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DYNAMIC AND SOCIOECONOMIC ASPECTS OF HISTORICAL FLOODS IN CENTRAL EUROPE

With 9 Figures

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Zusammenfassung: Dynamische und sozioökonomische Aspekte von historischen Flutereignissen in Zentraleuropa

Nach mehreren katastrophalen Flutereignissen in Zentraleuropa in den 1990iger Jahren und im Jahr 2002 wurde erneut die Diskussion entfacht, wie weit solche Ereignisse auf anthropogene Einflüsse wie Klimawandel oder Landnutzungsänderungen zurückzuführen sind. Im Rahmen eines europäischen Forschungsprogrammes mit dem Namen FLOODRISK wurden historische Flutereignisse aufgrund von historischen Dokumenten erfasst und in drei Wirkungsstufen eingeteilt. Die statistischen Ergebnisse wurden anschliessend mit rekonstruierten Druck- und Niederschlagsfeldern korreliert oder verglichen. Die Häufigkeitszeitreihen dreier Flüsse zeigen eine starke dekadische Variabilität. Perioden mit häufigeren Flutereignissen wurden zwischen 1630 und 1700, solche mit weniger Fluten zwischen 1720 und 1780 sowie zwischen 1880 und 1930 beobachtet. Im 20. Jahrhundert ist nur im Rheineinzugsgebiet ein klarer positiver Trend sichtbar. Der Vergleich mit gemittelten Bodendruckfeldern ergibt, dass während Flutereignissen ein verstärkter Feuchtetransport vom Atlantik auf das europäische Festland sichtbar wird. Neben der Frage nach dem zusätzlichen Einfluss von Landnutzungsänderungen, muss in Zukunft abgeklärt werden, welches die Rolle des Nordatlantiks und der dortigen Ozean-Atmosphären-Austauschprozesse (inklusive Nordatlantische Oszillation) im Hinblick auf die Häufigkeitsschwankungen von grossen Fluten ist. Die europäischen Gesellschaften sind mit den Schäden und Belastungen dieser Katastrophenereignisse insgesamt geschickt umgegangen, indem sie in den betroffenen Gebieten durch gezielte Information und Soforthilfe Linderung verschafft haben. Fallstudien zeigen, dass neben der Unterstützung durch die politischen Organe auch Medienkampagnen zur Unterstützung der betroffenen Bevölkerung sehr erfolgreich waren. Ein solch

erfolgreiches Katastrophenmanagement, eingesetzt und unterstützt durch die politischen Autoritäten, kann ganz wesentlich zur nationalen Integration beitragen.

Summary: After several disastrous floods in central Europe in the 1990s and in the year 2002 the discussion aroused whether or not these events are the result of an anthropogenic influence such as climatic and/or land use change. In the framework of the European research program FLOODRISK historical flood events were recorded in three severity classes based on historical documents and related to reconstructed air pressure and precipitation data. A strong, low frequency (decadal scale) variability becomes apparent in the recordings of all large river systems, indicating winter periods with higher (e.g., from 1630-1700 and 1830-1880) and lower (e.g., from 1720-1780 and 1880-1930) flood frequencies. During the 20th century a clear positive trend is only visible for the Rhine area. A circulation analysis based on a long-term Atlantic-European surface air pressure data set shows that humidity transport from the Atlantic Ocean to the European continent was strengthened during flood periods. Beside the problem of the additional influence of modified land use changes, future studies have to raise the question about the role of the North Atlantic sea surface temperatures and the ocean-atmosphere coupling (including North Atlantic Oscillation) in modulating the frequency of severe floods over the continental area. Confronted with harm and disorder of these flooding catastrophes, the European societies were eager to get specific information and quick support. Examples show that, beside the assistance of the political authorities, fund raising campaigns of the media were very successful. Finally, it becomes apparent that risk management, when consistently utilized by the political authorities, has strengthened the bonds of national unity.

1 Introduction

Flood events are natural disasters which occur with irregular intervals and which result in deaths, damage to property and economic losses. Because their consequences concern the whole socioeconomic and political system, severe floods are also social events. Extreme events such as flooding are not only critical in terms of their economic and social consequences. Their expression also reflects variable climate, changing land use and modified hydrological systems (THORNDYCRAFT et al. 1998).

Several devastating floods in central Europe in the 1990s (e.g., in the Rhine and Meuse areas in December 1993 and January 1995, in the Oder area in July 1997 and 2001, or in the Elbe and Danube area in 2002; see Figs. 1 and 2) provoke the question whether such events are just an expression of natural climate variability or rather a result of the recent global warming (ALVERSON et al., 2003). Worldwide, at least one third of all financial losses due to natural factors are attributed to flooding and have heavily increased over the last decades (BERZ 2000; KOCH 2000; PALMER and RÄISÄNEN 2002). For example, the losses in the past ten years amount to more than 250 billion dollars. Therefore, natural disasters always get on the top of the political agenda in the country where they occur, as they result in substantial damage, they disrupt community life and they tend to generate collective stress and widespread fear (ERIKSON 1994). In various countries floods place the highest burden of all disasters on the national economy, today (ROSENTHAL and T'HART 1998). These increasing costs lead to rapidly growing demands for statistical and dynamical studies about extreme precipitation and related runoff processes and floods (FREI et al. 2000). This article reports about the main results of a joint study by different European research groups called FLOODRISK ("FLOOD frequency analysis and public RISK management in a historical perspective").

Extreme events like severe floods are rare by definition. Therefore, the identification of a suitable probability distribution and the estimation of the model parameters as well as the return values for a certain period (VON STORCH and ZWIERS 1999) is a very difficult task, especially if an increasing anthropogenic induced climate change is likely to occur. In the case of strong flood events an additional difficulty has to be considered. Instead of a more or less well defined temperature and precipitation statistics, a complex, event-driven phenomenon is studied which is additionally controlled by catchment characteristics, such as topography, slope, land cover, land use, vegetation, water storage capacity as well as soil conductivity and stratification (EASTERLING et al. 2000; FREI et al. 2000). The term flood event is used if the water leaves the riverbed flooding to its surroundings or if the river discharge exceeds a

certain defined threshold. The classical statistical tool to characterize the severity of a flood is by calculating its return period with the help of suitable extreme value statistics (VON STORCH AND ZWIERS 1999). A corresponding study was carried out by ZHOU AND WANG (2002), who reconstructed the flood series in the Huaihe River basin in China for the last 500 years using historical records and annual hydrological data. They studied the behavior of the river system by means of spectral analysis and showed that it behaves like a chaotic system with a non-integer attractor. Another method, which is applied, consists in the calculation of the losses of finances and human lives. Severe flooding is a well known phenomenon in large central European river catchments (BRÁZDIL et al. 1999; PFISTER 1999; GLASER 2001). The Figures 2a and b show two typical representations of a historical and a recent flooding event in the investigated European area.

The empirical analysis and the modeling of extreme events are very challenging. Because the underlying processes are mostly nonlinear, climate models have difficulties to reproduce realistic probability density functions (EASTERLING et al. 2000). The statistical analysis of extremes needs very specific methods, and, above all, long-term data sets with uniform observation rules (KNOX 2000; FREI and SCHÄR 2001). When diagnosing a certain flooding event, we have to distinguish between the disposition and the responsible trigger mechanism. Important disposing factors are topography and land use of the catchment area, soil saturation and available water storage capacities by snow cover. Important trigger mechanisms are extensive precipitation, advection of very warm air causing rapid snowmelt (often combined with extensive precipitation), and, in mountainous areas, outbreaks of lakes after landslides, etc.

In central Europe there are mainly three types of synoptic situations leading to severe flooding events: i) short and intense rainfall due to low pressure gradients and moist convective instability which causes thunderstorms in the summer half-year, normally covering a small area of one or a few river catchments; ii) long lasting continuous rainfall due to a southern shift of the North Atlantic storm track causing persistent westerly to southwesterly or, in case of southeasterly moving and partially persisting Mediterranean cyclones, southeasterly airflow (occurring from spring to fall), covering a much larger, very often semi-continental area with several river catchments; iii) regional-scale winter or mainly spring snowmelt situations related to persistent westerly airflow leading to advection of warm and moist air. The 2002 Elbe flood was a typical type ii) event.

The diagnosis of historical flood events proves difficulty because of three reasons. First, the number and quality of available data is clearly restricted. In the case of the disposing

factors, precise descriptions concerning the land use of the catchment areas (e.g., old maps) and the condition of the riverbed must be included in the studies (DEUTSCH and PÖRTGE 2001). Concerning the trigger mechanisms, precipitation measurements or observations or, at least, synoptic reconstructions in form of surface air pressure patterns must be available (LUTERBACHER et al. 2002). Second, the databases show different time resolution. If, e.g., a flooding event has a typical time scale between some days and two weeks, surface air pressure reconstructions for the pre-1870s are mostly available as monthly means. As an exception, KINGTON (1988) derived daily surface pressure maps in the Atlantic - European area for the year 1780. Third, there is no strict statistical definition of "flood" in terms of stream flow measurements. For these reasons it is very difficult to compare pre-instrumental with instrumental flood events and thus create long homogeneous series (GLASER 2001).

This paper aims to answer four questions: (1) What is the natural variability of historical flood events in central Europe? (2) Is there any significant relation between extreme flood frequencies and atmospheric circulation? (3) Do the modern trends in variability show any significant change? (4) What have the important implications for economy and politics been - in the past and today? It is structured as follows: Section 2 describes data and methods. In Section 3, a statistical and dynamic analysis is presented. Section 4 summarizes the implications for economy and politics, and Section 5 discusses and concludes the main results.

2 Data and Methods

Two types of data form the basis of this study: historical flood descriptions (including maps) and modern gauge observations or measurements. The historical flooding data covers the so-called pre-instrumental period from 1500 to 1800. The second data type includes the instrumental period from 1800 to 2000. Data sets with three types of data are available for this period: Regular (daily) gauge readings, water level recordings and precise discharge measurements. The data that were reconstructed are based on different historical sources: the databanks HISKLID (GLASER 2001) and EURO-CLIMHIST (PFISTER 1999) as well as data from DEUTSCH and PÖRTGE (2001). Unfortunately, no overlap between the two data types was possible because of the sparse data in the transition period. Table 1 shows an overview of the different types of information and related data sources, which were used for the derivation of quantitative data. Figure 1 represents the main river systems with the gauge sites whose data were used in this study.

It is plausible that a precise determination of the date of the flood event, the trigger mechanisms, the flooded area, the losses and the political reactions is only possible if qualified specialists (mainly historians) read and verify the different data sources. As mentioned above, continuous data are not available. Very often, the extreme flooding events were described in chronicles, and, at the same time, the extreme water levels were marked on buildings or constructions (see example on Fig. 3). For the data used in this study, the calculation or estimation of extreme discharge rates was only possible if the water level and a rough description of the river flow speed as well as the momentary state of the riverbed cross section was registered. Recently, a first analysis on the huge central European millennial flood catastrophe in the summer 1342, which clearly exceeds the highest level ever recorded in this study (February 1784; see Figure 3), and which was possibly never observed in this extent since, was published by Tetzlaff et al. (2001). It will be of great interest to try to compare the devastating Elbe flood in 2002 with this event. The level of the Elbe was probably never as high as in August 2002 during the last 500 years.

It was one of the very difficult tasks of this study to receive a comparable definition or at least a similar representation of the two data sets. Firstly, a precise catalogue, defining three intensities of floods, was established for the historical period (1500-1800; see Table 2). The result is a seasonal statistics with the number of flood events omitting the lowest class 1 because of its inhomogeneities. Figure 4, in its left curve, shows the 31-year running means of the sums of class 2 and 3 winter events in Table 2 for the river Main. For the modern period 1800-2000 (right 3 curves on Figure 4) it was difficult to define a flood event of particular intensity. Besides the above-mentioned definition of a flood, a quantitative determination of different classes of flood events for a certain measuring site does not exist. Therefore, for each specific time series, the monthly maximum discharge was assigned to one of three intensity classes which were delimited by deviations from the mean maximum discharge m in $m^3 \cdot s^{-1}$ (1901-1990), expressed by multiples of the standard deviation s (see description in the upper middle part of Fig. 4). Running means of the sums of intensity classes 2 and 3 are matching best with the pre-instrumental flood frequencies if these intensity classes are delimited by steps of one standard deviation, respectively, i.e. if considering monthly maximum discharges exceeding the mean maximum discharge by at least the two-fold standard deviation (see Fig. 4). It is obvious that the flood frequencies show a well-marked decadal variability.

The second basic data source consists in form of gridded monthly mean sea level pressure (SLP) and precipitation fields. These reconstructions back to 1659 for the Eastern North Atlantic - European region (30°W to 40°E; 30°N to 70°N) were developed using principal

component regression analysis. A combination of early instrumental station series (pressure, temperature and precipitation) and temporally high resolved documentary proxy data (observations of sea ice, snow features and phenological as well as other biological observations, etc.) from various Eurasian sites have been used for the statistical SLP reconstructions (LUTERBACHER et al. 2002). The relationships were derived over the 1901-1960 calibration period and verified for the 1961-1990 period. Under the assumption of stationarity in the statistical relationships (which is not fully guaranteed; SCHMUTZ et al. 2000), a transfer function derived over the 1901-1990 period was used to reconstruct gridded surface pressure data between AD 1500 and 2000, with a spatial resolution of 5° (LUTERBACHER et al. 2002). Figure 5 shows the example of a reconstructed SLP field for February 1784, which brought about one of the most severe flood catastrophes - the second or third largest in the last 1000 years - at least in Germany and Switzerland. A representation of this devastating flood event is shown in Figure 2a for the city of Würzburg on the Main River. GLASER (2001) reports about strong warm air advection, snowmelt and build-up of ice floes, especially at the end of February 1784. The mean monthly surface pressure field (Fig. 5a) shows a strong westerly to southwesterly flow over central Europe with a small cyclone over Italy. The anomaly map (Fig. 5b) depicts a strong low pressure anomaly reaching from southwestern Great Britain to southern Italy. Daily analyses by KINGTON (1988) confirm our findings and demonstrate the dominance of a meridional circulation with a strong influence of the Mediterranean low and a sudden change to westerly airflow with warm air advection around February 24, 1784.

In addition to the air pressure data, a 500 year long reconstructed precipitation data set with monthly resolution between 1500 and 2000 was made available for continental Europe by using the same technique. However, quality checks showed that these precipitation data for the entire European continent are still questionable before the early instrumental period that is before about 1766. Only for sub-European regions they might show reconstruction skill even back to the fifteenth century. The question is whether or not monthly mean surface air pressure or precipitation fields are able to catch the synoptic characteristics causing a severe flood event. An analysis based on different case studies (not represented here) showed that it is only possible for the longer lasting winter floods as represented in Figure 2a (type iii) in the above mentioned list). These are normally the result of persistent westerly flows covering a large semi-continental area. During the warm season, monthly mean surface pressure maps can only exceptionally show the synoptic situation, mainly because most of the flood events

are related to local thunderstorms or rather small, but deep depressions (HIRSCHBOECK et al. 2000; CLARK 2001). Therefore, this study had to be restricted to winter season.

Based on usual methods, a short statistical overview of important time series of flood events is given in the first part of section 3. Normalized flood frequencies from different catchment areas were compared in terms of running correlations. Even this method has its limitations because it is difficult to estimate whether an observed signal is significant or not, it offers a first overview of longer-term flood frequencies. The dynamical analysis within section 3 is mainly centered on two aspects. First, the reconstructed precipitation patterns can be used to compare a composite of different months with strong flood events with the long-term mean. Second, the relationship between flood frequencies and atmospheric circulation patterns indicating strong or weak humidity (and heat) transport was investigated by means of major dynamical modes that were derived from the reconstructed SLP grids via T-mode principal component analysis. This was not only done for the whole period but also for subsets including only the months with flood events (pre-instrumental period) or with above-average maximum discharge (instrumental period). Finally, two specific circulation indices were calculated for the dominant dynamical mode (zonal, North Atlantic Oscillation (NAO)-like pattern) and correlated with the best central European flood frequency time series, i) an index describing the relative vorticity above central Europe in terms of the correlation coefficient with a typical cyclonic pressure distribution; ii) an index describing westerly flow intensity in terms of the pressure gradient between the mode-dependent centers of action. According to the representation of flood frequencies, these indices were calculated for moving 31-year periods, too (for a detailed description see JACOBEIT et al. 2002).

The focus of the social science studies within FLOODRISK was on “catastrophic floods” that have caused losses of life and property. The very definition of what society considers being a ‘catastrophe’, and what it considers to be the causes, greatly varies from one era to the next. Historical work on disasters is based on written or illustrative sources produced by contemporaries. Some of it was laid down with regard to posterity; some of it is just a by-product of bureaucratic routine. Research on historical catastrophes has only recently started. Most studies involve collecting local data for case studies (e.g., KÖRNER 1999/2000; PFISTER 2002; MASSARD-GUILLBAUD et al. 2002). It is too early to try to compare and to set up a list of common characteristics and a typology of consequences as each event has its own unique aspects. Regarding recent flood catastrophes there is a great amount of theoretical literature on risk management, without, however, looking into the past for more than one decade or two (JAEGER et al. 2001).

3 Statistical and Dynamic Analyses of the Flood Events

Figure 6a represents the running 31-year means of the sums of the winter flood statistics for the three central European rivers Main, Rhine and Elbe. All curves indicate a clear decadal variability that becomes apparent during almost the whole period observed. The maximum and minimum values are at least temporarily similar in all three river basins. A very remarkable decrease of the flood frequencies can be observed after about 1720. Unfortunately, the well-known peak around the mid-nineteenth century becomes not clearly visible because of the changing observing technique (measurements instead of observations) Only the Rhine curve shows a clear positive trend during the twentieth century.

A composite with the winter (DJF) precipitation anomalies (mm per month) for a set of 20 months with strong winter flooding events in at least one of the three studied central European river catchments represented on Figure 1 between 1784 and 1995 is represented in Figure 7a. It shows highly positive precipitation anomalies between southwestern France and the eastern German and Czech area. Compared to northern Europe, even the whole area between Great Britain and the eastern continental area shows positive anomalies. In contrast, the average winter precipitation map in Figure 7b – even the contour intervals are larger - shows highest precipitation amounts along the western borders of the European landmass as well as in the higher mountains. The anomaly pattern (Fig. 7a) therefore indicates that specific circulation patterns with differing moisture transport paths must have prevailed during the months with winter floods.

As mentioned above, this study focuses on the questions whether there are correspondences between flood frequencies and atmospheric circulation, and whether there is any evidence for a modern, say a twentieth century-trend in flood frequency? Figures 4 and 6 clearly show that strong persistent precipitation and flood events in central Europe underlay low frequency (decadal or longer scale) variability. Despite the evidence that, due to the temporally changing combination of natural and anthropogenic forcing factors, the reaction of the climate system represents a strong temporal instationarity, it makes sense to examine whether certain circulation patterns are significantly correlated with the number of flooding events or, whether patterns of months with strong flooding events differ from the long term mean.

Comparing the monthly mean SLP patterns during winter flooding events with the long-term mean was the first step we took to study this problem. Figures 8 a-c represent the first

three principal components (PCs) of the monthly mean SLP over the eastern Atlantic - western European area for winter. They clearly reproduce the well-known dynamical modes which generally govern the lower tropospheric circulation variability during winter time: i) the zonal mode, representing a NAO-like dipole pattern modulating the zonal flow component over Europe (Fig. 8a; WANNER et al. 2001); ii) a dipole pattern with a Russian high and an Atlantic low pressure system (Fig. 8b); iii) one single pole with its center west of Great Britain (Fig. 8c). These patterns are likewise the most important ones during the period since the 1780s (JACOBEIT et al. 2002), and they also emerge for an extended period dating back to AD 1500 (LUTERBACHER et al. 2002). In contrast to these well-known modes for winter, Figures 8 d-f show the monthly-derived winter patterns with central European flood events from 1659 to 1799, and Figures 8 g-i show those months with above-average maximum discharge rates from 1850 to 1994. Obviously, these flood-related patterns 8d to 8i are different from the average ones. First, we get a pronounced southwesterly flow ahead of an Atlantic low-pressure system in both flood periods (Figs. 8d, 8i) that is advecting warm, moist air towards central Europe and often allows for persistent precipitation combined with melting conditions. A further typical, flood-related pattern may be described as a southern European trough. It occurs in two forms during the earlier period (Figs. 8e and f) and is much less distinct during the modern period, even it was responsible for the Elbe 2002 flood event. Fig. 8 g shows a typical cyclonic wave over the northern European continent and is quite similar to the long term average 8 a. Only PC 2 of the period 1850 to 1994 (Fig. 8h) does not imply any major disturbance for central Europe. It rather represents some kind of disposition - due to enhanced freezing - for subsequently triggered flood events whose large-scale circulation is not emergent within the monthly averaged pressure fields. Of course, these flood-related circulation patterns also occur within the much larger sample of months without flood events, but in this case they do not represent the dominant modes of circulation variability (Figs. 8 a-c). Within the selected flooding samples, however, they become evident as major dynamical modes giving way for the development of weather systems leading to the observed flood events.

In a second step to study the correlation mentioned above, two central European circulation indices were calculated for the dominant European winter mode on Figure 8 a which clearly represents the zonal or NAO-like pattern. It was subsequently correlated with the observed flood frequencies of different rivers. Figure 9 gives an example referring to the most precise time series, that of the Main River. The vorticity and flow intensity indices - again based on 31-year moving windows - clearly show varying links to the Main flood

frequencies over the last five centuries. Figure 9a depicts that decreasing flood frequencies are mostly accompanied by decreasing (negative) vorticity values of the zonal circulation pattern, i.e. this pattern tends to occur more often with reduced cyclonic influence within the dominant mode over central Europe during these periods. This becomes visible during the second half of the sixteenth, seventeenth and nineteenth centuries, but not during the last century. At the moment, there is no explanation for the temporal structure of this phenomenon, and it would be too speculative or, at least, questionable to state that this pattern could represent an anthropogenic signal. Similar variations in intensity (Fig. 9b) - i.e. increasing pressure gradients within the NAO-like pattern concomitant with increasing flood frequencies and vice versa - do not occur before the end of the nineteenth century. The historical periods of enhanced flood frequencies during the sixteenth and seventeenth centuries, in contrast, are marked by lower intensities of the zonal circulation mode (negative correlations) thus indicating that rather a negative NAO-phase or state was governing during these flood periods of the Little Ice Age. This is surprising because a negative NAO index does normally indicate higher precipitation rates in the Mediterranean area. Especially the period of the Maunder Minimum between about 1645 and 1700 shows the interesting phenomenon that high flood frequencies are correlated with lower vorticity and weakened zonal flow indices. Does that indicate that a different climate regime was dominating during this period?

4 Implications for economy and politics

A severe flood is always a social event (WEICHSELGARTNER 2000) because its consequences concern the whole socioeconomic system. Table 3 represents an overview of observed consequences caused by historical floods. Political authorities might respond with varying efficiency, but they eventually all have to get down to organize and restore everyday life. At the same time, many people are highly troubled, disoriented and eager to get information. It is well known that the symbolic disorder of a catastrophe could potentially be even more disturbing than the material disarray. One of the first goals of the political authorities should therefore be to prevent the social chaos from spinning out of control. The people need to know why the natural disaster happened, whether it could have been prevented and who could be possibly be blamed. Disaster communication by members of the political and scientific elite has the function to "restore order in people's minds", relieve anxieties, and strengthen feelings of belonging together, which is achieved by evoking common values and by mobilizing outside support.

Switzerland in the nineteenth century demonstrated that appeals of the political authorities to assist the victims of the floods and the following fund raising campaigns of the press were an overwhelming success. As floods were particularly frequent in the Swiss Alps from 1830 to 1880 (peak in Fig. 6 a), there were many occasions to raise money for fellow citizens. Disaster communication was consistently made use of by the political elites to strengthen the bonds of national unity, which, in the early part of the century, had been rather vague. The money raised and distributed "in the name of the common fatherland" may have contributed to tie the different cultural and political parts of the country together. Per capita donations were highest in wealthy centers such as Basel, Geneva and Zurich, whereas the recipients lived in the Alpine peripheries. In the case of the severe Alpine flood in 1868, it is estimated that members of every second household in the whole country were involved in the fund raising campaign (PFISTER 2002). More recently, the Oder flood of July 1997 and the Elbe flood of August 2002 (Fig. 2b) were utilized by the politicians and the media of reunited Germany as a means of fostering the feeling of a united community between the two parts of Germany, and even of the whole European Community. For instance, war metaphors were propagated in the media to describe the disaster. In 1997 East and West Germans (i.e. soldiers of the Bundeswehr) were shown on TV fighting together against the flood (DOERING 2000). The situation was even utilized as a means of reconciliation with the Polish neighbors: German soldiers assisted the Poles on the other side of the dikes. "We will never forget", wrote a newspaper in Wroclaw.

Although fear and helplessness are common feelings in the wake of natural disasters, historians agree that these emotions were soon counterbalanced by a will to face the danger and defend against it. Frequently, the public thrust for action opened up windows of opportunity to implement innovative solutions to known problems. In the early modern period (1500 to 1800) floods and fires were instrumental to bring about improvements in administration, in law, in risk management and in urban planning (KÖRNER 1999/2000; MASSARD-GUILLBAUD 2002). During the nineteenth century, learning from natural disasters became both, more frequent and efficient. This can be demonstrated by several examples: In August 1834 a devastating flood affected the Alps. In the Canton of Grisons (Switzerland), this shock initiated a shift in the distribution of competence from the quasi-sovereign local communities to the Canton. Prior to this event, the local communities had successfully opposed attempts of the cantonal (state) administration to implement a supervision of their forests in order to prevent massive deforestation. However, after the flood in 1834 the

cantonal government could promulgate a law protecting parts of the forests from being overused without serious resistance from the communities (NIENHAUS 2000).

In France, emperor Napoleon III promulgated a law in 1860 that allowed taking strict measures for reforestation in mountain areas of France. Possible connections between an increased frequency and severity of floods and deforestation have been under intense discussion over the previous decades. It was a devastating flood of the Rhone River in 1856 that initialized the forestry legislation. Similarly, a severe flood in central Switzerland in 1868 was instrumental to pave the way for a Swiss federal forestry law (1876) that was tailored after the French model (MATHER and FAIRBARN 2000; PFISTER 2002).

5 Discussion and conclusions

It is possibly the first time that such a long-term data set of flood events has been processed and analyzed. Looking at the length and complexity of this data set the question is put forward whether the accuracy of these data and a strict source criticism is a necessary prerequisite of all corresponding studies. Looking at the meticulous way our data were investigated over many years and with the best possible criteria (see Tables 1 and 2), we are convinced that this data set shows the highest actually possible precision. In the course of this study we were also able to test the quality of the data by introducing new data sources. These tests showed that different reporters with fairly high precision normally described the floods that were included in this study.

Based on the investigation of daily discharges of the river Rhine since 1817, BENDIX (1997) found a significant increase in frequency and intensity of flood events since about 1975. This finding is remarkable because, around this date, the NAO index changed from a longer period with negative to more positive values, thereby indicating that the storm tracks shifted to a more northern position with increasing southwesterly flow configurations over central Europe. Our frequency curves show a decadal scale or even quasi-periodic behavior with periods of 30 to 50 years, alternating between higher and lower flood frequencies (Figs. 4 and 6), and, as mentioned above, the Rhine flood frequencies increased in the 20th century. Even if we take into account that this behavior of the natural river systems can be masked by changing land use and/or technical measures like dams or riverbed straightening, this decadal scale variability is very characteristic and has also been observed in other studies dealing with long flood time series (BENDIX 1997; BRÁZDIL et al. 1999). The more difficult question is whether this decadal variability is significant or not because also stochastic time series show

this behaviour (GERSHUNOV et al. 2001). We have to consider this question in a further study and concentrate in this paper on the question whether there is a relation between typical surface air pressure patterns and flood events.

Obviously, the most important triggering factor for flood events is extensive precipitation. As a characteristic example, Figure 5 shows that longer term winter precipitation events leading to strong floods are related to surface pressure anomalies like, in this case, a persisting trough over central Europe. In addition, the comparison between the precipitation fields on the Figures 7 and b indicates that central European floods are related to anomalous precipitation distributions. The question whether or not these anomalies are related to specific circulation patterns is answered in Figure 8, which indicates that months with catastrophic flooding show specific pressure patterns leading to distinct moisture transport from the important sources (Atlantic ocean, Mediterranean Sea) to the investigated area. It was also shown that, in an analysis exclusively for the winter PC 1 (NAO pattern), from 1500 to 1750 floods were mostly positively correlated with vorticity and anticorrelated to the strength of the zonal pressure gradient. Only after about 1890 the curves of zonal circulation intensity and flood frequency on Figure 9a are synchronized in the sense that higher precipitation amounts occurred if the zonal pressure gradients increased. The precipitation anomalies in Figure 7a also provoke the question whether or not the significantly positive values of almost the whole central to southern European area are the result of a southward propagation of the storm tracks causing advection of warm and moist air. Are these changed circulation patterns and the resulting precipitation anomalies the outcome of varying forcing factors, or are they an expression of the stochastic variability of the climate system? A definitive answer can hardly been given.

Based on long term observations, SCHÖNWIESE et al. (1993) found positive trends for central European precipitation during the period from 1891 to 1990 and, more significant, between 1961 and 1990. By using ensemble-based probabilistic predictions of 19 climate models PALMER and RÄISÄNEN (2002) demonstrated that the probability of extreme winter precipitation in Europe in boreal winters increases remarkably over the next 100 years in case of a transient increase of CO_2 (calculated around the time of CO_2 doubling). MILLY et al. (2002) investigated the risk of great floods with discharges exceeding 100-year levels from basins larger than 200,000 km^2. Based on stream flow measurements and numerical simulations, they showed that the frequency of great floods increased substantially during the twentieth century. So far, our analysis does not confirm these findings. One possible reason is that the river catchments that were studied are too small (MILLY et al. 2002). Another

explanation could be that the modern data were masked by land use changes or riverbed corrections.

To sum up we were able to show that a quasi-periodicity was observed in the flood time series during a 500-year period from 1500 to 2000 AD and, with high probability, this variability is due to circulation changes over the North Atlantic - European area. One can speculate that these circulation and precipitation changes, which are leading to strong flood frequencies, not only relate to the stochastic behavior of the climate system but also to low frequency changes in the North Atlantic - European climate system, namely the NAO (WANNER et al. 2001). As a great amount of documentary data is available in this area, though not yet recorded and analyzed, there is great hope to get a better insight into these dynamics soon.

Floods are of particular concern for present day decision-makers because of the potential scale of the effects they generate in the media and in the public. Very often, their unpredictability prevents from an adequate preparedness and high costs make adequate counter-measures impossible. The value of historical and paleoflood evidence lies in its use in producing better flood risk assessments and in being able to plan flood-prone zones for maximum floods that are documented within the last centuries. These longer-term records can reduce uncertainty in hydrologic analysis and therefore reduce substantial losses of human life and property.

Natural phenomena are usually not a direct topic of public discussion. They tend to be disregarded. Natural events are only noticed and communicated if they interfere with daily routines, which occurs in the case of a natural disaster. Such a disaster puts itself on the top of the political agenda. The Elbe flood in August 2002 has shown that here is a strong pressure for immediate actions to prevent similar disasters in the future. Such situations open up windows of opportunity to bring forward unconventional solutions, in particular, if those were previously discussed.

Acknowledgements

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Tables and table captions

Table 1: Descriptive historical sources and related quantitative or qualitative information; mainly before 1900 (after Deutsch and Pörtge 2001).
Historische Dokumente und die davon abgeleiteten quantitativen oder qualitativen Informationen für die Zeit vor 1900 (nach Deutsch und Pörtge 2001).

Historical Sources				
Printed sources	**Handwritten sources**	**Tide marks, other marks**	**Maps**	**Engravings, pictures, photos**
Chronicles, travel reports, newspapers, etc.	**Chronicles, diaries, calendars, administrative/ tax reports, gauge readings, etc.**	**Tide marks, inscriptions on buildings, etc.**	**Regular cartography, flooded areas, architectural plans, etc.**	**Views of flooded towns, river catchments, etc.**
Related quantitative or qualitative information				
Flooding data **Possible causes of floods (heavy precipitation, snowmelt, etc.)** **State of riverbed (before/after flooding)** **Extension of the flooded areas** **Losses (human lives, animals, destroyed crops, etc.)** **Socioeconomic impacts (indebtedness, bankruptcies of insurance companies, etc.)** **Crisis management (evacuations, donations, etc.)**				

Table 2: Classification criteria for the three classes of non-instrumental data between 1500 and 1800 (Pfister and Hächler 1991; Glaser 2001).

Klassifikationskriterien für die drei Klassen von Dokumentendaten zwischen 1500 und 1800 (Pfister und Hächler 1991; Glaser 2001).

Class	Intensity of flood	Primary indicators	Secondary indicators
1	**Small, regional flood**	**• Minor damages (e.g., flooded fields close to the riverbank) • Stored timber spilled away**	**• Short overflow period**
2	**Above average or supra regional flood**	**• Small damages on hydrological constructions (e.g., dams and locks or bridges, landing stages, water mills, etc.)**	**• Short period of overflow • Small damage on fields near the riverbank • loss of livestock • no loss of human life**
3	**Above average supra regional flood on a catastrophic scale**	**• Severe damage on hydrological constructions (e.g., dams and locks or bridges, landing stages, buildings near the water like water mills or buildings remote from the riverbed)**	**• Overflow for several days • Severe damage on fields near the riverbank • massive loss of livestock • loss of human life • morphodynamical processes causing damages to fields at least one year**

Table 3: List of observed consequences caused by different historical flood events (outlined by M. Deutsch).

Liste der durch die historischen Flutkatastrophen erzeugten Schäden (Entwurf M. Deutsch).

1. Short term consequences
• Destruction of houses, streets and bridges **• Breakdown of water supply systems** **• Destruction of water mills** **• Destruction of crops and strong reduction of food supply** **• Short run of feed for animals**
2. Medium term consequences
• Shut down of industrial plants (e.g., mining) **• Soaked pastures, animal diseases, epidemics** **• Morphodynamical consequences (destruction of riverbeds, deposition of sand and gravel on pastures, etc.)** **• Lack of money**

Figure captions

Fig. 1: Map of the study area with the river system.
Karte des Untersuchungsgebietes mit dem Flusssystem.

Fig. 2: Representation of two extreme flood events: a) Historical: The flooded city of Würzburg on the Main River around the end of February and early March 1784 (Glaser 2001; see also Fig. 5). b) Recent: Aerial photo of the disastrous flooding at Dessau (Saxon, Germany) on August 14 2002 at the site where the Mulde River meets the Elbe.
Bilder von zwei extremen Flutereignissen: a) Historische Darstellung: Überflutung der Stadt Würzburg durch das Mainhochwasser Ende Februar und anfangs März 1784 (Glaser 2001; siehe auch Figur 5). b) Gegenwart: Luftaufnahme des zerstörenden Hochwassers in Dessau (Sachsen) am 14. August 2002 an der Stelle, wo der Fluss Mulde in die Elbe fliesst.

Fig. 3.: Historical tidemarks on a building in Wertheim near the point where the Tauber River flows into the Main.
Historische Hochwassermarken an einem Gebäude nahe der Stelle, wo die Tauber in den Main mündet.

Fig. 4.: 31-year running frequencies of winter flooding events in the Main River area for the pre-instrumental period from 1500 to 1799 (left: red line) and of extreme discharge rates at the Würzburg gauge for the instrumental period from 1823 to 1999 (right: green, red and blue lines; see the explanations concerning the different thresholds in the upper right corner). D: monthly maximum discharge / m: mean of monthly maximum discharges / S: standard deviation of monthly maximum discharges.
Gleitende, 31-jährige gleitende Häufigkeiten der historischen Winterhochwasser am Main für die vorinstrumentelle Periode von 1500 bis 1799 (links: dicke Linie) sowie Statistik der extremen monatlichen Abflussmaxima am Pegel Würzburg (rechts: dünne, gestichelte und punktierte Linie). D: Monatliches Durchfussmaximum / m: Mittelwert / s: Standardabweichung.

Fig. 5: Representation of the reconstructed mean SLP field for February 1784 (Luterbacher et al. 2002), a month whose synoptic configuration was responsible for one of the most severe flood catastrophes in central Europe in the last centuries (see Fig. 2a). a) monthly

mean surface pressure, contours of the isobars at 4 hPa intervals. b) anomaly pattern (February 1784 minus February 1901-1999), contour intervals at 1 hPa.
Darstellung der rekonstruierten mittleren Bodendruckfelder für Februar 1784 (Luterbacher et al. 2002). In diesem Monat trat in Zentraleuropa eine der grössten Flutkatastrophen der letzten Jahrhunderte auf (siehe auch Figur 2 a). a) Druclfeldnaomalien (Mittel Februar 1784 minus Mittel Februarmonate 1901-1999), Konturintervalle betragen 1hPa.

Fig. 6: 31-year running mean values of the winter flood frequencies for three larger central European rivers Main, Rhine and Elbe.
31-jährige gleitende Mittel der Winter-Fluthäufigkeiten für drei grosse zentraleuropäische Flusseinzugsgebiete.

Fig. 7: Reconstructed European precipitation patterns: a) Composite of precipitation anomalies (mm per month) of 20 winter months with strong winter flooding in at least one of the central European river catchments between 1784 and 1995, related to the 1961-1990 mean. b) Reconstructed average winter precipitation (mm) for continental Europe between 1784 and 1995.
Rekonstrierte europäische Niederschlagsfelder: a) Kompositen der Niederschlagsanomalien (mm per Monat) für 20 Winter mit starken Flutereignissen in mindestens einem der Einzugsgebiete der mitteleuropäischen Flüsse zwischen 1784 und 1995, bezogen auf 1961-1990. b) Rekonstruierte mittlere Winterniederschläge (mm) für Kontinentaleuropa zwischen 1784 und 1995.

Fig. 8: SLP patterns of the first three PCs of monthly mean SLP grids during winter months: a-c) for all SLP grids between 1659 and 1999; d-f) for the winter months with flood events at the rivers Main, Rhine, Elbe or Weser between 1659 and 1799 (pre-instrumental period); g-i) like d-f, but for 1850-1994 (instrumental period).
Monatliche Winter-Bodendruckmuster der drei ersten Hauptkompkonenten: a-c) für alle Bodendruckwerte der Periode 1659 bis 1999; d-f) für alle Wintermonate mit Flutereignissen in den Flussgebieten von Main, Rhein, Elbe und Weser 1659-1799 (vorinstrumentelle Periode); g-i) wie d-f, aber für 1850-1994 (instrumentelle Periode).

Fig. 9: 31-year running mean of the flood frequencies during winter at the river Main (blue lines) and of two important circulation indices, determined in the central European area

for the large-scale zonal, NAO-like circulation on Fig. 8 a (Jacobeit et al. 2002): Relative vorticity (green curve on Fig. 9 a) and pressure gradient intensity between the mode dependent centers of action (green curve on Fig. 9 b). Red areas represent the running correlations between the two represented curves.
31-jährige gleitende Mittel der winterlichen Fluthäufigkeiten im Gebiet des Mains (blaue Kurven) und von zwei wichtigen Zirkulationsindizes, welche für den Raum Mitteleuropa für die Zonalzirkulation auf Figur 8 a gerechnet wurden (Jacobeit et al. 2002): Relative Vorticity (grüne Kurve in Figur 9 a) und Druckgradient zwischen den wichtigsten Aktionszenten (grüne Kurve in Figur 9 b). Rote Flächen markieren je die gleitenden Korrelationen zwischen den beiden Kurven.

Figure 1

.


0°
5°E
10°E
15°E
20°E
25°E
30°E
55°N
50°N
45°N
North Sea
East Sea
Daugava
Elbe
Weser
Meuse
Oder
Wisła
Rhine
Danube
Po
Adriatic Sea
Ligurian Sea
Danube
0
100
200
300 km

Figure 2

a)



b)



Figure 3

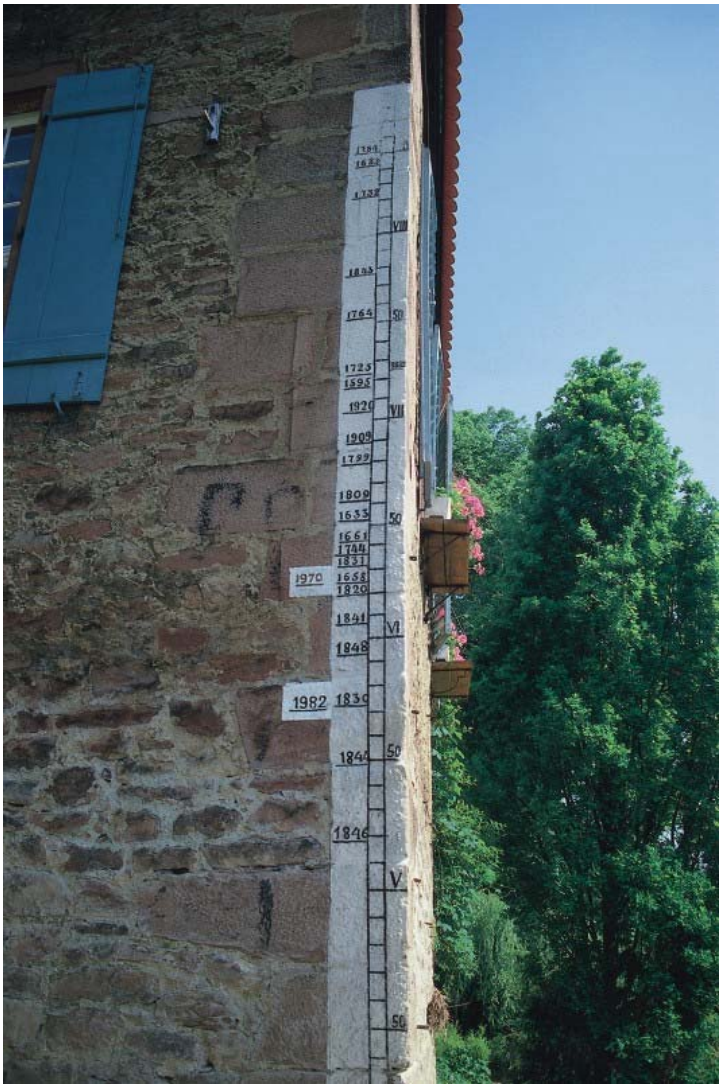

1764
1725
1595
1920
1909
1799
1800
1633
1661
1744
1831
1970
1658
1820
1841
1848
1982
1830
1844
1846
VIII
VII
VI
V
50

Figure 4

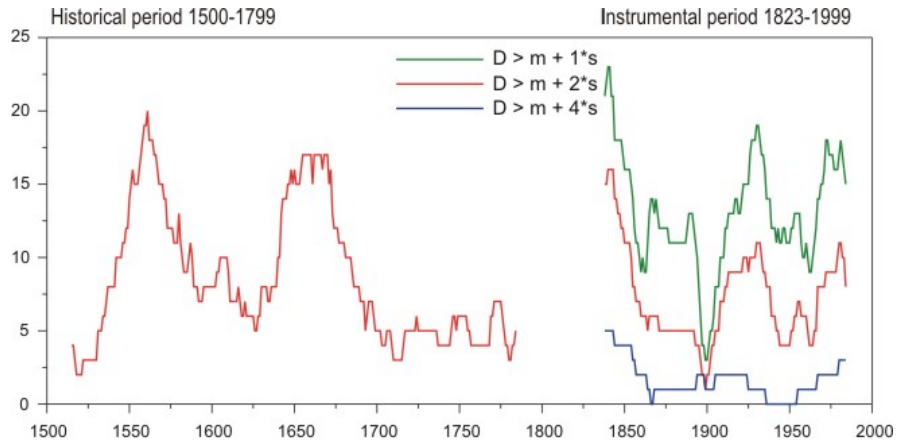


Figure 5

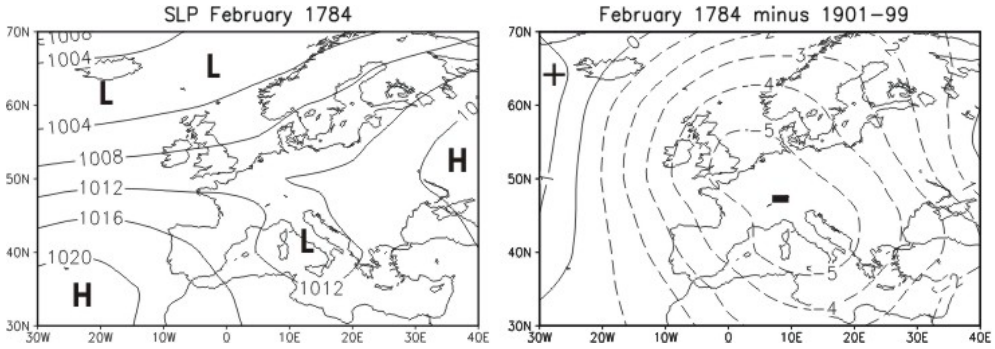


Figure 6

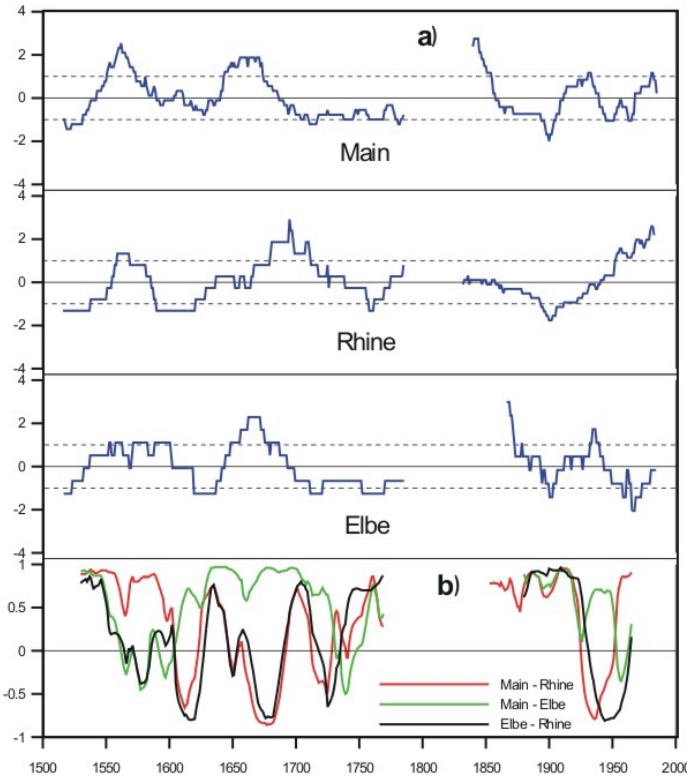

a)
Main
Rhine
Elbe
b)
Main - Rhine
Main - Elbe
Elbe - Rhine
4
2
0
-2
-4
1
0.5
0
-0.5
-1
1500
1550
1600
1650
1700
1750
1800
1850
1900
1950

Figure 7

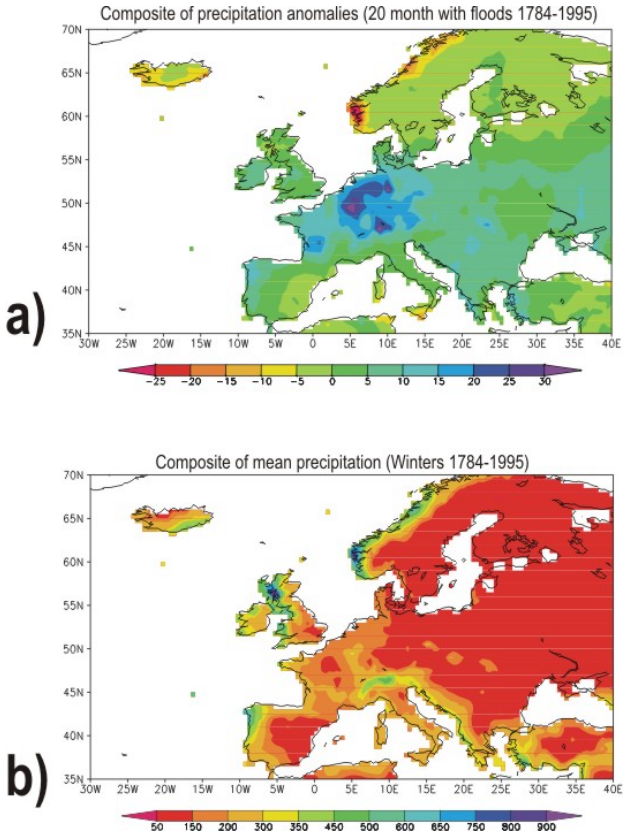

a)
Composite of precipitation anomalies (20 month with floods 1784-1995)
70N
65N
60N
55N
50N
45N
40N
35N
30W 25W 20W 15W 10W 5W 0 5E 10E 15E 20E 25E 30E 35E 40E
−25 −20 −15 −10 −5 0 5 10 15 20 25 30
b)
Composite of mean precipitation (Winters 1784-1995)
70N
65N
60N
55N
50N
45N
40N
35N
30W 25W 20W 15W 10W 5W 0 5E 10E 15E 20E 25E 30E 35E 40E
50 150 200 300 350 450 500 600 650 750 800 900

Figure 8

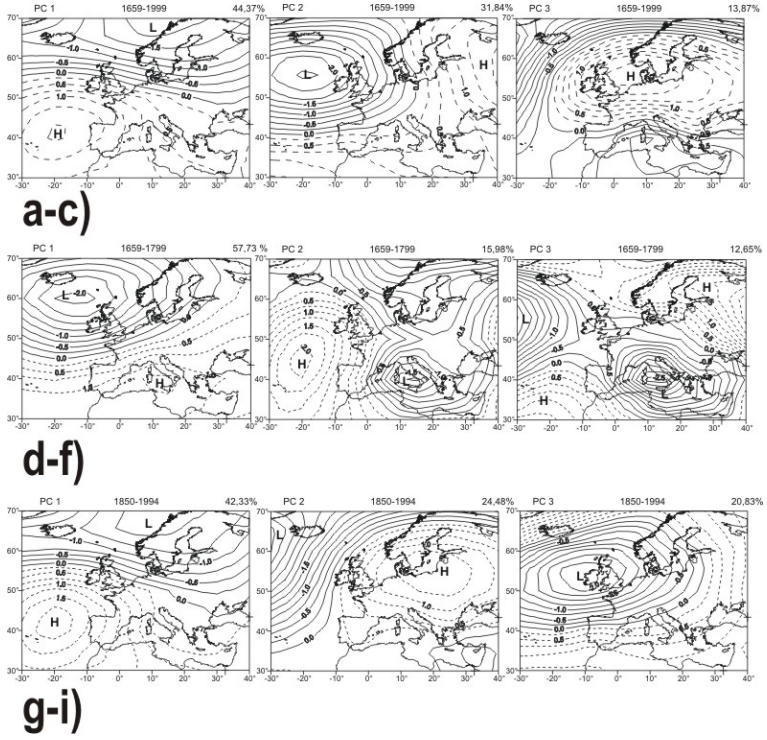
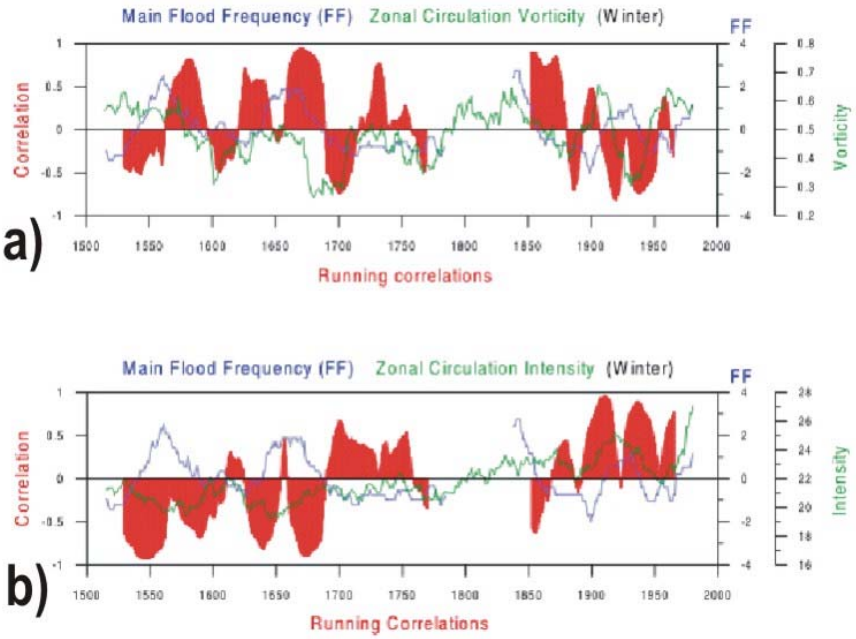

PC 1 1659-1999 44,37%
PC 2 1659-1999 31,84%
PC 3 1659-1999 13,87%
a-c)
PC 1 1659-1799 57,73 %
PC 2 1659-1799 15,98%
PC 3 1659-1799 12,65%
d-f)
PC 1 1850-1994 42,33%
PC 2 1850-1994 24,48%
PC 3 1850-1994 20,83%
g-i)

Figure 9


Main Flood Frequency (FF) Zonal Circulation Vorticity (Winter)
FF
Correlation
Vorticity
a)
Running correlations
Main Flood Frequency (FF) Zonal Circulation Intensity (Winter)
FF
Correlation
Intensity
b)
Running Correlations

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