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Millennial scale variability in high magnitude flooding across Britain

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Abstract

The last decade has witnessed severe flooding across much of the globe, but have these floods really been exceptional? Globally, relatively few instrumental river flow series extend beyond 50 years, with short records presenting significant challenges in determining flood risk from high-magnitude floods. A perceived increase in extreme floods in recent years has decreased public confidence in conventional flood risk estimates; the results affect society (insurance costs), individuals (personal vulnerability) and companies (e.g. water resource managers – flood/drought risk). Here we show how historical records from Britain have improved understanding of high magnitude floods, by examining past spatial and temporal variability. The findings identify that whilst recent floods are notable, several comparable periods of increased flooding are identifiable historically, with periods of greater frequency (flood-rich periods) or/and larger floods. The use of historical records identifies that the largest floods often transcend single catchments affecting regions and that the current flood rich period is not exceptional.

1 Introduction

One of the greatest challenges presently facing river basin managers is the dearth of reliable long-term data on the frequency and severity of extreme floods, with an average gauged record length of ~ 40 years in the UK (Marsh and Lees, 2003). Historical accounts represent a precious resource when considering the frequency and risks associated with high-magnitude low-frequency floods (Williams and Archer, 2002). Historical flood records are found in a variety of forms, directly or indirectly chronicling historic floods (Brázdil et al., 2005); sources include, documentary accounts e.g. journals, newspapers, diaries (McEwen, 1987; Brázdil et al., 2012); flood stones (markers indicating the greatest spatial flood extent) and epigraphic markings (inscribed water levels on structures; see Macdonald, 2007) for sites around the globe (Brázdil, 1998; Demarée, 2006; Bürger et al., 2007). Historical accounts often contain important details including incidence, magnitude, frequency (comparable to other historic events) and seasonality, particularly since AD 1500 as records are more frequent and coeval descriptions permit account corroboration (Brázdil et al., 2006). Historic centres often retain the most complete series of historical records as the presence of literate individuals associated with important monastic, trade and/or governmental functions provide detailed flood accounts (Macdonald et al., 2006), an important aspect in the preservation of early materials. This paper presents the first coherent large scale national analysis undertaken of historical flood chronologies, providing an unparalleled network of sites (Fig. 1), permitting analysis of the spatial and temporal distribution of high-magnitude flood patterns and the potential mechanisms driving periods of increased flooding at a national scale (Britain) over the last 800 years.

2 Series construction

Site inclusion within this study is dependent on the availability of detailed historical accounts and the presence of relatively long instrumental river flow/level series (> 40 years in length). Historical accounts were collated and augmented onto existing instrumental series, with historical flood levels estimated based on documented descriptions (see Wetter et al., 2011), physical evidence or epigraphic markings providing estimates of flow (Herget and Meurs, 2010), with greater significance placed on ranking event severity than on precise discharge estimation (Payrastre et al., 2011) (Fig. 2). Only those floods (historical and instrumental) exceeding the 90th percentile based the instrumental period are included, thus ensuring only the largest events are considered, providing a threshold of events comparable to those likely to have been recorded within the historical period. The largest flood events are unlikely to be significantly impacted by moderate anthropogenic driven changes within catchments (Mudelsee et al., 2003; Macdonald and Black, 2010; Hall et al., 2014); where significant catchment/channel and floodplain (see Lewin, 2010) changes have occurred (e.g.

channel cross-section, land use, urbanisation, etc.), the impact where possible has been accounted for using available information (Elleder et al., 2013), with greater confidence in comparable catchment form for the later period (ca. 1750–) compared to earlier periods (Macdonald et al., 2013).

The absence of flood record(s) for any given year does not necessarily indicate flooding did not occur, simply that no record of flooding remains, or the account(s) included insufficient detail to provide an estimation of the flow. However, it is likely that the largest events have been included since ca. AD 1750, as record density increases and becomes more systematic nearing the present, with greater confidence given to high-magnitude flood event inclusion after AD 1750. The period AD 1500–1749 includes a number of high-magnitude flood events, but when compared to the period after 1750 it is clear that the frequency of events is considerably lower. Whilst this may be a function of climatic variability, the significant growth in flood recording during the mid-eighteenth century (Fig. 3) corresponding to newspaper distribution growth (Williams, 2009), suggests that an increase in recording is actually detected, as such this increase in recording needs to be accounted for.

3 Flood indices (FI)

The issue of increased recording of floods nearing the present represents a challenge when attempting to analyse long time-periods, as the availability and recording frequency increase. Previous studies have applied a variety of approaches, e.g. polynomial function of the 5th degree (Bohm et al., 2014), but these were felt to present the data poorly in this case. A method was developed to adjust the data based on its frequency and distribution over time. This allows for growth in record number but does not assume linear growth, two distinct timeframes are identified within the records AD 1200–1750 and AD 1750–2012 which are treated separately, the later timeframe has considerable growth in flood recording with a 10-year count rising from 0 records (AD 1752) to 22 records in AD 1968 and 1969. The FI (Eq. 1) is calculated to determine periods of increased flood incidence (flood rich periods):

$$\mathrm{FI} = \bar{z}^{10}\left(1 - \left(\frac{\left(\frac{z^{\max} - z^{\min}}{n}\right) \cdot t^{1} \ldots t^{n}}{e}\right)\right), \qquad (1)$$

where $\bar{z}^{10}$ is the mean number of flood records within a consecutive 10-year period, $z^{\max}$ is the maximum number of records during 100 consecutive year period, $z^{\min}$ is the minimum number of records during 100 consecutive year period, n is the total number of years within the study period t, t is the number of years after the start of the period (e.g. 1760 is 10), and e is the total number of extreme events over study period.

Those years exceeding the 0.8 percentile of FI are considered to represent flood rich years.

4 Spatial and temporal flood variability

The flood series are compiled from archival materials and previously published series for the rivers Findhorn (McEwen and Werritty, 2007), Tay (Werritty et al., 2006; Macdonald et al., 2006), Tweed (McEwen, 1990), Tyne (Archer et al., 2007), Eden (Macdonald, 2006), Dee, Yorkshire Ouse (Macdonald and Black, 2010), Trent (Macdonald, 2013), Severn, Thames, Sussex Ouse (Macdonald et al., 2013) and Exe (Fig. 4). An additional chronology for the River Kent in the southern Lake District has been constructed, but is relatively short compared to those presented here and is therefore not included. In each case the estimated discharges are derived from historical accounts and records, where previous studies have been conducted the original archive materials were reviewed, a detailed review of the different materials and chronologies for each site is beyond the scope of this paper (please refer to the site specific studies for further information where available). These series represent the sites for which the most detailed and complete historical series exist; the Thames reconstruction is based at Oxford above the tidal limit, as determining the influence of tidal input to the historical floods in London is challenging, though the potential of the historical flood record at London is considerable (∼ 1500 accounts to date have been collected).

The individual flood series are compiled into grouped series at a range of spatial scales: national (all sites); east (Tay, Tweed, Tyne, Ouse-Yorkshire, Trent, Thames) and west (Findhorn, Eden, Dee, Trent, Severn, Exe) UK draining catchments; and, Wales (Dee and Severn), Scotland (Findhorn, Tay, Tweed), northern (Eden, Tyne, Ouse-Yorkshire, Trent) and southern England (Thames, Exe, Ouse-Sussex), permitting further detailed regional analysis (Fig. 4). The focus on relatively large catchments, within a British context, inevitably constrains the generating mechanisms that are likely to result in high-magnitude floods; which are likely to be either snowmelt, or persistent/heavy rainfall on saturated/frozen ground, or a combination of the two (Black and Werritty, 1997); intense rainfall events generally have greater impact on small catchments with high relief, although sub-catchments of those studied may contain high relief, these are unlikely to result in significant flood events at the sites examined. The potential role of snowmelt as a flood generating mechanism since AD 1800 with the Yorkshire Ouse was examined (Macdonald, 2012), the ratio of floods deriving a snowmelt component were found to be consistent, though potential changes in accumulation within the upper catchment may vary (no records exist of snow depth). The role of ice jamming in the UK as a cause for significant flood events is limited, with only the 1814 flood on the River Tay clearly exacerbated by ice floes (jamming under Smeaton's Bridge, see Macdonald et al., 2006); though historical accounts identify a number of ice fairs over the period of study, that were held on several of the rivers, including the Thames, Trent and Severn.

Flood rich and poor phases

Discernible flood-rich periods are identified at a national scale, across multiple catchments and within specific catchments during the last 812 years (1200–2012;

Fig. 2). The flood index (FI – Fig. 4) generated for Britain correspond well to events/periods recorded elsewhere within the literature as containing significant flood events e.g. ca. 1200s and ca. 1600s, while long periods with a low FI, e.g. drier phases ca. 1300–1400s, correspond well with proxy series e.g. the peat wetness record (Charman, 2010).

The regional FIs (Fig. 4) show both coherent flood-rich phases (e.g. 1770s) across all catchments but also regionally specific flood rich periods (e.g. Wales, ca. 1883). The division of Britain east – west shows similar patterns in the FI, with some subtle differences, e.g. stronger flooding ca. 1770 in eastern Britain, though overall it illustrates that there are not considerable differences in flooding on an east-west basis. Division into four regions provides more variability and permits an assessment of spatial variability, with clear differences in FI for Scotland and Wales, with the flood peak around 1883 in Wales not evidenced in Scotland and a lower FI score for the 1853 event in Wales than Scotland. The northern and southern England divisions also show considerable differences, particularly for the period since 1950, with considerably more events in northern England during this period. Consideration of the regional flood rich periods, as indicated by the black boxes on the right vertical axis (Fig. 4) illustrates the temporal and spatial variability of flood rich periods across Britain. Flood-rich periods can be determined within individual catchments, e.g. River Tay AD 1567–1621 (seven floods) and River Ouse (Yorkshire) AD ca. 1620 with five notable events (AD 1564, 1614, 1623, 1625 and 1636) (Fig. 2) and these can be identified at a national level.

National flood-rich periods are identified during the periods 1550–1650, 1850–1890 and 2000-present, the period 1850–1890 may reflect two shorter periods, during which flood activity was prominent, in the early 1850s and 1875–1885, with several short flood-rich phases: 1765–1880, 1920s, late-1940s, and mid-1960s. High-magnitude floods in the mid-to-late 19th century are widely documented across Britain (e.g. Brookes and Glasspoole, 1928), with the period AD 1875–1885 identified as including a number of years with severe floods (Marsh et al., 2005). The current flood-rich period (2000–) is of particular interest with several extreme events documented in recent years, though it should be noted from a historical perspective that these are not exceptional, with several periods with comparable FI scores during the last 260 years, it remains unclear at present whether the current period represents a short or long flood-rich phase. It is notable that the current flood-rich phase is more evident in northern rivers than those of the south, though several of the southern rivers examined recorded high flows in winter 2014. The spatial coherence of the FI varies, illustrating the importance of good spatial coverage, and suggests that an understanding of flood rich periods needs to be undertaken first at a catchment scale, with subsequent studies examining larger areas/regions. The spatial variability in the series suggests that regions are behaving differently, with periods of synchronous (e.g. national 1770s) and non-synchronous (e.g. regional 1920s) activity.

In the context of the long historical flood series available for mainland Europe, flooding appears to be synchronous and asynchronous during different phases in comparison to the British series. Benito et al. (2003) identified flood rich periods for the Tagus river in southern Spain during the periods *1590–1610*, 1730–1760, 1780–1810, *1870–1900*, *1930–1950* and *1960–1980* (italicised coinciding with British flood-rich periods). Sheffer et al. (2008) study of the Gardon river in southern France identifies several flood rich phases: 1740–1750, *1765–1786*, 1820–1846, *1860–1880* and 1890–1900; with Llasat et al. (2005) identifying flood-rich phases for Catalonia in *1580–1620*, *1760–1800* and *1830–1870*. Comparison of the British FI to the historical flood series presented by Glaser et al. (2010) for central Europe shows a more complex story, with a number central European systems appearing to be asynchronous in relation to the British (e.g. Vistula), whilst others provide similar flood-rich and -poor phases (e.g. Rhine). The flood-rich phase ca. 1600 identified in Britain though is identified at a central European scale from *1540–1610*, and the mid-late eighteenth century flood-rich phase in Britain coincides with a longer flood-rich phase in central Europe from *1730–1790* (Glaser et al., 2010), the other phases identified (1640–1700 and 1790–1840) coincide with periods of little flooding in Britain. Brazdil et al. (2005) identified a series of flood phases on the Vltava at Prague, with peaks *1560–1600*, ca. 1750, ca. 1825, *1840–1860*, 1890, *1940–1950* and 1975–1990, again these show some overlap with flood-rich periods witnessed in Britain, but also periods of little flood activity e.g. 1975–1990. Wetter et al. (2011) identify a number of large floods for the Rhine: ca. 1350, *1560–1600*, ca. *1740–1791*, *1850–1880*, *1994–2007*, of the published flood series this shows good comparison to the British FI. The flood peak identified ca. 1350, is in close proximity to the Britain FI identified for AD 1360, closer inspection of the Rhine series shows two events, AD 1342 and 1374, with examination of the British series also identifying two events, AD 1352 (Dee) and 1360 (Eden), though analysis of the early records is restricted because of the limited detailed data, it may suggest that this period may be one for further examination as a number of descriptive accounts for which estimates were not derived detail the loss of bridges during the 1340s, 1350s and 1370s for catchments around Britain. Few studies have examined the flood history of Irish rivers, an account of the history of Dublin (Dixon, 1953) identifies a number of floods in the mid-eighteenth century (1726, 1728, 1739, 1745 and 1749) often associated with bridge damage/destruction, with subsequent events in 1794, 1802, 1807, *1851* and 1931, though it is difficult to ascertain any further information from these, accounts other than event occurrence. Tyrell and Hickey (1991) identify the three most severe floods in Cork, southern Ireland as 1789, *1853* and *1916*, with increases in flood frequency in the *1920s*, 1930s and *1960s*. Whilst both the Tyrell and Hickey (1991) and Dixon (1953) studies provide some information for Ireland it is challenging to determine whether these are small- or wide-scale flood-rich periods, with the flood-rich phase in Dublin of the mid-eighteenth century occurring before that in Britain, the increased frequency in Cork in both 1920s and 1960s and large flood of 1853 coincides with those identified in the British FI.

5 Flood drivers

During much of the Holocene, three forms of natural forcing of climate are evident: orbital (Esper et al., 2012), solar (Lean, 2000; Vaquero, 2004) and volcanic (Brázdil et al., 2010), these have influenced the global climate, and as such potential flood generating mechanisms. Orbital forcing over the last millennium has changed little.

Solar forcing can manifest itself in a variety of different ways on flood patterns through modification of the climate (Benito et al., 2004); No flood events are recorded in the British FI during the Sporer minimum (1450–1550). The increase in high magnitude floods in central and southern Europe ca. AD 1700, linked to the cold and dry climate of the Late Maunder Minimum (AD 1675–1720) (Mudelsee et al., 2004) have not previously been identified within British flood chronologies, with the British FI identifying the period 1672–1698 as including a number of extreme events (Fig. 4), with two clearly identified as snowmelt events, though generally the period 1650–1750 is characterised as flood-poor, with no floods recorded in Scotland, Northern or Eastern England (Fig. 4). Several series (Fig. 4) indicate increased flood frequency during the late eighteenth century corresponding to the Dalton minima (AD 1790–1830), with notable flooding across catchments in the eight-year period AD 1769–1779, a climatic period considered to include the sharpest phases of temperature variability during the "Little Ice Age" (Lamb, 1995; Wanner et al., 2008). The spatial and temporal variability in relation to these events may suggest that snowmelt becomes a more important driver for flooding relative to heavy precipitation, suggesting that flood response to solar forcing may be regionally and temporally heterogenous (Benito et al., 2004) (Fig. 4). The flood-rich phase in different catchments around Britain (except Wales) during the late sixteenth and early seventeenth century corresponds to a phase of increased storminess in the North Atlantic (Lamb and Frydendahl, 1991) and increased solar activity (Muscheler et al., 2007), and is evidenced in flood accounts from catchments across southern and central Europe (e.g. Brazdil et al., 1999) suggesting a wider flood-rich period, which relates to a particularly strong phase of solar forcing (Fig. 4). A positive significant relationship exists (95 % level) between solar magnetic activity and the British FI (AD 1750–2012), the only significant relationship identified between British FI and the potential drivers examined (Fig. 4).

Previous studies have attributed flood-rich phases to both positive (Dixon et al., 2006; Hannaford and Marsh, 2008) and negative (Macklin and Rumsby, 2007; Folland et al., 2010; Foulds et al., 2014) phases of the North Atlantic Oscillation Index (NAOI), though these studies have used different river flow series, with those evidencing positive NAOI relationships using short instrumental series (often from ca. 1960–), conversely those evidencing negative relationships have applied palaeo-historic-geomorphic flood series for several centuries. This suggests that the relationship between NAOI and flooding is more complex, with potentially different flood generating mechanisms responding to different NAOI states, with different levels of threshold of inclusion being used in the different datasets considered. The relationship between historical floods and NAOI remains unclear (Fig. 4), as flood-rich periods identified in the British FI correspond to negative (e.g. ca. 1620 and ca. 1880) and positive (e.g. ca. 1770) phases of NAOI. The presence of flood-rich phases across multiple catchments suggests abrupt changes in flood frequency/magnitude, reflecting wider climatic variability, permitting an assessment of regional palaeoclimatic change (e.g. Schillereff et al., 2014).

Aerosol optical depth was used as a proxy for volcanic forcing (Crowley and Unterman, 2012), with no relationship evident to the British FI, though a number of large volcanic events are followed by wet years (above the threshold) in Britain (e.g. Krakatoa, 1883 and Tarawera, 1886) (Fig. 4), these are also preceded by wet years. The clear peak in AOD following the Tambora (Indonesia) eruption of 1815 results in elevated AOD for several years (Fig. 4), whilst there have been clearly documented impacts felt across Europe in relation to temperature, with the “year without a summer” (Oppenheimer, 2003), no evidence is presented from the British flood chronologies of any associated change in flood magnitude or frequency. The widespread flooding documented across much of Central Europe during the winter of AD 1783–1784 following the Laki fissure (Iceland) eruption is not widely evidenced within British catchments (Brázdil et al., 2010). Overall, there appears to be little evidence in British systems of volcanic forcing influencing flood events directly during the period of study.

6 Summary

The apparent increase in flooding witnessed over the last decade appears in consideration of the long term flood record to be unexceptional, whilst the period since 2000 is considered as flood-rich, the period 1970–2000 is relatively “flood poor”, which may partly explain why recent floods are often perceived as extreme events. The much publicised (popular media) apparent change in flood frequency since 2000 may reflect natural variability, as there appears to be no shift in long term flood frequency (Fig. 4). In reviewing the flood series for European systems for which long flood series have been reconstructed, a complex picture is identified, whilst flood rich phases appear synchronous across many systems (ca. 1600 and 1765–1780), others show less synchronicity (1920s), whilst a number of prominent flood-rich phases at a European scale appear subdued or are not evident in the British FI (e.g. ca. 1740–1750).

The principal finding of this work is that of the strong correlation between flood-rich phases and solar magnetic activity, indicating a clear driver for flooding patters across Britain, what is still unclear is the relationship between the spatial/temporal distribution of flood clusters and solar activity. This work suggests that flood-rich periods relate to both positive and negative NAOI, with reasonable correspondence with previously diagnosed periods of climatic variability identified from individual series from across Europe. The inclusion of historical flood information provides a better understanding of long-term flood patterns. The detection of flood-rich periods and attribution to periods of climatic change are tentative. The historical records still hold a wealth of untapped information within the records for which specific discharges cannot be estimated, but from which indices could be extracted (Barriendos and Coeur, 2004). The wealth of information presented by the historical records presents valuable new information for flood risk assessment and management (Kjeldsen et al., 2014); as new flood chronologies become available, more detailed and complete indices based chronologies will improve the resolution and enhancing understanding of flood-rich and -poor periods, presenting a more complete depiction of the role of climate and extreme floods.

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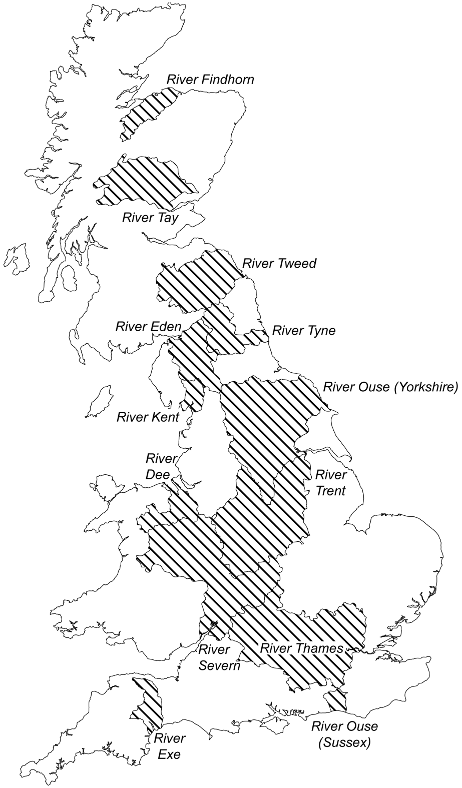

Figure 1. Catchments for which historical flood reconstruction has been undertaken, where a county is included in brackets multiple catchments exhibit the same name.

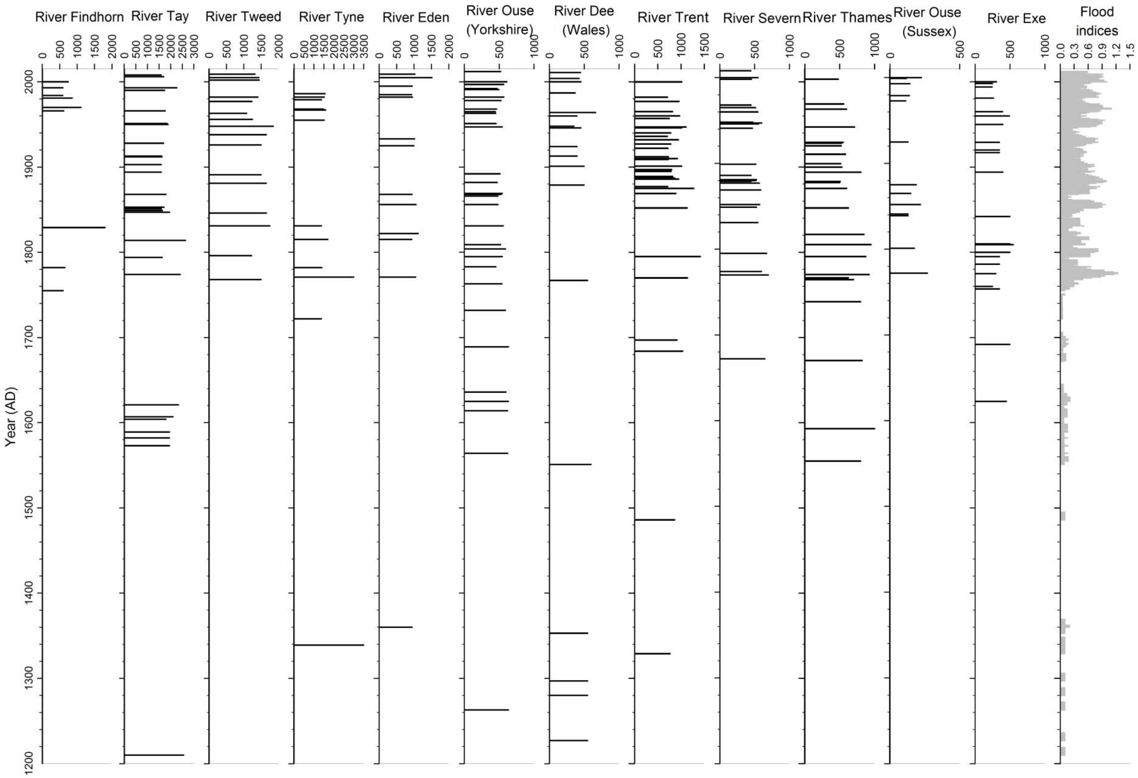

Figure 2. Historical flood chronologies for sites across Britain, showing events that exceed the 0.9 percentile (based on the instrumental record; river discharges are given as m^3 s^{-1}). River chronologies (l–r) Findhorn; Tay; Tweed; Tyne; Eden; Ouse (Yorkshire); Dee (Wales); Trent; Severn; Thames; Ouse (Sussex); Exe; and Flood Indices (Britain) 1200–2012.

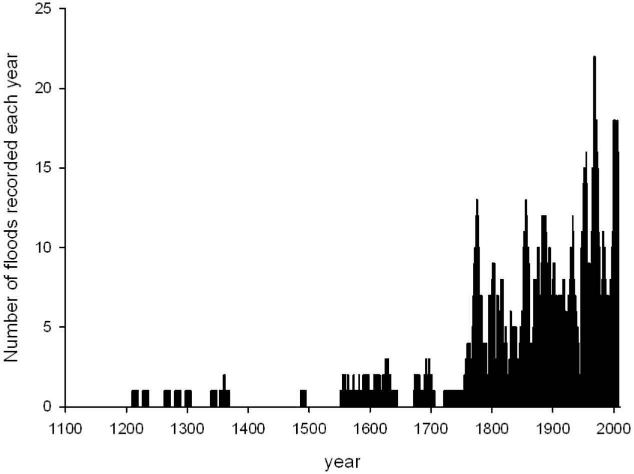

Figure 3. Number of floods with a recorded/estimated discharge exceeding the 0.8 threshold.

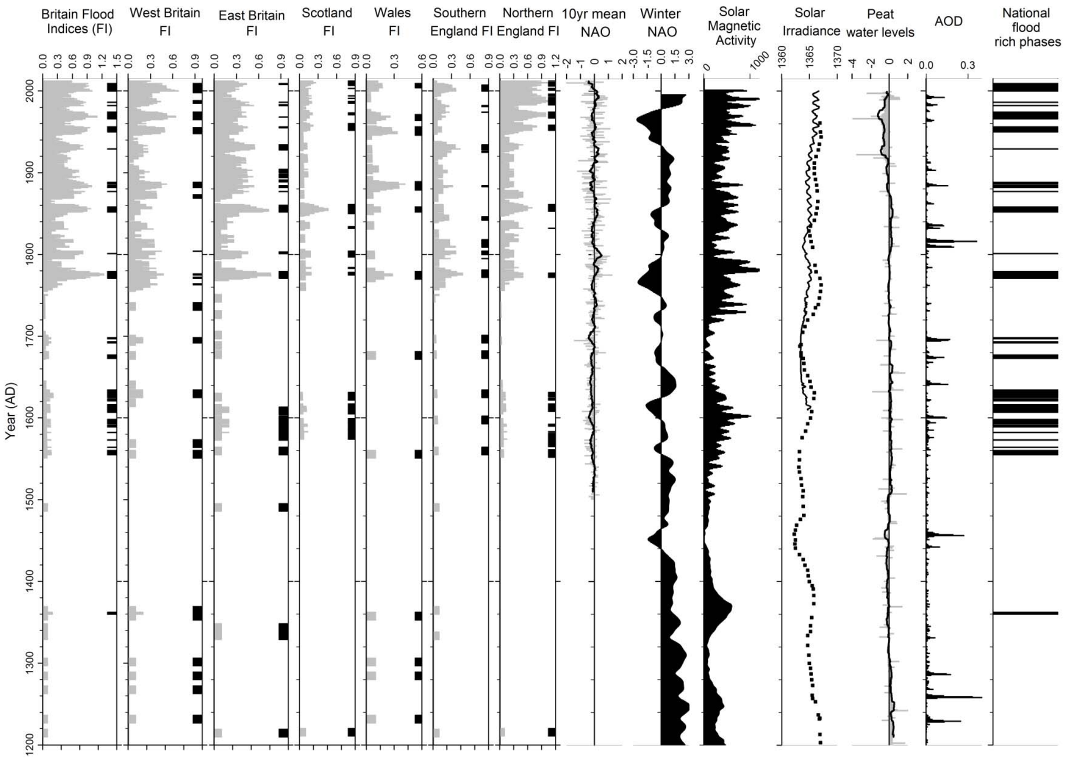

Figure 4. Historical flood chronologies (grey) by region and associated flood-rich periods (black): Britain (1200–2012); West Britain FI; East Britain FI; Scotland FI; Wales FI; Northern England FI; Southern England FI; NAO reconstruction (with 10-year running mean; Luterbacher et al., 2002), extended with CRU data; winter NAO (Trouet et al., 2009); solar magnetic (Muscheler et al., 2010); solar irradiance levels (solid: Lean, 2000; dotted: Solanki et al., 2004); annual stacked peat water level (10-year running mean; Charman et al., 2006); volcanic signal derived from aerosol optical depth (AOD; Crowley and Unterman, 2012).