be discussed below. In order to prove significant changes within the time series of the 31 year running flood-frequencies of the Bavarian Foreland, we have depicted the estimators of the t test in Fig. 4 (cf. Glaser and Stangl, 2003b). In this context, changing climatic parameters like the NAO index and the sunspot numbers will be approached briefly (a more extensive discussion follows subsequently).

5.1 Flood-rich period #1: 1300–1335

The first flood-rich period, though with a low data density, can be associated with changes in the atmospheric framework. Wanner et al. (2000) are dating the onset of the Little Ice Age at the beginning of the 14th century, based on Miller et al. (2012), triggered by multiple volcanic eruptions. Period #1 coincides with the beginning of LIATE3, a first period of advancing glacier tongues during the Little Ice Age, additionally enhanced by the Wolf solar activity minimum (1282–1342, cf. Glaser, 2008). Following the sunspot numbers after Usoskin et al. (2004), the first flood-rich period exactly coincides with a period of sunspot minima. According to Fig. 4, the *t* test value shows significant changes with the beginning and the end of Period #1. The estimator declines during the flood-active phases (this can be verified for most of them). While LIATE3 approaches a climax, the flood frequencies decline considering a time lag due to mass input into the alpine glaciers (cf. Wanner et al., 2000). Most of the significant fracture points in Fig. 4 coincide with the beginning and the end of the flood-rich or flood-poor periods in Fig. 3.

5.2 Flood-rich period #2: 1370–1450

The increase of flood frequencies is accompanied by significant *t* test estimators. Despite the absence of significant estimators, the end of period #2 coincides again with changing climate conditions characterized by the beginning of the Spoerer Minimum, another sunspot minimum between the years 1450 and 1534 (cf. Glaser, 2008).

5.3 Flood-rich period #3: 1470–1525

The transitional period between the flood-poor-period #2 and the flood-rich-period #3 coincides with an obviously rising estimator (significant at the α-level 0.05) as well as with the end of a distinct period of negative temperature anomalies in the Alps (cf. Wanner et al., 2000). The end of period #3 is marked again by highly significant *t* test estimator values. The maximum value is accompanied by the end of the Spoerer Minimum, again an indication for changing climate conditions which affect the flood frequencies in the Bavarian Foreland.

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From 1500 onwards we can use reconstructed NAO-Index (NAOI) values (cf. Luterbacher et al., 2002). The end of period #3 (= first grey bar in Fig. 5) is accompanied by an obviously declining NAOI for annual (Fig. 5) as well as summer seasonal values (Fig. 7). Due to the impact of precipitation to the entire hydrological year on flood progress, the full year development of the NAO may reflect mean weather conditions. In general, however, the correlation between weather conditions and the NAOI is more significant during the winter than the summer half of the year.

5.4 Flood-rich period #4: 1555–1590

Between the years 1550 and 1700 the normalized NAOI is generally characterized by low index-values. Within this period, variations in flood frequencies can be identified (see Fig. 5) with increasing and declining values being accompanied by rising and falling NAOI-values, respectively, for the whole year as well as for the seasons of winter (not shown) and summer (cf. Fig. 7). The *t* test estimator indicates significant values (> 2.00 at α-level of 0.05) at the beginning and significant values at the end of period #4 (cf. Fig. 4). The flood frequency maximum coincides with a distinct period of negative temperature anomalies that lead into LIATE2.

5.5 Flood-rich period #5: 1615–1665

Period #5 is again accompanied by significant *t* test estimators as well for the beginning as for the ending (see Fig. 4). The transition period between period #5 and the Maunder Minimum (1645–1715, cf. Schönwiese, 2008) is accompanied by a conspicuous behavior of the *t* test estimator, a possible evidence for unsettled atmospheric conditions. Period #5 took place during LIATE 2 (1570–1640, cf. Wanner et al., 2000); the retreat of the glacier tongues (peak around 1650) coincides with declining flood frequencies. Period #5 also fell into a period of declining sunspot numbers which have been directly observed for the first time since 1610 (cf. Fig. 6). The absolute minima of sunspots starting in 1660 turned into the Late Maunder minimum and were accompanied by the absolute flood frequency minimum from 1500 till today. With the beginning of direct sunspot number observations, we can refer to a distinct correlation between the 31 year moving sunspot numbers and flood-rich and flood-poor periods until 1930. The end of LIATE 2 coincides with the beginning of the Maunder Minimum, compare Fig. 5 and Wanner et al. (2000).

The flood frequencies are rising while the mean NAOI-values for the full year are declining; the flood frequency peak coincides with minimal NAOI-values. The following decline of the flood frequencies is accompanied by rising NAOI-values (see Figs. 5 and 7). The development of the winter NAOI reveals a different pattern. The absolute maximum value of flood frequencies coincides with a short-termed increase of the winter NAOI. This could be an indication for wet winter conditions resulting in vast water retention which could favor summer floods during snow melt.

5.6 Flood-rich period #6: 1730–1780

Period #6 is again marked by significant *t* test estimators during increased flood frequencies; the end of the period is marked by a distinct evolution of the estimator values. The *t* test estimators in general will not show significant variations for the next 80 years (cf. Fig. 4). Period #6 is accompanied by a noticeable development of the NAOI-values. The whole-year development shows a parallel increase of flood frequencies and NAOI-values, but during the flood frequencies' peak the NAOI-values decline in a distinct way (cf. Fig. 5). The development of the Little Ice Age in terms of glacier tongue movements shows a slight stagnation.

The following flood-poor years until 1820 are characterized by a next sunspot minimum, the Dalton Minimum (1790–1830, cf. Schönwiese, 2008), again accompanied by relatively low flood frequencies (see Fig. 3). The end of the Dalton Minimum and the beginning of the next flood-rich period is accompanied by extreme flood frequencies (cf. Fig. 3) as well as extraordinary *t* test estimators (cf. Fig. 4). The reasons for this will be explained below.

5.7 Flood-rich period #7: 1820–1870

Period #7 is marked by a changing database (transition between documentary period and early instrumental period). In addition, it represents the beginning of the transition period between the end of the Little Ice Age and the beginning of the Modern Climatic Optimum as well as the beginning of (systematic) anthropogenic interference into the natural river systems. Thus, period #7 falls into a section of different overlapping trends. The *t* test estimators reveal this transition at the beginning of the period (unique *t* test estimator values, see Fig. 4). The end of the period, based on *t* test estimators, can be interpreted as inhomogeneous climatic conditions during the transition to the Modern Climatic Optimum. The increasing flood-frequencies of period #7 coincide with increasing sunspot numbers (cf. Fig. 6).

The development between LIATE1 (1810–1850) and period #7 requires a particular reflection, because LIATE1 and the flood-rich period end at about the same time, whereas the preceding LIATEs (# 3 and #2) did not end at the same time like the corresponding flood-rich periods. The maxima of the preceding LIATEs fall into intervals of low flood frequencies framed by the end and the beginning of flood-rich periods. A noticeably aligned development between the NAOI-values and the flood frequencies can be highlighted for the whole year as well as for the summer and winter seasons (cf. Figs. 5 and 7). The following years are characterized by both declining flood frequencies and NAOI values. In this context we can generally identify an increasing impact and significance of the summer NAOI for the development of flood frequencies in the Bavarian Foreland (discussion see below).

5.8 Flood-rich period #8: 1910–1955

Period #8 is again framed by significant *t* test estimators with a last significant estimator-value within the time series (see Fig. 4). Until 1930 similarities (or correlations) between flood frequencies and sunspot numbers do exist. Thereafter these time series seem to be decoupled, as depicted in Fig. 6. The beginning of period

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#8 coincides with rising NAOI-values, the amplitude of these values in general shows a parallel development (cf. Figs. 5 and 7).

5.9 Flood-rich period #9: 1980 – ?

A last flood-rich period starts in 1980 intersecting with the end of the time series. Due to the use of 31 year running quantities, its validity remains unclear.

5.10 The flood frequencies of the Bavarian Foreland accompanied by different climatic conditions in detail

5.10.1 The correlation of flood frequencies and sunspot numbers

The meaning of varying solar activity for the climate conditions is currently a matter of fierce discussion (cf. Shindell et al., 2001; Feulner and Rahmstorf, 2011; Feulner, 2011). Generally the variability of solar activity can affect the large-scale atmospheric circulation including climate parameters like temperature, precipitation and transpiration (cf. Endlicher and Gerstengarbe, 2007). Despite the uncertainty in which way solar activity could have an effect on climate development within the research area, it can be shown that solar trends (of different sign) coincide with changing climatic conditions which affect the flood frequencies in the Bavarian Foreland. Within these relationships, one conspicuousness must be emphasized but not discussed at this point. It has to be distinguished between direct observations and reconstructions based on proxy data. Both periods differ with respect to the sign of the correlation between flood frequencies and solar activity. In general, before direct observations started, high flood frequencies coincided with reduced solar activity, while afterwards flood-rich periods coincided with increased solar activity. The best fit between the 31 year running frequencies is achieved with direct observations starting in 1610 and ending with the years around 1930 (cf. Fig. 6). The year 1930 occupies a special position which will be discussed later on. Considering the four sun-spot minima encompassed within the investigation period, we can chronicle the following:

The Wolf Minimum (~ 1280–1340) coincides with the first calculated flood-rich period. This temporal correspondence between high flood activity and low sunspot numbers is unique within the total time series (cf. Fig. 3).

The duration of the Spoerer Minimum differs amongst different authors. According to Glaser (2008), the Spoerer Minimum takes place between the years 1450 and 1534, whereas Schönwiese (2008) identifies the years 1400–1510. According to the first definition of the Spoerer Minimum, another sunspot minimum coincides with a flood-rich period (here period #3). According to the sunspot data of Usoskin et al. (2004), the flood frequency maximum of period #3 also corresponds to the low sunspot numbers of the Spoerer Minimum.

With the beginning of the Maunder Minimum period the relationship changes its sign. As depicted in Fig. 6 running flood frequencies and sunspot numbers are varying in a similar way. The course of both graphs during the Dalton Minimum (1790 – 1830) again shows a similar development. These data indicate a significant trend, between the years 1610 and 1995 the Pearson correlation coefficient amounts to 0.62, between 1700 and 1930 to 0.7. Considering autocorrelation could be achieved by using the effective sample size based on a method by Werner (2002) which regards the statistical persistence of database-inherent autocorrelations ($\alpha = 0.01$). After 1930, the relationship of sunspot numbers and flood frequencies seems to be decoupled. A comparison of global temperatures and GAR (Greater Alpine Region) temperatures shows a temperature leap over the calculated neutral-point temperature development since the beginning of the early instrumental period (cf. Auer et al., 2007).

Not all flood-rich and flood-poor periods can be connected to sunspot minima or maxima, but all sunspot extremes can be connected to changes of overall climatic conditions independent of its trends (cf. Böhm, 2011).

5.10.2 Correlations of flood frequencies and NAOI-values in detail

Is it possible to associate (in a statistical sense) the variability of the NAO and the flood history of the Bavarian Foreland? Based on the reconstruction of the NAOI by Luterbacher et al. (2002), the time series of the flood frequencies (31 year running mean values) and of the NAOI (likewise 31 year running mean values) can be com-pared from AD 1500 onwards (cf. Figs. 5 and 7). The NAO is one of the dominating teleconnection-patterns regulating the regional characteristics of many climatic parameters. The NAO also reveals seasonal variations (in context of the climatic seasonal cycle).

The annual and the summer time series of flood frequencies and of NAOI-values have been compared. The confrontation of the annual valuables is depicted in Fig. 5, the comparison for the summer seasonal in Fig. 7. The particular importance and the general dominance of summer floods in the Bavarian Foreland were already accosted. The winter flood occurrences are mainly relevant in terms of the retention potential of the alpine catchment areas which supports the development of floods in general. In spite of the general decline of the NAO importance during summer, significant correlations of the NAO (-index) and the time series of summer floods can be recognized. In a first step 100 year intervals have been considered. For the centuries 1500–1599 ($r = 0.78$, $\alpha = 0.01$) and 1900–1999 ($r = 0.65$, $\alpha = 0.01$) significant correlations occur (again verified by the calculated persistence). Shifting the time-interval by 50 years, a significant correlation can be observed for the period 1650–1749 ($r = 0.8$). Further-more, the years from 1830 to 1999 exhibit another highly significant correlation coef-ficient of $r = 0.8$ ($\alpha = 0.01$). The changing sign in the relationship around 1820 (cf. Fig. 7) coincides with the important transition period between the Little Ice Age and the Modern Climate Optimum.

6 Discussion

The flood history of the Bavarian Foreland could be analyzed in a statistical way from the beginning of the 14th century onwards (based on the existing data). The flood history of the entire Bavarian Foreland was compiled and analyzed, based on both documentary and instrumental data. We could identify statistical correlations between the flood frequencies and conditions of the atmospheric framework up to today based on different climate proxies and historical observations and transmissions.

The investigation period commences amid the latest climatic depression of the Subatlantic stage (2.5 ka–present) until today. Despite the reduced availability of data at the beginning of the time series including the absence of reconstructions of pressure fields, temperature and precipitation (until 1499), significant changes in the correlation between climate conditions and flood frequencies can be identified. Virtually each shift in the flood frequencies' trend (towards flood-rich or flood-poor periods) coincides with significant fracture points within the time series (according to two-sided t tests). These fracture points provide indications of changing atmospheric conditions which may affect the flood development in general.

The NAO is of particular importance for the climatic conditions in the Bavarian Foreland as well as in the Alps in general. However, according to Casty et al. (2005), the NAO alone cannot explain the very sophisticated climatic events of the Greater Alpine Region (GAR). The present work describes multiple mechanisms with influences to major atmospheric conditions. With a view towards the changing directions of the flood frequencies the shifts themselves within multiple climatic factors are playing an important role in the climatic circumstances of flood development. In this context, the dominant role of the summer NAO from 1830 onwards is conspicuous. This atmospheric parameter coincides with the beginning of the transition period between Little Ice Age and Modern Climate Optimum. Till the end of the time series, high correlation coefficients do exist. For this special period a statistical unique coherence within the present work can be emphasized.

Another remarkable influence on flood frequency development might come from solar activity. Despite marginal changes of global radiation, the correlation between flood frequencies and sunspot numbers from 1610 till 1930 is high. For the Maunder Minimum, the solar radiation was merely reduced by about 0.24 % (compared with the present mean value, cf. Lean and Rind, 1998). This means a cooling effect of 0.5 °C for the Northern Hemisphere (at the most). Seemingly, the slight change of solar radiation should lead to a significant alteration of atmospheric fluxes, particularly concerning the moisture content of air masses. Nevertheless, the high correlation between flood frequency and solar activity cannot explain the mechanism of action from the solar surface through the atmospheric stories towards the surface. To explain this mechanism of action further investigations are necessary.

After the year 1930, the natural relationships seem to be superimposed by an increasing anthropogenic influence on the climatic conditions. In this context a decoupling of a retrograde signal could be revealed. That assumption will be indicated by trespassing the threshold of the average temperature deviation for the GAR in 1930 (cf. ZAMG, 2011).

The current report emphasizes the importance of long time series. The complexity of northern hemispheric (or even global) circulation dynamics as well as the range of natural climate variability is, however, only partially understood.

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Table 1. Reference data of the Bavarian Foreland rivers, modified after different authors. The information "Medium Discharge Summer" refers to the lowest official downstream gauge.

River	Headwaters	Rivers Length	Overground Catchment Area	Medium Discharge Summer
Iller	Allgäu High-alps (Germany)	~ 160 km	2215 km^2	79.3 m^3 s^{-1} (Gauge Wiblingen)
Wertach	Allgäu Alps (Germany)	~ 135 km	1290 km^2	16.7 m^3 s^{-1} (Gauge Türkheim)
Lech	Rhaetic Alps (Austria)	~ 250 km	4162 km^2	136 m^3 s^{-1} (Gauge Augsburg)
Isar	Karwendel Mountains (Austria and Germany)	~ 260 km	8960 km^2	191 m^3 s^{-1} (Gauge Plattling)
Inn	Maloja Saddle (Switzerland)	~ 520 km	26 100 km^2	972 m^3 s^{-1} (Gauge Passau)
Salzach	Kitzbühl Alps (Austria)	~ 220 km	6700 km^2	332 m^3 s^{-1} (Gauge Burghausen)

Table 2. Seasonal distribution of flood events (percentages refer to the individual outer alpine river sections) in the Bavarian Foreland for the period 14th century–2008.

	Iller	Wertach	Lech	Isar	Inn	Salzach
Summer	42 %	39 %	57 %	58 %	79 %	73 %
Spring	16 %	20 %	14 %	14 %	10 %	6 %
Winter	28 %	23 %	12 %	12 %	2 %	7 %
Autumn	14 %	18 %	17 %	16 %	9 %	14 %

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Flood history of the Alpine Foreland of Germany in context of climatic circumstances

O. Böhm et al.

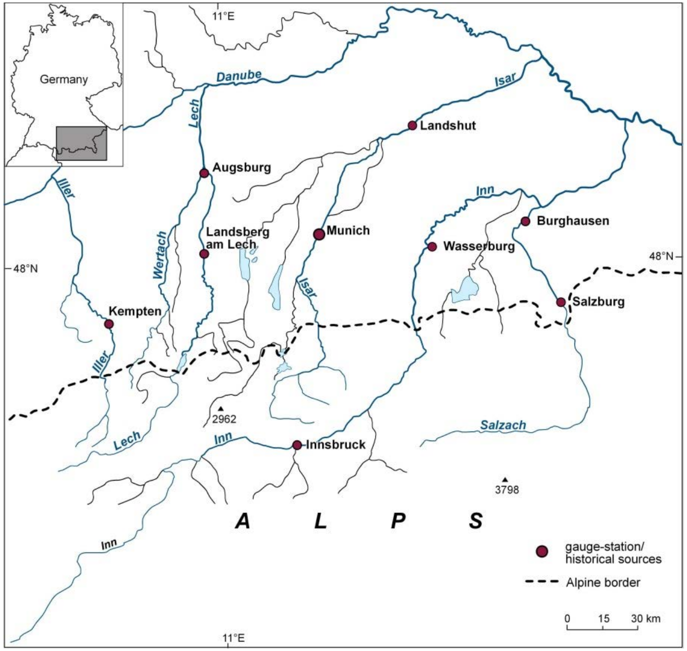

Figure 1. Research area of the Bavarian Foreland (located between the Alpine Border and the Danube) including the investigated rivers from the northern Limestone Alps.

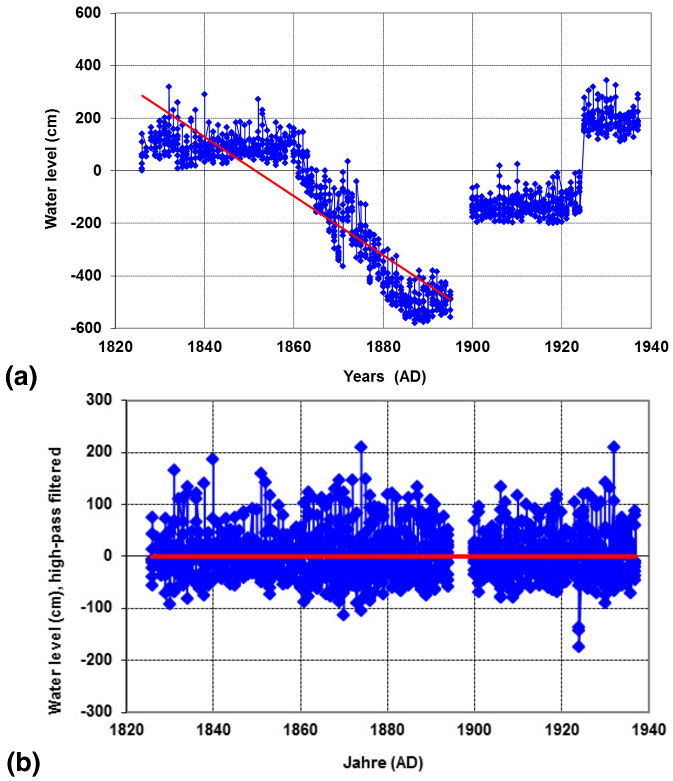

Figure 2. (a, b) Monthly maxima of water level (in cm) 1826–1937 at gauge Ettringen/Wertach (35 km south of Augsburg). **(a)** Original data from official records, **(b)** high-pass filtered data.

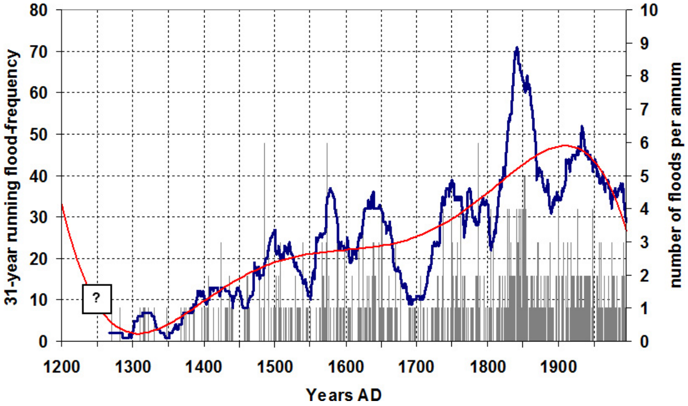

Figure 3. 31 year running flood frequencies of the Bavarian Foreland. Right ordinate: grey columns show the annual flood frequencies.

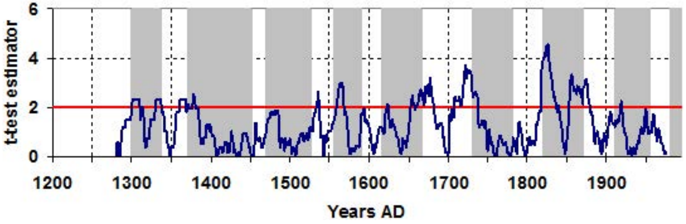

Figure 4. 31 year running *t* test estimator of flood frequencies of the Bavarian Foreland, threshold value for the two-sided *t* test is 2.00 (see red line). Grey bars label flood-rich periods #1 to #9.

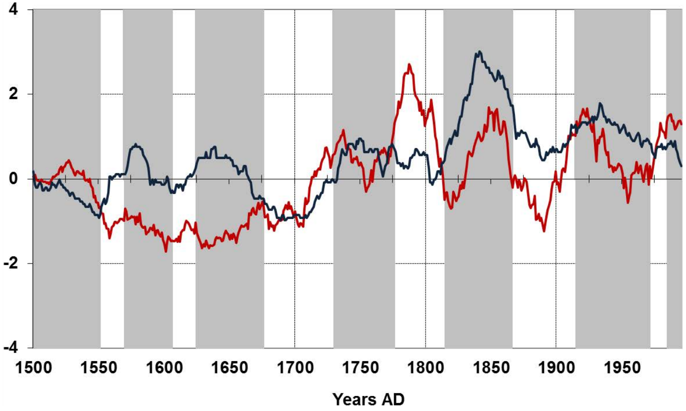

Figure 5. Normalized time series of annual 31 year running flood frequencies in the Bavarian Foreland (blue) and of annual 31 year running NAOI (red) (NAOI data after Luterbacher et al., 2002). Grey bars label the flood-rich periods #3 to #9 based on the full-year development.

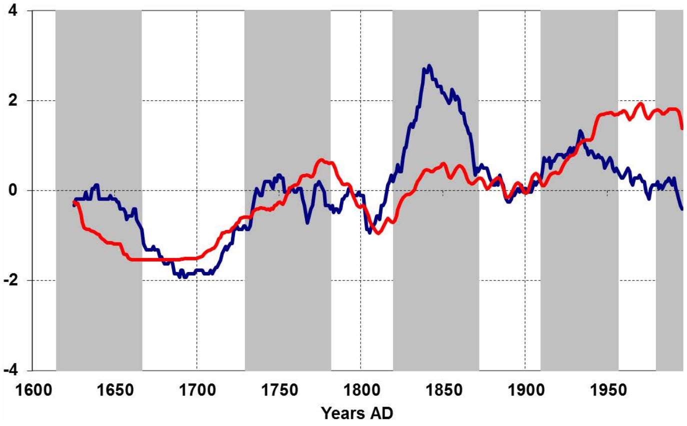

Figure 6. Normalized time series of annual 31 year running flood frequencies in the Bavarian Foreland (blue) and "sunspot activity" (red) since 1610 (Data for sunspot activity modified after Hoyt and Schatten, 1997). Grey bars label the flood-rich periods #5 to #9 based on the full-year development.

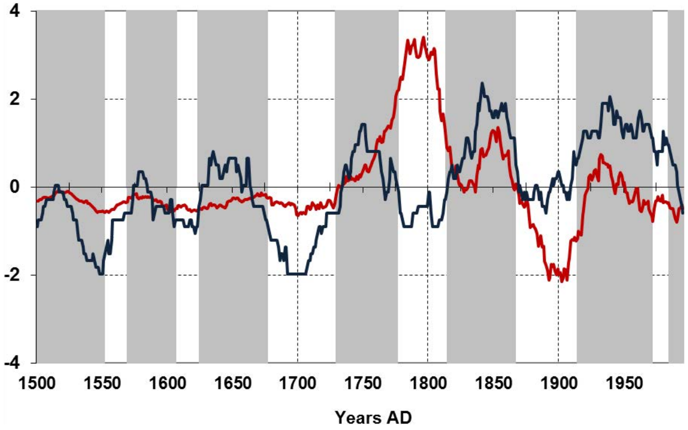

Figure 7. Normalized time series of 31 year running flood frequencies in the Bavarian Foreland (blue) and NAOI values (red) for the meteorological summer (JJA) (NAOI data after Luterbacher et al., 2002). Grey bars label the flood-rich periods #3 to #9.