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The variability of European floods since AD 1500

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Abstract The paper presents a qualitative and quantitative analysis of flood variability and forcing of major European rivers since AD 1500. We compile and investigate flood reconstructions which are based on documentary evidence for twelve Central European rivers and for eight Mediterranean rivers. Flood variability and underlying climatological causes are reconstructed by using hermeneutic approaches including

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critical source analysis and by applying a semi-quantitative classification scheme. The paper describes the driving climatic causes, seasonality and variability of observed flood events within the different river catchments covering the European mainland. Historical flood data are presented and recent research in the field of historical flood reconstructions is highlighted. Additionally, the character of the different flood series is discussed. A comparison of the historical flood seasonality in relation to modern distribution is given and aspects of the spatial coherence are presented. The comparative analysis points to the fact that the number of flood events is predominately triggered by regional climatic forcing, with at most only minor influence on neighbouring catchments. The only exceptions are extreme, supra-regional climatic events and conditions such as anomalous cold winters, similar to that of 1784, which affected large parts of Europe and triggered flood events in several catchments as a result of ice-break at the beginning of the annual thaw. Four periods of increased occurrence of flooding, mostly affecting Central European Rivers, have been identified; 1540–1600, 1640–1700, 1730–1790, 1790–1840. The reconstruction, compilation and analysis of European-wide flood data over the last five centuries reveal the complexity of the underlying climatological causes and the high variability of flood events in temporal and spatial dimension.

1 Introduction

Floods are regarded to be one of Europe's most widespread disasters causing large losses. The recent extreme floods of 1990, 1993 and 1995 on the rivers Rhine and Meuse (Heylen 1995; Ulbrich and Fink 1995) and those of 1997 and 2002 on the Elbe (Labe) and Oder River (Ulbrich et al. 2003a, b) show a sequence of so-called "100-year events" which, nevertheless, occurred in a short interval of time. To some extent, this higher number of observed severe floods is assumed to be induced by climate change. In this regard, emphasis recently has been put on statistically analysing flood occurrences, return periods, probabilities and the vulnerability of economy and society to those events (Kundzewicz and Robson 2004; Lindström and Bergström 2004; Radziejewski and Kundzewicz 2004; Kundzewicz et al. 2005; Svensson et al. 2005). In order to gain insight into the frequencies of the occurrence and impact of floods and the vulnerability of societies, Barredo et al. (2007) compiled flood events in several states of the European Union since 1950. It was concluded, that there is a need for long, comprehensive, geo-referenced and verified compilations to evaluate and research floods in Europe in the context of risk analysis. The loss of 155 lives and costs of € 35 billion by the major flood events from 2000 to 2005 point clearly to the need for coordinated mitigation strategies on a European wide scale (Barredo et al. 2007).

Additional interest in forecasting and modelling of future river behaviour responds to economic considerations in general as well as to the insurance industry's

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needs, and as humans extend their settlements into potentially unsafe areas. However, many available instrumental records are insufficient to provide representative information about return periods of catastrophic flood events or the influence of climatic forcing (Pohl 2004a, b; Bürger et al. 2006). Scientists and water management engineers agree that the study of flood variability needs to be investigated on a longer time scale perspective. To address this, a number of projects have been undertaken, such as the SPHERE project (Benito and Thorndycraft 2004; Benito et al. 2004b) which have brought together flood researchers investigating the historical river behaviour in Southern France and Eastern Spain in a multidisciplinary approach. For the French–German–Swiss border region the ongoing project TRANS-RISK is addressing similar research questions (Deutsch et al. 2010).

Based on documentary evidence we have analysed flood occurrences and their impacts in Europe. Many of them display long term changes in flood occurrence and flood frequency, e.g. for Italy (Camuffo and Enzi 1994, 1995, 1996; Camuffo 1995; Camuffo et al. 2003) and for the Iberian Peninsula (Díez-Herrero et al. 1998; Fernández de Villalta et al. 2001; Benito 2003; Benito et al. 2003, 2004b; Barriendos and Rodrigo 2006). Brázdil et al. (1999) investigated the occurrence of extreme flood events in Central and Southern Europe for the sixteenth century. Pfister (1999) focused the same analysis on Swiss rivers. Both papers concluded that there are long-term changes in flood frequencies, which can be correlated with the main periods of the so called Little Ice Age (LIA). Glaser and Stangl (2003) analysed causes and effects of flood events of the lower Rhine River and the Rhine delta area and detected multiple factors such as morphological changes following frequent flood periods which can lead to changes in the main reaches of the river. Hesselink (2002) investigated the morphological history of the lower Rhine River and added valuable insight into morphological changes by identifying the anthropogenic impact on a river system. Brázdil et al. (2005) presented a series of floods for the rivers Elbe, Vltava, Ohře, Morava and Oder in the Czech Republic based on documentary data and hydrological measurements. Mudelsee et al. (2003, 2004) studied records of winter and summer floods of the Elbe and Oder River in Germany and found only a weak correlation between them although the two rivers are located relatively close to each other. Böhm and Wetzel (2006) confirmed the existence of periods of a weaker correlation of long-term flood frequencies for similarly neighbouring river systems. This might be the result of technical alterations, different medium scale meteorological situations or morphological characteristics of the catchment area. For example, they identified some bogs in the Isar catchment, which buffered the discharge peaks. In the same paper there is also a detailed presentation of the correction of early instrumental data and historical information in relation to modern run-off records. In addition, changes in land use and land cover contribute to the characteristics of the flood and the river bed itself (Gerlach 1990; Deutsch 2007). In particular, the alteration of riverbed and riparian structures during the era of the industrialization had a strong impact on the run-off characteristics (Sudhaus et al. 2008). Glaser and Stangl (2003) showed that morphological changes within the river system, as for example moving positions of sandbanks, could similarly alter the flood characteristic of the river. Floods can also influence the morphological structure of the river basin if given enough time thereby demonstrating the main characteristics of a feedback operation (Thorndycraft et al. 2003). It is important to note that all these control mechanisms are mutually interacting and hence contribute to defining flood variability and magnitude.

An important aspect of the interpretation of long-term flood records is related to the derivation of their meteorological forcing (Brázdil et al. 2006). Jacobeit et al. (2003) studied the relationship between flood frequency and atmospheric circulation changes. They concluded that flood catastrophes during historical times, as in for example LIA, could be linked to a prevailing circulation mode such as the dominant Atlantic low and a Russian high. On the other hand a prevailing zonal circulation pattern is thought to be linked to floods in the twentieth century. In particular the presence of high-pressure systems during boreal winter over western Russia and/or Fennoscandia lead to long-lasting frosty winter conditions over mainland Europe. Under these persistently cold conditions, most of the larger rivers, or at least the wet or flooded area of the floodplains, froze. The floods caused by ice had often been triggered by an advection of warm air masses causing rain and (partly) the melting of the snow cover within the catchments, which lead to rising river levels and the detachment and downstream movement of the ice blocks. This was, for example, the case during the AD 1784 flood event on the river Main. The ice was dammed at obstacles and thereby destroyed structures like bridges and most of the mills (Glaser and Hagedorn 1990; Demarée 2006; Brázdil et al. 2010). There is also evidence that some of these long-term changes can be explained by changes in the circulation mode, which can be understood as system-internal changes caused by variations of the circulation mode itself (Jacobeit et al. 2006). In this context, Bárdossy and Caspary (1990) have identified the primary importance of westerly flow types linked with the positive mode of the North Atlantic Oscillation (NAO) for Central European flood events in the cold season for the more recent past.

While the above-mentioned papers are related to large-scale phenomena, there are some more recent case studies based on small-scale phenomena with daily resolution showing different results. Bürger et al. (2006) conducted a detailed reconstruction of the flood event at the Neckar river in October 1824 linking it to its meteorological causes. They focused on the relation of forest-covered areas against bare ground and/or sealed surfaces. The findings confirm that the impact of surface sealing is very much dependent on the contemporary characteristics of the specific event.

Historical flood data can extend existing instrumental series and help to improve the statistical analysis of return periods and flood intensity. In addition, historical flood evidence provides detailed background information on the impacts of hydrological extremes on society, as well as on the different adaptation strategies developed over the ages. The major advantage of historical data is the high-quality dating control, the mostly precise description of the underlying causes, the temporal development of the flood-event, the damages and their impacts on society as well as their defined spatial coverage. The spatial significance of historical data however comes with the need for a large number of observations to provide information over an extended area, like an entire river system. However, available historical information is in most cases limited to a few sites on each river, decreasing the significance of the flood analysis with increasing distance to the river and the points of where information is available.

The presented series of flood events for the rivers Aare, Adige, Arno, Danube, Guadalquivir, Ill, Elbe, Llobregat, Main, Meuse, Oder, Pegnitz, Piave, Rhine, Segura, Tiber, Vistula, Vltava and Werra and their tributaries provide such detailed information. The available reconstructions show the potential for the analysis of flood trends and variability of each catchment in terms of flood frequency, meteorological causes and seasonality. Moreover, we aim to provide a spatially comprehensive history and analysis of mainland European flood variability since AD 1500. In particular, we focus on two well-known climatic periods of the last 500 years, the LIA and the Modern Optimum, to investigate the coherence of the long-term flood frequencies with regard to extreme climatic states. Furthermore a comparison of the historical flood seasonality in relation to the modern distribution is given and aspects of the spatial coherence are presented on the basis of a descriptive interpretation as well as on the basis of a Principal Component Analysis (PCA).

2 Study sites

The different regional aspects of the river systems, catchment specifications, geographical and hydrological characteristics are summarized in Table 1. The location of the rivers and their catchment areas are presented in Fig. 1. Spreading over four climatic zones between maritime sub-tropical for the Mediterranean rivers to continental and moderately warm mid-latitudes according to the Köppen classification (Köppen 1931) the selected rivers also show distinct regional characteristics regarding river discharge, landscape settings and fundamental technical modifications (e.g. Spreafico and Aschwanden 1991; Weingartner and Spreafico 1992).

3 Data and methods

In Europe, climate information embodied in historical documents such as town chronicles, weather diaries and annals, are able to faithfully represent the period since AD 1500. Prior to the sixteenth century, written information is scarce and often restricted to severe and catastrophic events, while descriptions on small and medium impact floods are rare. For wide parts of Europe, the beginning of the sixteenth century can be regarded as a turning point with respect to the availability of sources. A notable increase in the availability of documentary information on climate-induced events came with the invention of the printing press developed by Johannes Gutenberg around AD 1439. The paper industry increased significantly and more people learned to read and write. This increase is mirrored in a rising density and quality of information. Figure 2 schematically illustrates the increasing number, quality and reliability of climatic information. The beginning of early instrumental readings is of considerable help for flood reconstruction as the recordings allow for the reliable calibration of historic climate reports. However, data from the early instrumental period often have several shortcomings. Most commonly, uncertainties emanate from not knowing the metric equivalent of the utilised unit, or the exact location where the measurement was taken or from the physical characteristics of the instrument itself.

The extraction of scientifically reliable data from historical sources and its re-expression as quantitative data is a difficult task. When dealing with historical data, the subjectivity of the written sources has to be considered. Since each individual observes and interprets a natural event based on personal experience and knowledge, it is essential to separate subjective from objective components within the document. The method of critical hermeneutics is suitable to deal with this task (Alexandre 1987; Glaser 1991, 1996, 2001, 2008; Pfister et al. 1999; Koenig 2007). First, in order

Table 1 Characteristics of rivers investigated

River	Length (km)	Catchment area (km^2)	Mean discharge (m^3/s)	Discharge range min–max (m^3/s)	Floods mainly triggered by	Discharge pattern	River bed correction (when/what/effects)	Order of river/empties into	Reference period	Main source of historic information
Aare	291	17,620	590	220–620	Convective rain	Pluvio-nival	1860s and 1970s the latter succeeded in mitigating heavy precipitation events	1/Rhine	1901–2007	Newspapers, meteorological observations, insurance calculations
Danube	115	7,536	10.8		Convective rain, long lasting-rain, snow melt	Pluvio-nival		0/Black Sea	1947–2004	Town archive of Ulm; uppermost part until Ulm
Ill	223	4,760	53.7	Up to 280	Snow melt, convective rain	Pluvio-nival	Normalisation and canalisation in tree attempts; 1846, 1856, 1873	1/Rhine		
Elbe (only CZ)	370	51,392	312	Up to 5,600	Snow melt, long lasting rain	Pluvio–nival		0/North Sea	1931–2000	Flood marks at Děčín, different documentary sources
Main	524	27,292	225	Up to 3,300		Pluvio-nival	To 1962, 34 barrages to enable traffic for vessels up to Vb	1/Rhine	1986–1995	
Meuse	353	34,548	350	30–3,000	Convective rain (leading to so called Meuse-surges (+10m in 24h))	Pluvial, pluvio-nival in earlier times	Normalisation and canalisation Meuse-surges don’t appear no longer, but floods do	0/North Sea	1931–2000	
Pegnitz	102	7,536	12	Up to 370		Pluvio-nival		3/Rednitz	1947–2004	

Rhine	1,324	198,735	2,330	Up to 5,000	Snow melt	Pluvio-nival	Several attempts starting with the normalisation of the Rhine between Basel and Karlsruhe by Tulla in 1817	0/North Sea		Between Worms and Lobith
Vltava	430	28,090	148	Up to 5,160	Snow melt	Pluvio-nival	1954,1962 barrages, mitigates flood impact up to century flood level	1/Elbe	1931–2000	Watermarks on different buildings
Werra	292	5,496	14–51	Up to 605	Convective rain	Pluvio-nival		1/Weser	1951–1980	
Adige	490	12,200	235		Snow-melt	Pluvio-nival	1950–1960, building of 29 barrages and underground canals,	1/Po	1931–2000	
Arno	241	8,228	110	0.56–3,540	Torrential rain	Pluvial	After 1966, building of barrages, sufficient flood protection since	0/Mediterranean Sea	1911–1998	
Barcelona non-perm. Rivers	< 10	< 100	–		Torrential rain	Pluvial			–	
Guadalquivir	640	57071	164		Torrential rain	Pluvial	Early barrages build for irrigation purposes did not affect flood frequency or severity; 1970, complex river regulation, reduction of severe floods	0/Mediterranean Sea	1950–1964	
Llobregat	157	4,948	20.8	−3, 080	Long lasting rain	Pluvio-nival	1971, barrage, diminish frequency of severe floods	0/Mediterranean Sea	1912–1971	

Table 1 (continued)

River	Length (km)	Catchment area (km^2)	Mean discharge (m^3/s)	Discharge range min–max (m^3/s)	Floods mainly triggered by	Discharge pattern	River bed correction (when/what/effects)	Order of river/empties into	Reference period	Main source of historic information
Piave	220	4,127	125	−4, 000	Torrential rain	Pluvio-nival		0/Mediterranean Sea		
Segura	325	19,525	26		Torrential rain	Pluvial	1970, complex river regulation, reduction of severe floods	0/Mediterranean Sea	1911–1950	
Tiber	410	17,375	267	100–2,000	Torrential rain	Pluvial	Slight modification of river banks before 1870; after 1870 construction of a new barrage, no more floods recorded afterwards	0/Mediterranean Sea		

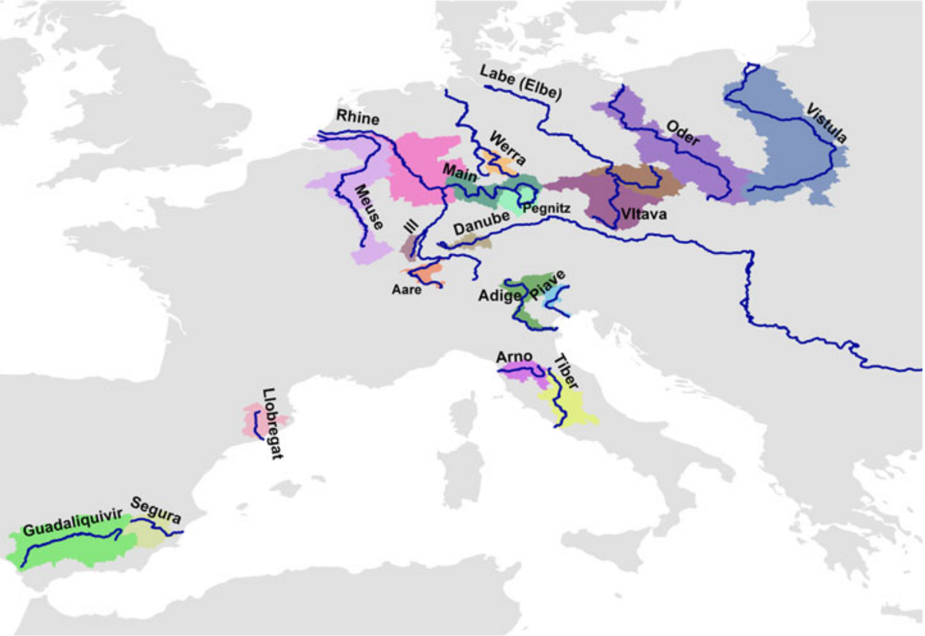

Fig. 1 Catchment areas and location of rivers studied

to understand and interpret the facts stated within the primary source text, it is of great importance to seek knowledge about the original author. Additionally, the circumstances and era in which the author was living and the educational and social

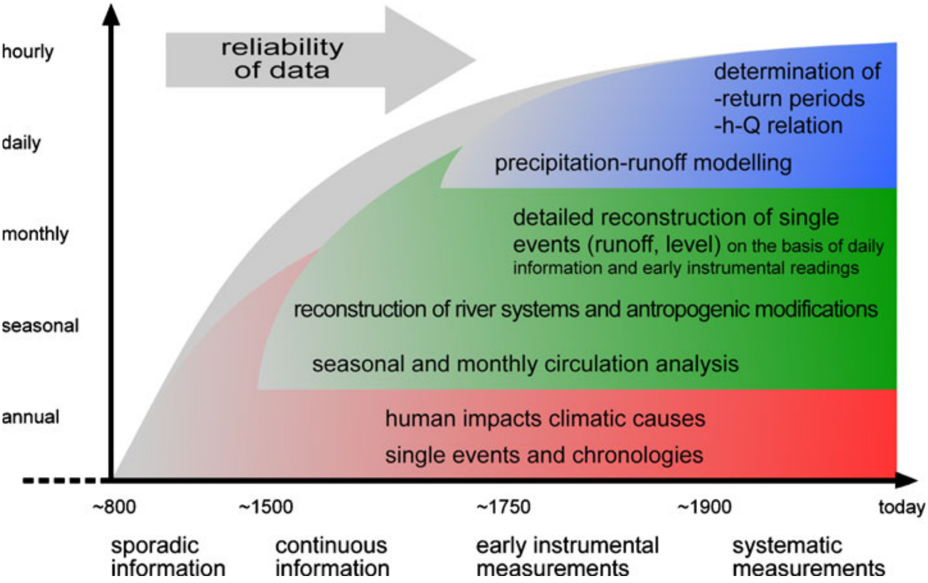

Fig. 2 Reliability, type and temporal coverage of available information and the appropriate analysis

background may have influenced their choice of words to describe a certain event. Furthermore, a bias in the chosen language may also emanate from the degree to which any individual was affected by the event in question. For example, a town chronicler would probably use a more moderate language to describe a disastrous event than a person who suffered personal loss.

Interregional comparison by means of source synopsis gives, if its quantity allows, additional information for the further evaluation of the data. Critical evaluation of sources, semantic profiles, the derivation of indices, calibration by means of regression analysis, comparisons with present-day standard data sets, regionalization, synoptic reconstruction, and comparisons based on descriptive statistical evaluations are methodological procedures which need to be used if historical data are going to be interpreted. Based on a combination of the hermeneutical profile and additional information, the reliability of any historic source can be determined and quantitative data can be extracted from the texts.

A common procedure for the derivation of semi-quantitative datasets is the classification of single historical flood events by deriving indices that reflect their degree of severity. A suitable approach was presented by Sturm et al. (2001) who introduced a classification scheme of three classes accounting for the severity of the damage, the duration of the flood and the spatial dimension (see Table 2). The documentary data used in this presentation have been classified according to this scheme, which is based on the assessment of information on severity of each flood, taking duration, spatial dimension, human impacts and damages into account. In historical climatology this method is widely accepted, because it is suitable and robust

Table 2 Scheme for the intensity-classification of historical floods (Sturm et al. 2001)

Level	Classification	Primary indicators	Secondary indicators
1	Smaller, regional flood	Little damage, e.g. fields and gardens close to the river, wood supplies that were stored close to the river are moved to another place	Short-term flooding
2	Above-average or supra-regional flood	Damage to buildings and constructions related to the water: dams, weirs, foot-bridges, bridges and buildings close to the river such as mills etc., water in buildings	Flood of average duration, severe damage on fields and gardens close to the river, loss of animals and sometimes people
3	Above-average or supra-regional flood on a disastrous scale	Severe damages to buildings and constructions related to the water: dams, weirs, foot-bridges, bridges and buildings close to the river such as mills etc., water in buildings. Buildings are completely destroyed or torn away by the flood	Duration of flood: longer; several days or weeks; severe damages on fields and gardens close to the river, extensive loss of animals and people. Morphodynamic processes such as sand sedimentation cause lasting damage and change to the surface structure

enough to cover possible uncertainties (Brázdil et al. 2006). Among others, Koenig (2007) and Luterbacher et al. (2010), demonstrate the quantitative applicability of documentary evidence in reconstructing climatic and hygric parameters.

In addition, a reliable proxy for floods can be found in historical flood markers on riverside structures or buildings. However, the proxy has to be verified against secondary information as the flood marks might have been moved over time.

Another important research field is the interpretation of the underlying meteorological causes. There is a wealth of direct information in many flood descriptions including for example the precise observation of the duration and intensity of a rainfall event. In addition, indirect information on the underlying cause of the described meteorological event is also often helpful, for instance the carrying capacities of sea- or river ice. Buisman and van Engelen (1994) reconstructed a dataset containing flood data of the river Meuse for the period of AD 858 to AD 1880. Based on the historical information the derived dataset contains additional information on potential flood causing effects. Melting of snow and ice, occurrence of thunderstorms or long lasting rain are distinguished. Such classification schemes have a long tradition (Baur 1947), and have been constantly improved and elaborated (Brázdil et al. 2002). In this paper we apply the methodological approach by Brázdil et al. (2002) to the historical data.

To evaluate the time dependent structures of the flood series of Central-West to Central-East European Rivers (CER) a PCA was performed. For the Mediterranean rivers (MR) the data set is not sufficiently continuous to allow a PCA to be conducted.

4 Results and discussion

4.1 Long-term series of flood events

The long-term series of flood events for the rivers Aare, Adige, Arno, Danube, Elbe (Labe), Guadalquivir, Ill, Llobregat, Main, Meuse, Oder, Pegnitz, Piave, Rhine, Segura, Tiber, Vistula, Vltava and Werra are presented in Figs. 3 and 4 in which the rivers are grouped regionally into the CER (Fig. 3) and the MR (Fig. 4). Both figures show the period between AD 1500 and AD 2000.

A certain similarity between the flood frequencies of the CER is visible in Fig. 3. However, observed flood frequencies are not synchronous over the observed time period. However four noticeable periods can be identified within which some of the observed river systems display a similar behaviour.

Being characterized by similar flood frequency behaviour of five CER river systems (Rhine, Main, Pegnitz, Vltava and Elbe) an increase in flood frequency can be observed during the late 1540s, reaching its peak during the 1570s and ending around AD 1600. It is noticeable, that this signal is not being reproduced simultaneously: the Main/Pegnitz system seems to react with increased flood occurrences starting about a decade prior to the Rhine, Vltava and Elbe. Interestingly, this phase is, to a minor degree, also visible in the variability of the Mediterranean rivers of the Piave and Arno.

This phase is followed by a period of constant or slightly decreased occurrence of floods until the late 1630s which can be reconstructed for all Central and East European rivers with the exception of the Rhine and Meuse.

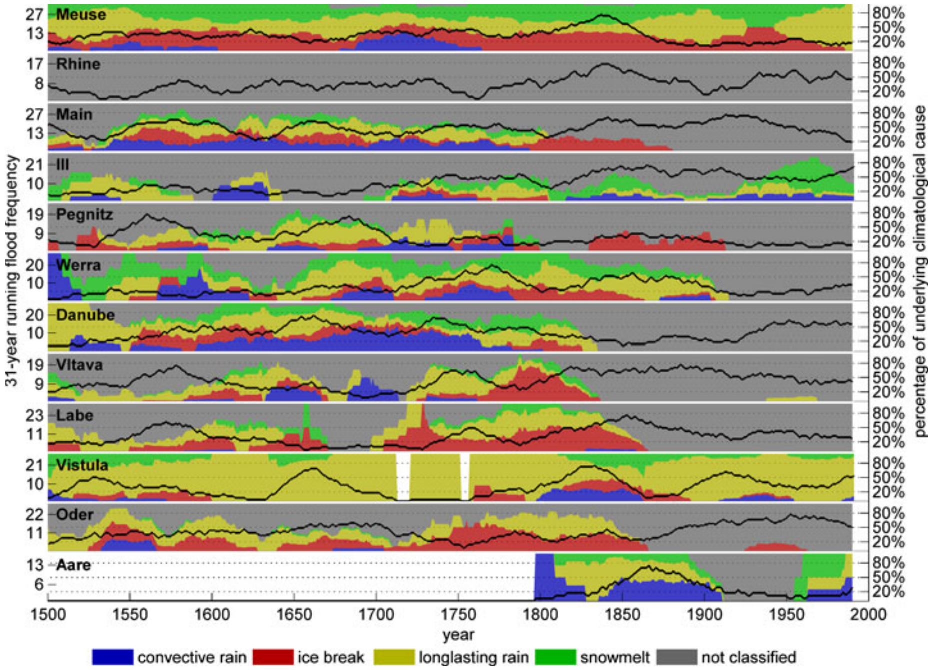

Fig. 3 Time series of 31-year flood frequencies for selected Central European rivers with respect to their causes. The *black lines* represent the sum of floods occurring within a moving 31-year period. The *coloured background* displays the underlying climatological causes differentiated into convective rain, long-lasting rain, ice break up and snow melt as discussed earlier. If no information about the triggering climatic cause was identified *grey background colour* was applied

The second period of increasing flood frequency can be identified between the early 1640s and around the year AD 1700, reaching a peak in the 1660s. This phase is present in four of the river systems (Main, Pegnitz, Vistula and Danube). The signal from the Danube river, however, is unclear and shows only the declining phase with any notable clarity. The rivers Werra and Vltava show only a subtle increase in flood occurrence for the aforementioned period whereas the Rhine shows a constantly high number of floods, but without showing any noticeable increase of flood occurrence during the discussed time period. Yet, this second period is also noticeable in the Mediterranean rivers of the Piave, Adige and, starting during the 1670s, the Arno also a higher incidence of flooding.

Again, this period is followed by roughly four decades of a lower flood frequency within Central Europe. In contrast to the interval between AD 1600 and AD 1630, however, the analysed rivers each react quite differently.

A third phase of an intensified flood occurrence starts during the 1730s, peaks in the 1760s and finds its end in the 1790s. This phase shows the most severe floods recorded within the last five centuries, namely the flood from February 1784. This flood, which was described by the historical sources as a coincidence of ice damming and snow melt, affected six independent catchments. The third phase shows a considerable increase of flood events within five catchments (Main, Ill,

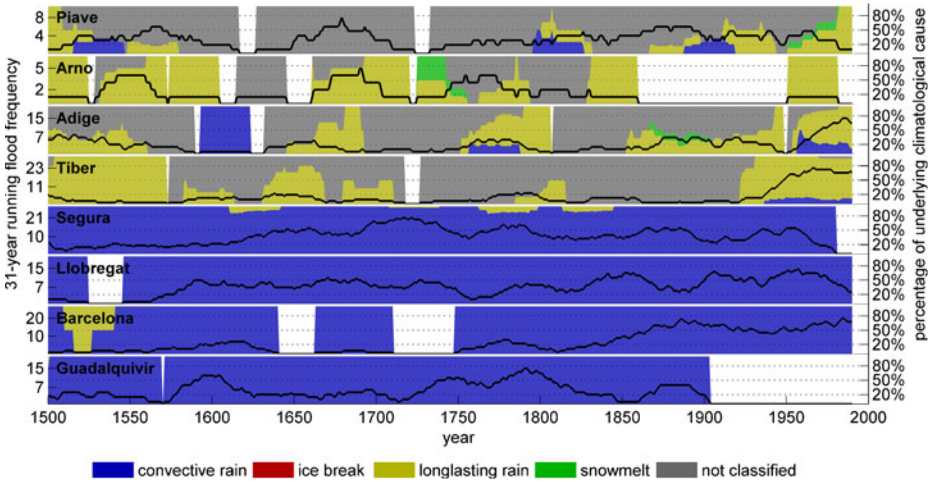

Fig. 4 Time series of flood events in the Mediterranean displaying the distribution of flood causes in 31 years. Colours same as in Fig. 3

Werra, Vltava and Elbe) and an additional—less pronounced—signal recorded in the Pegnitz, Danube and Oder rivers. The Mediterranean rivers of the Arno, Adige and Tiber also display an increase in flood occurrence at this time. Even if most of the analysed rivers show a more or less clear increase of flood frequency, this signal in contrast did not reveal itself in the Meuse River or the Rhine. Unlike to the previous two periods, no prolonged phase of low flood occurrences separate the declines of the flood intensity of the third phase from the increases of the fourth phase, however, a short-period minimum is identifiable. The fourth period stretches across about five decades (from AD 1790 to AD 1840) featuring a significant increase in flood occurrence within all catchments, with the only exception of the Danube River and only a minor signal for the Pegnitz.

The lack of sufficient and detailed data does not yet allow the identification of any direct meteorological/climatological cause for the periods of elevated flood occurrence. Additional and spatially more distributed historic sources as well as complementary natural proxies will allow for further identification of the triggering causes in future.

However, recent research can link the observed river behaviour to distinct phases of Central European climate (Glaser 2008). Numerous regional studies describe European climate variation since AD 1500 including the period of lower than average temperature which is commonly known as the LIA (Pfister 1999; Glaser 2008). Despite the ongoing debate on the exact dating, a significant drop in temperature and change in precipitation was prevalent for this time. Historical sources document that during the LIA winter temperatures were significantly lower due to a more persistent Siberian anticyclone advecting cold air masses into (Central) Europe. Precipitation on the other hand was more pronounced in the summer half-year triggered by an increased occurrence of a north westerly circulation over Europe (Glaser 2008). The climatological signal concurring within the periods of elevated flood appearance, however, is not homogeneously during the four identified periods

(AD 1540–1600, 1640–1700, 1730–1790, 1790–1840). The first two phases coincide with phases of colder than normal climate over Central Europe—the second phase roughly coincides with the Maunder Minimum. The third and fourth phase, as far as they are separable, coincide with drier than normal climate conditions.

To evaluate the time dependent structures of the series a PCA was performed. The first two principal components (PC) explain 32% and 18% of the variance. The associated dominating series—those with more than 20% explained variance—are the Ill and Elbe for the first PC and Meuse, Vistula and Oder for the second PC. Coefficients for the first two PCs of a PCA as presented in Fig. 5 and show a positive signal for the first and third period but exhibit no distinct signal during the second period of elevated flood occurrence, pointing to the fact, that the triggering cause might not be the same in the first and second periods. The PCA thus evaluates the general river behaviour but seems here unable to distinguish triggering causes initiated by large-scale climatological variability.

At the catchment specific scale, detailed information on the flood triggering climatic conditions can be given (Figs. 3 and 4). Figure 6 additionally displays the distribution of the different causes against the number of catchments affected based on the flood triggering causes for the CER. The grey area represents the number of flood events which had been recorded (light grey) and for which events information about the triggering cause are available (dark grey). Precipitation-related events—in particular convective rain—trigger floods at a local scale, whereas floods triggered by snow melt or ice-break events become more frequent as the spatial scale extends and more catchments are involved. This finding supports the widely agreed opinion that

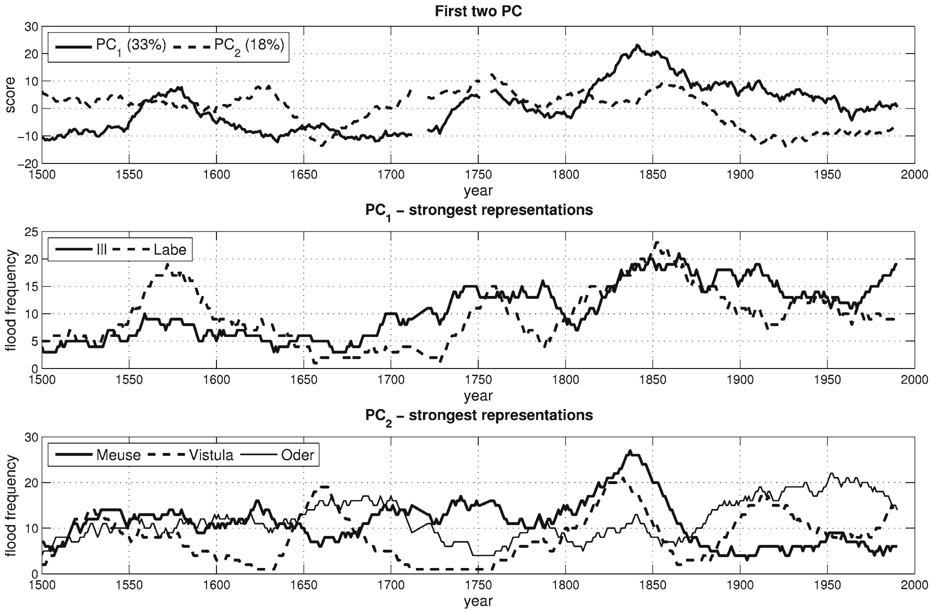

Fig. 5 Time coefficients for the first two PC of the Central European flood frequency series. Ill, Vltava and Elbe (Labe) account for most of the explained variance of the first PC, Vistula and Oder for the second PC

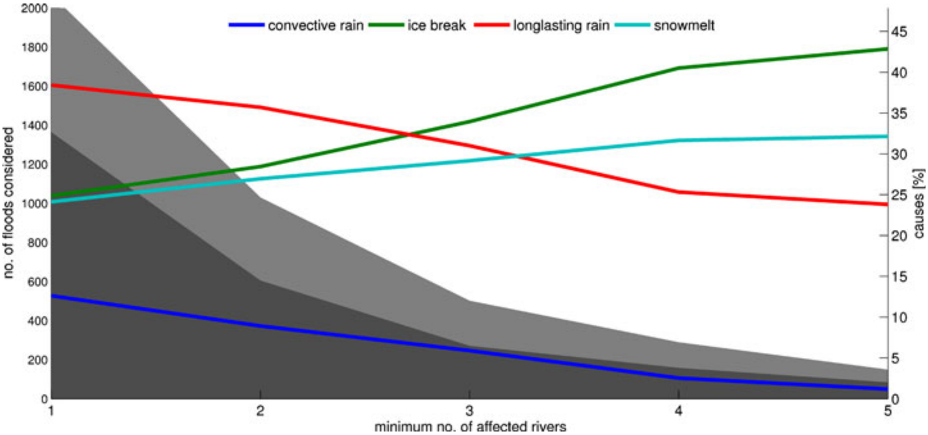

Fig. 6 Distribution of the different flood causes depending on the number of catchments affected for Central European rivers. The *grey area* represents the number of flood events, which in total had been recorded (*light grey*) and for which events information about the triggering cause are available (*dark grey*)

the atmospheric condition triggering convective events is normally expressed at a limited spatial dimension, whereas snow melt and ice break events are triggered from long lasting periods of high pressure systems over Eastern Europe affecting large areas. Table 3 suggests that those flood events affecting four or more catchments occurred during the winter half of year, and reported ice-break or snow-melt as the main triggering events. Convective events normally do not have sufficient size to trigger flood events spreading out over a large area as observed for Central and East European rivers.

During the fourth period of elevated flood occurrence synchronous river behaviour cannot be observed over all catchments. In addition to climatological explanations, which surely played their role, we need to link the observed river behaviour to anthropogenic factors. The Era of Enlightenment improved awareness of the natural world meanwhile settlements started to expand towards the rivers during the first phase of industrialization increasing the number of people at risk of flooding and, at the same time, intensifying interest in flood protection. Given this, the observed trend can partly be correlated with available data density, however this alone would not convincingly explain the loss of synchronicity between the catchments observed after the 1840s. During this period, the first river regulations took place (that of the Rhine starting in 1810, or the building of canals by passing or supplementing rivers), all of which resulted in a severe alteration of the flood regime and thereby accounting for the loss of inter-catchment correspondence. Nevertheless, it is known from climate measurements and historical records, that the period around 1800 was characterized by a significant shift to drier conditions during winter, spring and summer in Central Europe (Glaser 2008). During winter and spring the observed change of magnitude in hygric climate signal is of significant magnitude to link it to synchronous river behaviour between the 1790s and the 1840s.

Regarding flood frequency the phase around 1840 is characterized by the strong signal of the first PC as displayed in Fig. 5. Yet the proposed triggering causes (Fig. 3) do not show a similarly homogeneous pattern of behaviour. Other than the eastern

Table 3 Selected major flood events (affecting minimally five catchments) in Europe until 1900

Date	Region/location	Type
August 1501	Main, Danube, Vltava, Rhine, Oder	Long-lasting rain
March 1565	Main, Ill, Werra, Elbe, Oder	Ice-break and snow-melt
January 1682	Main, Pegnitz, Werra, Vltava, Elbe	Long-lasting rain
February 1775	Main, Werra, Vltava, Elbe, Vistula, Oder	Ice-break and snow-melt
February 1784	Rhine, Main, Pegnitz, Werra, Danube, Vltava	Ice break flood
April 1785	Main, Werra, Danube, Vltava, Oder	Ice-break and snow-melt
February 1799	Meuse, Main, Pegnitz, Vltava, Elbe, Oder	Ice-break and snow-melt
December 1819	Rhine, Ill, Danube, Vltava, Labe	No specification
March 1827	Meuse, Main, Vltava, Vistula, Oder	Ice-break and snow-melt
December 1833	Rhine, Main, Ill, Werra, Danube, Vltava	No specification
March 1845	Pegnitz, Werra, Vltava, Elbe, Oder	Ice-break and snow-melt
February 1862	Rhine, Main, Pegnitz, Vltava, Elbe	Ice-break and snow-melt
February 1876	Rhine, Main, Pegnitz, Werra, Danube, Vltava, Elbe	Ice-break and snow-melt

Vltava and Elbe rivers, which exhibit an increased occurrence of ice break as the probable cause for the observed flood events, there is no significant change in the flood triggering events.

Except for the period mentioned above, the PCA presented in Fig. 5 does not show any other strong correlations between the catchments. This confirms the general impression, that the observed river systems react independently to each other, which in turn implies limited regional expression of the triggering causes. The only exceptions are spatially extensive winter floods, which are caused by snow melt or ice-break (see Fig. 6).

Turning to the question of the variability of historical floods over the course of the centuries, the rivers Tiber and Adige show a maximum in flooding frequency during the Spörer Minimum (SM) of low solar activity (1416–1534). The same holds true for the other main river in Italy, the Po River and its tributaries, located further to the north (not shown, cf. Camuffo and Enzi 1994, 1995, 1996). Moreover, the Tiber and Adige experienced a second maximum at the onset of the Maunder Minimum (MM: AD 1645–1715). Once again, the situation is complex with strong teleconnections during the SM, but weaker in the other cases. We further analysed the relationship of solar activity and flood variability for other rivers of the Mediterranean Basin. In particular, we examined whether a relationship exists between the floods of the rivers Tiber in Italy and Tagus in Spain. Those two rivers appear to be asynchronous in respect of their flood incidences. This inverse relationship is accounted for by the fact that the two rivers are at risk of floods under different atmospheric circulation patterns. The Iberian Peninsula is more exposed to wintertime Atlantic depressions, than Italy. On the other hand, southern circulations reinforced by Mediterranean depressions may lead to heavy rain in Italy and possibly the eastern coast of Spain, but not in the interior of the Iberian Peninsula (Camuffo et al. 2003). The Tagus basin floods were analysed although the result are ambiguous there being an increase in the frequency of extreme events but no homogeneity in its spatial distribution (Benito 2003; Camuffo et al. 2003; Benito et al. 2004a; Vaquero 2004).

Spanish rivers show the complexity of the geographical context of different basins of the Peninsula. The time series of flood frequencies for the many individual rivers are characterized by oscillations of similar duration but are not homogeneously distributed. The most marked oscillations with increasing flood frequencies occur at the end of the eighteenth and second half of the nineteenth centuries; the oscillation between the sixteenth and the seventeenth centuries is less evident.

As far as flood events of rivers within the wider Western Mediterranean Basin are concerned, a strong relationship with torrential rainfalls can be observed in the context of changing patterns of rainfall variability. These events are rather unusual during twentieth century but do, in contrast, explain anomalies in flood frequencies during the LIA. An example available and supported with evidence from old instrumental data is the period between 1760 and 1800, when the predominant atmospheric circulation pattern was meridional, suppressing the commonly more frequent zonal circulation over Europe (Barriendos and Llasat 2003).

4.2 Comparison between historical and modern annual flood distribution

Figures 7 and 8 summarise the annual distribution of flood occurrences from the CER and MR during historical and modern times. The historical period refers to all data collected from documentary sources (up to 1800); the modern period refers to the available instrumental readings (in general from 1800 onwards).

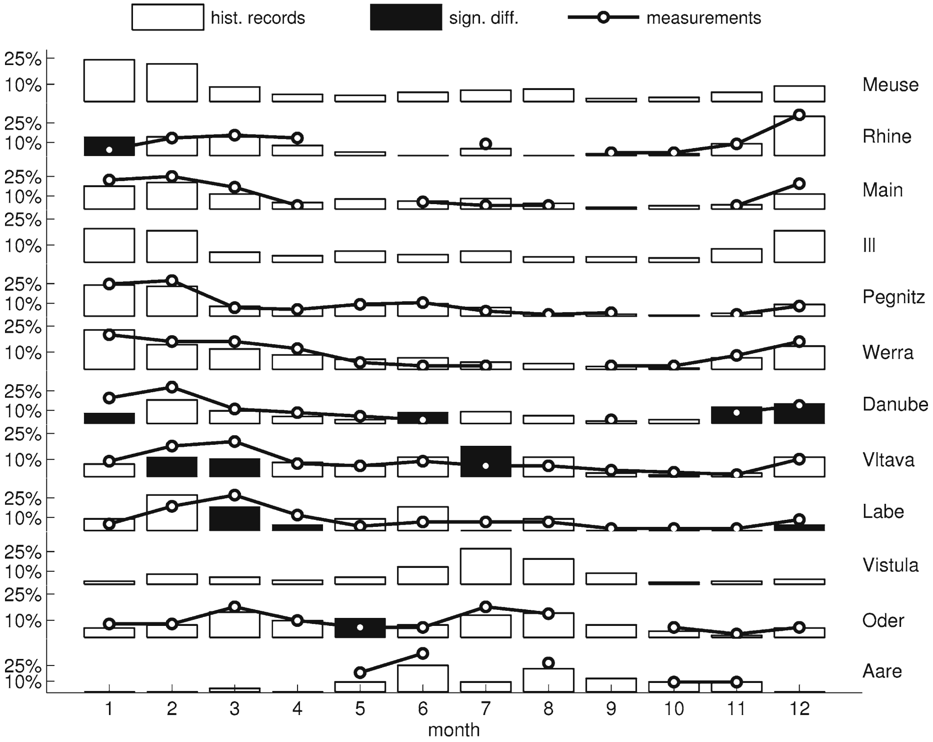

Fig. 7 Annual distribution of floods at Central European rivers. The *black line* shows the annual distribution of measured data (see reference period in Table 2)

The key question is whether, and to what extent, the seasonality has changed between the historical period (1500–1800) and the period of instrumental measurements (1800–2005). In order to identify possible changes the data have been normalized and significant changes (difference larger than one standard deviation) had been emphasised by using solid colour in the figures.

At a first glance, the differences between historical and modern flood occurrences seem marginal. The river Pegnitz, for example, does not exhibit any different flood occurrences between the two periods and the differences for rivers Rhine, Main and Aare are minimal. The rivers Werra, Vltava, Elbe and Danube, however, show a tendency to a reduced number of summer floods in modern times. This change is significant for Danube during June and for the Vltava during July. During late winter and spring the rivers Danube, Vltava and Elbe show an increased flood occurrence which closely approaches significance.

The comparison of historical flood records with instrumental measurement data for the MR is presented in Fig. 8. The Spanish river Llobregat as well as the Italian river Tiber also shows a good correlation between measured and historical flood events and no significant changes have been identified.

In addition to the above-mentioned changes in the flood distribution, the general distribution from the CER as well as from the MR between historical and modern data show strong similarities, indicating a high level of reliability for the data derived from historical sources.

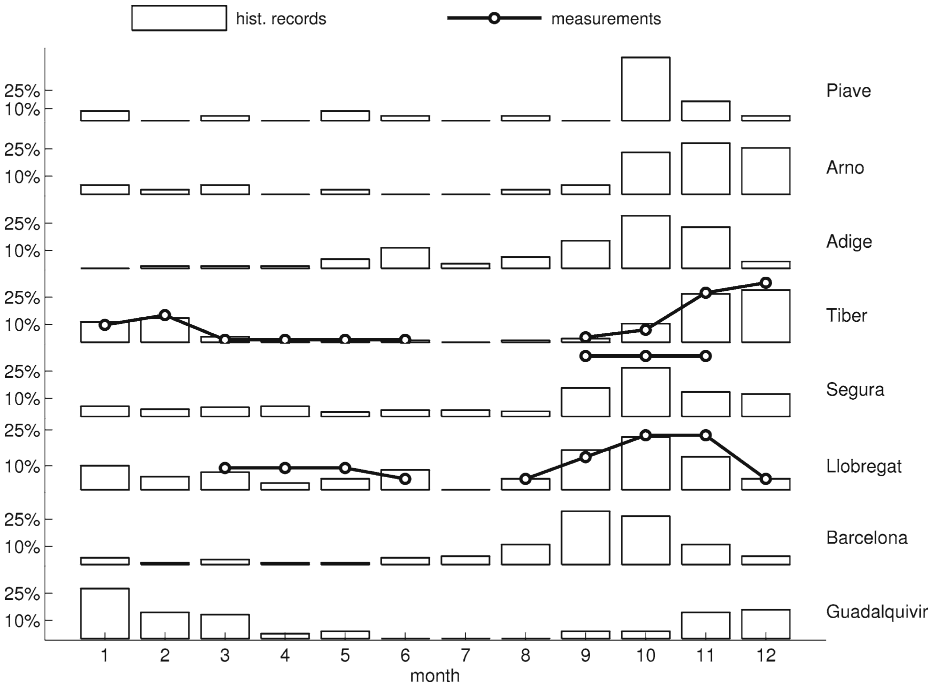

Fig. 8 As in Fig. 7 but for Mediterranean rivers

5 Conclusion

Historical documentary data provides valuable information to derive and analyse long term flood frequencies of CER and MR. There is a broad methodological framework including critical source analysis available to evaluate and analyze such historical records. Long term flood frequencies changed significantly over time within the different river catchments but there is some spatio-temporal coherence regarding the identified periods of increase and decrease in flood frequencies. This is based on the analysis of independently reconstructed time series as well as on the quantitative results of a principal component analysis. We identify four periods of increased flood frequency (AD 1540–1600, 1640–1700, 1730–1790, 1790–1840) in which a notable coherence between the CER is evident. To some degree, these periods are also visible within the MR. A number of these changes can be correlated to the well known climatic periods during the LIA. On the other hand each river system has its specific characteristics, which only can be interpreted from a local perspective.

Even for the last years from 1950 onward, when flood information is based on instrumental records, no consistent patterns of the flood development can be found. The decrease in flood frequency during this period can be explained for some rivers like Pegnitz and Main by reference to the results of modern flood protection. Most significantly, recent changes in the variability of flood frequencies are not exceptional if compared to the flood frequency of the past 500 years and show no overall trend similar to the widely-cited "hockey-stick" trend for temperatures. There is a similar conclusion drawn by the SPHERE project which for north-east Spain has shown that events during the last 400 years produced discharges significantly greater than the biggest gauged flood events of modern times (Thorndycraft et al. 2005). Hence, the study of historical floods permits a more comprehensive risk analysis to be undertaken and appropriate flood protection to be planned.

Although for many cases the underlying meteorological causes triggering a flood event can be defined, the incompleteness of the data does not allow a conclusive climate related analysis of the links. However, a general connection between the meteorological cause for a flood event and the number of affected catchments can be suggested. Simultaneous floods at different catchments are mostly linked to cold phases with subsequent snow-melting.

For the future more locally-focussed research is necessary to understand and to determine the detailed meteorological situation and the circulation patterns with information being available at a catchment specific level. The data-set we have used here is suitable for integration with existing modern European databases on flood events from 1950 onwards. This will broaden our understanding of spatio-temporal variance of flood incidence over Europe as a basis for risk analysis and evaluation of vulnerability.

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