EXTREME WEATHER EVENTS IN THE UK

ONR Research Project RRR-055

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Extreme weather events in the UK.

Successful and meaningful use of Extreme Value Analysis (EVA) for weather characteristics requires that extrapolated data sets are representative of current and future weather trends. Over the past few decades the UK has experienced extreme weather events, but the extent to which these are changing in magnitude and frequency is not clear. Nor is it clear whether attribution of weather events to climate change has been made.

In this paper we have undertaken a literature review to consider these problems and to produce a state of the scientific understanding of weather and climate extremes currently affecting the UK. The aim of the review is to establish to what extent the UK is experiencing more frequent extremes. It will also advise on future work to establish the potential effects of any identified changes in weather patterns on the evaluation of design basis weather parameters at various exceedance frequencies.

Methodology

We used an extensive literature search using a range of sources including:

- Google Scholar
- Research Gate
- ISI Web of Science
- Scopus

The paper reviews extreme weather events in the UK and classifies these by the time period in which they occurred and the nature of the event. As a result, the paper is subdivided as follows:

- Section 1 Methods of assessing extreme weather events
- Section 2 The record of pre-historical weather events
- Section 3 The record of historical weather events
- Section 4 Extreme events in the instrumental period (19th century to present)
- Section 5 Discussion of the methodological and technical issues for understanding extreme weather events
- Section 6 Conclusions

Extreme Weather

A key element of developing a safety case for nuclear plant at a nuclear licensed site is the demonstration that the plant is adequately protected against external hazards, including those related to meteorological processes. A crucial part of this process is the characterisation and quantification of the external hazards that can credibly challenge nuclear safety at the site. Guidance for inspectors on the assessment of site-specific studies to quantify the threat from external hazards at nuclear sites is provided in Nuclear Safety Technical Assessment Guide NS-TAST-GD-013 (ONR, 2018a), generally referred to as TAG 13.

Extreme weather events include, but are not limited to: extremes of rainfall, subsequent fluvial and pluvial flooding; extreme high and low temperatures and the duration of these; extreme wind storms and snow fall. These extreme weather events have the potential to impact on nuclear safety by affecting the operation of nuclear plant and associated structures, and the availability and performance of resources, including operators and support staff. Climate change is expected to affect the magnitude and frequency of extreme weather events, and it is therefore necessary to investigate how this will occur and the impact on extreme events. Extreme weather may be driven by anthropogenic global warming, (AGW) (described as forced variability) and natural climate variability (i.e. unforced variability); distinguishing between the forced and unforced components is difficult and represents one of the issues that climate change attribution studies are concerned. The attribution issue is described in Section 5 (Discussion section).

One of the components of the climate system that complicates the distinction between forced and unforced variability is the operation of large-scale variability in the atmosphere. In the British Isles this can be viewed as forming two major climate systems. The first is the North Atlantic Oscillation (NAO), which is one of the most important regional atmospheric systems on Earth. The NAO is commonly defined as the difference between the standardised mean sea-level pressure anomalies for the Azores and Iceland (e.g. Rogers, 1984; Washington et al., 2000; Murphy and Washington, 2001) and is an important control on the types of weather the British Isles experience, particularly in winter months (Figure 1). The second is a closely related atmospheric pattern known as the Arctic Oscillation (AO), it is responsible for much of the variability in weather in the mid- and high-latitudes of the Northern Hemisphere.

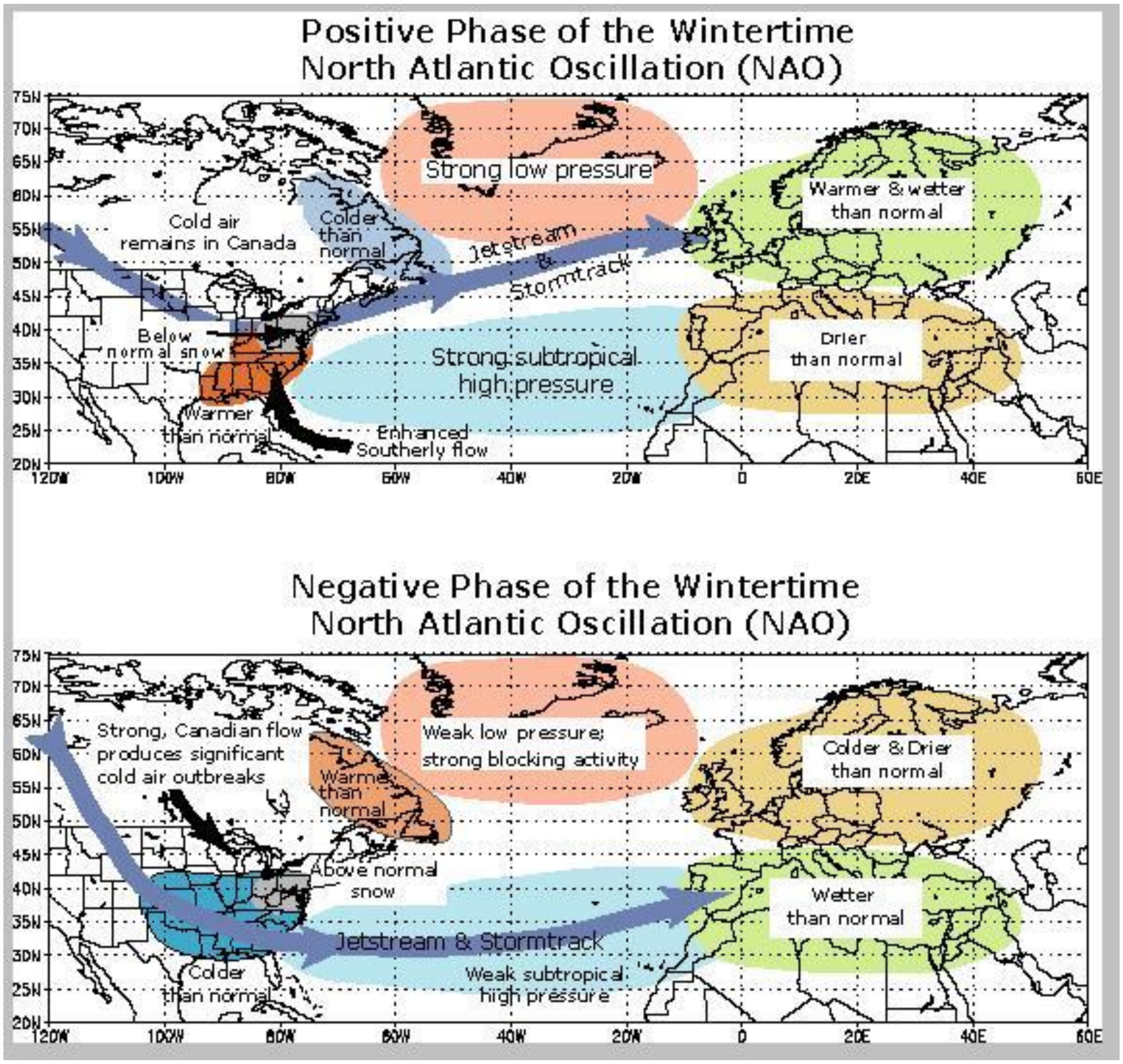

Figure 1 – The North Atlantic Oscillation (NAO) is an index of the pressure difference between the Iceland low pressure and Azores high pressure. The positive phase occurs when the pressure difference is at a maximum, which brings warm, moist winds from the Atlantic to the British Isles. The opposite, negative phase, brings cool dry air to the British Isles. (Figure from The Weather Centre, 2019).

This report reviews the nature of extreme weather events by taking a temporal perspective. As a result, the report distinguishes between:

- pre-historical events (i.e. those occurring before written archives, and taken here to mean those events that have occurred since the beginning of the Holocene geological era);

- events that occurred in the historical record when observations and records were written down; and
- those events that occurred in the 20th and 21st centuries.

Successful reconstruction of the type, magnitude and frequency of past extreme events must take into account the uncertainties in records that exist during these time periods, as well as the fact that that older time periods are likely to have less precise and accurate records of extreme weather events. These issues are discussed in Section 1.

Section 1: Methods of assessing extreme weather events

Statistical methods of assessing extreme weather events

A wide range of statistical techniques are used in the analysis of climate and weather systems and patterns. These include the statistics to test for significance of trends in data, correlation between multiple and single variables and tests for randomness. Problems arise when data are not available, of short duration, are incomplete or of poor quality, or are from sites at a distance from the study location and where spatial and/or temporal extrapolation is required. This section reviews these methods and outlines some of the uncertainties in data analysis that remain and the challenges of using alternative assessments of extreme climate and weather events.

Increased temperature over a range of spatial scales is a characteristic of AGW. For instance, the warmest 20 years globally in the instrumental record (using a 1880-1910 baseline) have occurred in the last 22 years (NOAA, 2020) and there is clear evidence using a multitude of observational and proxy evidence that this is part of a sustained warming, largely driven by changes in atmospheric greenhouse gas concentrations (e.g. Wuebbles et al., 2017; Nerem et al., 2018). However, as Wergen and Krug (2010) discuss, record breaking weather or climate event will occur at a certain rate in any stationary, random process. A record is an entry in a time series that is larger (upper record) or smaller (lower record) than all previous entries. If these are independent and identically distributed random variables drawn from a continuous probability distribution, the probability, Pn, to observe a new record after n steps, called the record rate, is $Pn = 1/n$, because all n values are equally likely to be the largest. Applying this result to maximal temperatures measured at a specific calendar day over a time span of n years, it follows that the expected number of records per year is $365/n$, i.e. about 12 records for an observation period of 30 years. As Rahmstorf and Coumou (2011) discuss, this prediction is entirely independent of the underlying probability distribution.

Non-stationarity is regarded as a clear obstacle in using past observational data to assess future climate trends. Non-stationarity can be caused by a shifting mean value or a changing shape of the probability distribution with time (Katz and Brown, 1992). Ballerini and Resnick (1987) show that for a time series with a linear trend the rate of records becomes constant in the asymptotic limit. With a Gaussian distribution, the increase in a new record compared with a previous record should become progressively smaller.

A number of different methods have been used to better understand extreme weather events (Gilleland et al., 2103). These include:

- the use of statistical EVA to extrapolate extremes of observed data or climate model simulations (e.g. Coles et al., 2001; Fowler and Ekström, 2009);
- the use of metrics including the 95th annual percentile for rainfall or the total rainfall on the 10 wettest days in the year;
- downscaling of metrics and assessment of the connections between extremes and model outputs; and
- using proxy measures of extremes that can be resolved by climate models (e.g. Heaton et al., 2011).

It is often the case that several statistical models can fit the data well.

From these studies the extreme value (EV) distribution is shown to provide a useful methodology for assessing extremes, although a known weakness is the omission of data that could be reasonably considered extreme (e.g. an annual event that is more extreme than other annual maxima, but not extreme in the context of that year) and weaknesses in deriving useful statistics from the tails of the probability distributions (Mannshardt and Gilleland 2013). For the annual maxima approach they assess these issues in the context of: return levels; tail behaviour and models deriving a temporal trend in the EV distribution.

Extreme Event Analysis (EEA)

Recent advances in detection and attribution (D and A) studies have focused on the analysis of extreme weather and climate events (for a recent review see Swain et al., 2020 and also Sippel et al., 2020). They identify four steps for EEA:

- The first step is to define the spatial, temporal and physical characteristics of the event in question ;
- The second step is to assess the probability and magnitude of the event in a world where anthropogenic climate forcing is not occurring (they call this the counterfactual climate and others have called this the unforced variability). This is achieved by running climate models forced by pre-anthropogenic drivers. This can also be done by removing the long-term trend from the historical climate series “using statistical relationships between the climate variable and global temperature, and using observational data from a time period with little anthropogenic influence” (Swain et al., 2020 pp.523);

- Step three compares the statistics of the observed climate against the modelled ‘counterfactual’ climate. This has been done using the fractional difference in the magnitude of the climate or weather event; assessment of the proportion of risk created by anthropogenic forcing (the fraction of attributable risk) and the ratio of the probability of the event ; and
- The final step is to create a formal attribution statement based on reasonable doubt (i.e. rejecting a null hypothesis that states that the climate event could have occurred by chance with a given level of probability).

There are numerous uncertainties associated with this EEA procedure; many of them relate to the issue of assessing unforced climate or weather variability. With short observational data sets, it is not always easy to obtain a clear view of how the climate has behaved during times when anthropogenic forcing was largely absent. This issue is particularly important when assessing contemporary river floods in the context of incomplete understanding of past river flood regimes. This is discussed below.

Flood Frequency Analysis (FFA)

This has been a particular focus of EVA and one common approach to FFA is to use the annual maximum series (e.g. Bezak et al., 2014). This is defined by the annual maximum peak flow. Again, however, this approach can lead to gaps in relevant data, as high flood peaks can be omitted in years with higher floods, while much lower floods can be added during years with low flood peaks. In addition, given the short length of most flood series (e.g. perhaps only 30-90 years), the available data sample can be small. An alternative to annual maximum series is the peaks-over-threshold approach (POT), which is also called the partial duration series approach, defined as the peak values above a previously defined threshold. The difficulty using this approach is to define an appropriate threshold value.

In summary, to assess flood risk it is necessary to:

- define the annual exceedance probability (return period) for floods at different levels;
- determine ‘design storms’ to convert flood levels with associated probability to storm hydrographs (e.g. using a defined unit hydrograph or other methods) that can be used to predict inundation;
- assess the impact of these floods through use of a hydraulic flood model;

- assess damage potential based on predicted flow depths and velocities, allowing conversion of model output to a quantification of potential impact; and
- convert each damage potential into an annualised damage likelihood, based on the annual exceedance probability associated with each event.

Extreme wind

This issue is treated similarly to FFA. Assessment of future wind characteristics has used EVA to extrapolate data from time limited datasets to generate hazard values at 10^{-3}/yr and lower frequencies. A question arises as to which EV method to use for analysis of extreme wind. The most commonly used distribution in studies of wind extremes is the Generalised Extreme Value Type I (Gumbel), applied to a set of annual maxima. This decision will likely be influenced by the length of the available dataset(s). Rather than selecting one EV from a time period, alternative approaches may be used to increase the number of values for analysis (e.g. r-largest, method of independent storms, peak-over-threshold). This means that for a given time series more points are selected for analysis, which reduces the standard errors. The time series can be lengthened by using comparison with neighbouring stations, simulation modelling, or parent distribution methods. However, the results can never be as reliable as those obtained from a long dataset. A short dataset implies large standard errors and may not capture the full range of extremes. The EVA should also aim to quantify the full range of uncertainty surrounding the results.

Extreme Sea-Levels

Similar techniques with similar limitations are used in the analysis of extreme sea levels (ONR Expert Panel on Natural Hazards, 2018a) and this document argues that:

> *The annual exceedance probability is the probability that a flood will exceed a given level in any year[1], and is the inverse of the return period, or frequency interval (i.e. an event with a 1 in 100 year return period has a 1/100 or 1% annual exceedance probability). These probabilities are usually determined using observations of river level or flow for past events. However, extreme events are rare, leading to few observations and this*

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[1] The concept of annual exceedance probabilities can (and are) applied to many different natural hazards variables including earthquake ground motion severity, wind speed and sea level.

> *means that there is considerable uncertainty in the estimation of the most extreme events. In the United Kingdom, flow records are available up to 100 or more years, but often the duration of the timeseries is considerably shorter. With a longer observational record, more reliable estimates of probability are possible, but, irrespective of the record length, the most extreme events will always have the most uncertainty associated with them. In order to estimate flood levels for very extreme events as required for nuclear sites, such as the 1 in 1,000 year or 1 in 10,000 year events (0.1% or 0.01% annual exceedance probability), extrapolation well beyond the length of the observational record is required. This is achieved through the fitting of a statistical model to the observed data, such as the Extreme Value Type I (Gumbel) or Log-Pearson Type III distributions (e.g. Frances et al., 1994). These models are then used to predict the value at each required level.*
>
> *A major assumption with this is that observed flood events (and those that are likely to occur in future) occur under homogeneous conditions – in other words, that the floods occur under the same type of conditions within the catchment and climatically (i.e. the probability of flood events is assumed to be stationary or unchanging). However, anthropogenic basin alterations such as urbanisation or deforestation can change the likelihood of flooding, reducing the reliability of probability estimates, or shortening the usable length of the observational record. Importantly, changes in the climatic conditions that lead to floods (e.g. increases in the proportion of convective rainfall with high intensity) means that past observations of flooding may not provide reliable estimates of future flood probability.*

Other techniques

UK floods display high levels of variability. This results from shifts in the NAO over annual and decadal timescales, and these changes are a major driver of flood variability across northwest (NW) Europe. If current floods are being measured against past flood magnitudes and frequencies that occurred in a flood-poor period (e.g. when the NAO was in a negative mode and its associated floods were few and of low magnitude) then this skews assessments of current flooding. It also skews our assessments of flood detection and attribution.

At the site-specific level, weather and climate hazard analyses need to draw upon all available information comprising geological (where appropriate), historical and instrumental data sources.

Some of the following is derived from the TAG 13 (2018, pages 11-14). Where some of these data are not readily available (as might be the case for sediment cores that will provide proxy palaeoclimate data) then these may be sought. It should also be stressed that various data sources can be used in combination to complement each other or to provide long term context to understand natural and forced climate variability. For example, sedimentary records of past hurricanes have been used to reconstruct changes in hurricane strength and frequency (e.g. Liu and Fearn, 2000; Mann et al., 2009), enabling comparison with current instrumental data and to assess recent patterns and trends in hurricanes against the palaeo-record. An overview of these areas is provided in this section.

Observational data sets on relevant climate hazards are generally of short duration, are spatially variable and therefore only cover small regions of interest. As a result, developing hazard assessments for events with high magnitudes but very low frequencies is made very difficult by the nature of these data sets. Given this, the use of geological and palaeoclimate proxy data for climate events should be considered to provide information on potential climate hazards. Such data have been used extensively in the UK and elsewhere for assessments of the nature and timing of river flooding and other extreme climate and weather events.

Data on past climate change can be used to better assess the significance of contemporary events (i.e. whether extreme events in the observational record are extreme in the context of longer time periods) and place future projections in context. Palaeoclimate data will also allow scientists and practitioners to understand unforced (natural) variability, and therefore gain insight into the probable behaviour of climate and coupled earth systems over time. However, paleoclimate data must be used with caution because the data being used to interpret past climate are only proxies for climate and interpretation of these can be misleading. Use of past proxy data to better understand the future behaviour of the climate system also makes the untested assumption that future system behaviour is as constrained as past behaviour. Clearly, non-stationarity in data sets makes this assumption invalid.

Palaeoclimate reconstructions for the British Isles are numerous and include work on peat bogs (e.g. Barber et al., 2000; Barber et al., 2013), tree ring dating (Rydval et al., 2016) and lichen dating (e.g. Armstrong, 2006; Bradwell, 2010). However, analyses of past weather extremes are strongly biased towards extreme floods as these produce clear geomorphological and sediment signals which can be interpreted. Extreme temperatures, droughts or snowfalls are not as easily reconstructed and reliable records may only be available for the instrumental record.

The use of geomorphological data sets.

Recently, Naylor et al. (2017) have provided a useful review of the ways in which geomorphology can be used to derive assessments of extreme weather and climate events. Geomorphologists have improved flood risk calculations by assessing and modelling the ways in which combinations of climate and weather events impact geomorphological responses, and by providing decision-relevant information on geomorphological change and erosion risk to flood agencies and policymakers (Naylor et al., 2017).

The United States have helped pioneer the use of geomorphological data sets in flood risk analysis. As elsewhere flood frequency assessments in the United States relies on EV approaches such as Gumbel analyses or log Pearson Type III. However, because annual floods series are generally limited temporally and lack a series of extreme events to include in the calculus, the United States Geological Survey (USGS) provides regional skew coefficients to augment gauging stations with temporally limited flood series. The key reference for FFA in the United States follows guidelines from Bulletin 17B (USGS, 1982). However, these guidelines lack information from pre-gauge records and outliers are excluded (e.g. Stedinger and Griffis, 2008). This may reduce the accuracy of risk assessments.

The range of geomorphological data that has been used include the dating of boulder berms and floodplain sediments. Boulder berms are depositional landforms in river valleys that record the timing and magnitude of past floods (e.g. Anderson et al., 2004). They have been dated using radiocarbon dating of included organic material, dendrochronology (tree ring dating) and lichenometry (dating using lichen growth curves). Analysis of flood plain sediments uses sediment cores to reconstruct the size of past floods and dating of these using radiocarbon dating and luminescence techniques (e.g. Macklin et al., 2010).

The use of geomorphological data to augment and extend instrumental approaches can help deal with the issue of outliers in the record that may represent real (but rare) events, and which may not be captured in standard statistical approaches (e.g. Baker, 2000; Toonen et al., 2016). Naylor et al. (2017) use the example of Pitlick (1997) who showed for the Mississippi River flood of 1993 that estimates of its recurrence interval are sensitive to the incorporation or not of outliers, with flood recurrence intervals ranging from 500 to 1000 years depending on outlier selection.

Challenges in using geomorphic and sedimentary indicators to reconstruct flood and storm frequencies

There are five challenges in using palaeogeomorphological data to improve our assessment of the magnitude and frequency of extreme climate and weather events, such as storms and floods.

1. Until recently, records of geomorphic change in response to floods (e.g. boulder berms, floodplain incision and avulsion) and sedimentary data from floodplains were assumed to lack the age and magnitude precision and accuracy to derive flood estimates of use to policymakers and planners (Macklin et al., 2013; Benito et al., 2015). However, improved dating of sedimentary deposits and metadata sets of flood events at national and international scales have increased enormously our understanding of the role of climate in driving flood events at a range of timescales.
2. There are problems in comparing short but annual or sub-annual observational data sets with geomorphic and sedimentary data that are able to reconstruct extreme floods at event scales (e.g. Toonen et al., 2016). In addition, geomorphological reconstructions rarely provide continuous data on flood frequency. The data from palaeoecological records (such as pollen analysis) are capable of reconstructing longer-term climate events such as droughts, but not the shorter events that are of interest to planners and flood managers.
3. Third, the relationship between a climate or weather event and a corresponding change in a climate proxy is rarely linear and uncomplicated. For instance, there are temporal and spatial lags between climate events and the response of a proxy, and the nature of these lags may themselves change (e.g. Harrison et al., 2019). It is also difficult to isolate the climate signal in a proxy. For instance, it may be difficult to distinguish between a storm surge and tsunami inundation in marine sediments. As a result, while climate proxies may be used to extend data series, caution must be taken in their assessment.
4. Distinguishing between unforced events and those produced by historical human activity may be difficult and therefore isolating forced variability from unforced variability in relevant earth systems may be problematic.
5. Finally, there has been little comparison of palaeoflood reconstructions from geomorphic or sedimentary signatures and gauged records. As a result, it is difficult to determine the uncertainties in palaeoflood estimates from proxy data. There needs to be a better understanding of the distributional assumptions behind using proxy flood data.

Use of Historical Records and Accounts

Documentary records have been used to assess the size and extent of past climatic events, although these records are often qualitatively described, are likely to have considerable epistemic uncertainty and are not generally used in hazard analysis. However, they have been used in tsunami and storm surge research (e.g. Bryant and Haslett, 2007), to examine past wind storms (Dawson et al., 2004) and, routinely, for extending flood time series (e.g. Glaser et al., 2010; Kjeldsen et al., 2014). Here, historical records usually predate the installation of gauging stations and can provide indirect information on peak flood discharge, often in the form of a water-level marker, information that a specific location had been flooded, damaged or destroyed, or that a flood reached a level relative to a structure. There are, however, three well recognised limitations of documentary records in the UK, in terms of flood frequency and particularly flood magnitude analysis (Rumsby and Macklin, 1994):

1. the accuracy and reliability of measurements deteriorates before AD 1700;
2. the record is biased towards populated areas; and
3. most significantly, changes in channel capacity resulting from river aggradation and incision (e.g. Newson and Lewin, 1991; Macklin et al., 2013), floodplain morphology through sedimentation and wetland drainage (e.g. Lewin and Macklin, 2010) and construction of bridges, embankments and transport infrastructure make it very difficult to convert a historical water level to a peak flood discharge.

Although peak discharges of major floods have been reconstructed using historical water-level information, as a consequence of major channel and floodplain modifications such as changes in channel-margin sedimentation, they are likely to have large, unsystematic and presently unknown errors. Unfortunately, in the UK instrumental documentary and palaeoflood records have rarely been investigated in an integrated manner (Macklin et al., 2012). This is in strong contrast to the USA (e.g. O'Connor et al., 2014) and mainland Europe (e.g. Glaser et al., 2010; Toonen, 2015) where combined studies of instrumental documentary and geological records of major floods are becoming increasing routine and are being used by regulatory and environmental protection agencies to inform flood risk assessment. The UK lags significantly behind this rapidly developing field of water-resource risk assessment and planning.

Despite this, over recent years new methodologies have been developed to construct long-term assessments of flood frequencies and magnitudes, and these have used a range of geomorphological and sedimentological archives.

Instrumental data

This section is partly taken from ONR Expert Panel on Natural Hazards (2018b) available from the ONR website[2].

Rainfall and snow measurements are collected at weather stations. The UK Met. Office (UKMO) operates an extensive network of (at the time of writing) 270 stations, supplemented with an additional network of 162 stations for climate monitoring. The historical archive of station observations at the UKMO extends back to 1853 for a small number of sites. The UKMO also produces long term climate monitoring series such as the Met. Office Hadley Centre UK Precipitation (HadUKP) series (Alexander and Jones, 2000), including daily averages back to 1931 and a monthly series back to 1766. However, climate series such as HadUKP are designed for monitoring climate change over long timescales and are less suitable for EVA of rainfall from convective thunderstorm events; they are at an insufficient temporal resolution to allow for the assessment of pluvial flood risk. Hourly rainfall data is available from the UKMO Integrated Data Archive System (MIDAS) (UKMO, 2012). Digital records exist for a small number of sites back to 1949. However, these data are currently restricted to approved Centre for Environmental Data Archival (CEDA) users. The MIDAS database also contains daily rainfall measurements from the full network of registered rain gauges, including several thousand additional sites managed for hydrological purposes by a number of government agencies and private authorities.

The Centre for Ecology and Hydrology Flood Estimation Handbook and associated software (2016) represents the most comprehensive collection of data from the Environment Agency, the UKMO and data from distributed Water Boards.

Automated measurements for snow depth are sparser, augmented until 2007 by the Snow Survey of Great Britain (Kay, 2016). Snow depth by itself does not provide the necessary snow water equivalent (i.e. the volumetric quantity of liquid-equivalent water contained in the snow) since the density of the snowpack will vary, depending on the conditions in which the snow fell. In addition, snow may be a significant source of error in precipitation measurements, with few automated stations equipped with heated precipitation gauges to improve its measurement (Kay, 2016).

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[2] https://www.onr.org.uk/operational/tech_asst_guides/index.htm

The observational system includes: Regional Basic Synoptic Network; Basic Synoptic Network; Supplementary Network and an Aviation Network. Other networks include those for: climate, wind, rainfall and sunshine[3].

Reliability of data sets

What is not possible at present for most types of sediment-based flood record in the UK is directly to convert recorded flood events into former discharges (Jones et al., 2010). It seems quite likely that contrasting sedimentary environments are recording floods of different frequency and magnitude, unlike that suggested for the slack water deposits/palaeostage indicators (SWD/PSI approach). Even that approach involves a degree of self-censoring (with floods of large magnitude removing the deposits of earlier ones), but it is less susceptible to the problem of obtaining flood channel dimensions and flood levels (and thus discharges) on floodplains that have been transformed by later events.

Variability of weather can be shown by changing extreme events. The paper now gives examples of extreme events from prehistoric, historic and contemporary (20th and 21st century) timescales.

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[3] *Further details are provided in: https://artefacts.ceda.ac.uk/badc_datadocs/ukmo-midas/ukmo_guide.html*

Section 2: The record of pre-historical weather events

These are events occurring before written archives and are taken here to mean those events that have occurred since the beginning of the Holocene geological era (post 11,650 cal. years BP). Before the Holocene there were, no doubt, extreme weather events but these occurred during a period of global deglaciation (the late glacial) that produced climate shifts on decadal scales and major changes in earth-surface systems. These included very rapid sea-level rise, tsunamis, reorganisation of ocean and atmospheric circulation and huge changes in ecological systems. Consideration of extreme weather in this section (as distinct from shifts in climate) has been omitted, partly because the record of short-term weather events is usually absent from late-glacial records.

Most of the proxy records used to record extreme weather during the Holocene uses sedimentology or palynology to interpret sedimentary records from floodplains, lakes and peat bogs. However, it should be cautioned that it is difficult to distinguish between storms (combination of rainfall and high winds) and purely rainfall/flooding using these techniques, because the sedimentary signature is similar and event resolution is poor.

Extreme storms during prehistorical times have been described from various locations in the British Isles. Caseldine et al. (2005) used analysis of peat profiles and radiocarbon dating on Achill Island in western Ireland to reconstruct the nature of an extreme climate event that occurred sometime around 5300–5050 cal. yr. BP. The extreme event, probably a rainstorm followed by extreme flooding, was likely larger than any other event in that area during the whole of the Holocene period.

Macklin and Lewin (2003) used radiocarbon dating on different topographical units in alluvial valleys to identify whether dated units coincided with changes in the rate of sediment accumulation or removal. This allowed them to reconstruct geomorphological changes associated with changes in river activity during the Holocene (last 11,000 years). They show a strong relationship between periods of cool and wet climates and major flood periods in Britain and especially at ca. 8000 cal. yr BP and since ca. 4000 cal. yr BP (see Table 1). However, between 5000 and 6000 cal. yr BP, a cold and wet period, few floods are observed. This either means that the correspondence of floods with climate deterioration is only partial, or is being obscured in the later record by land-use changes.

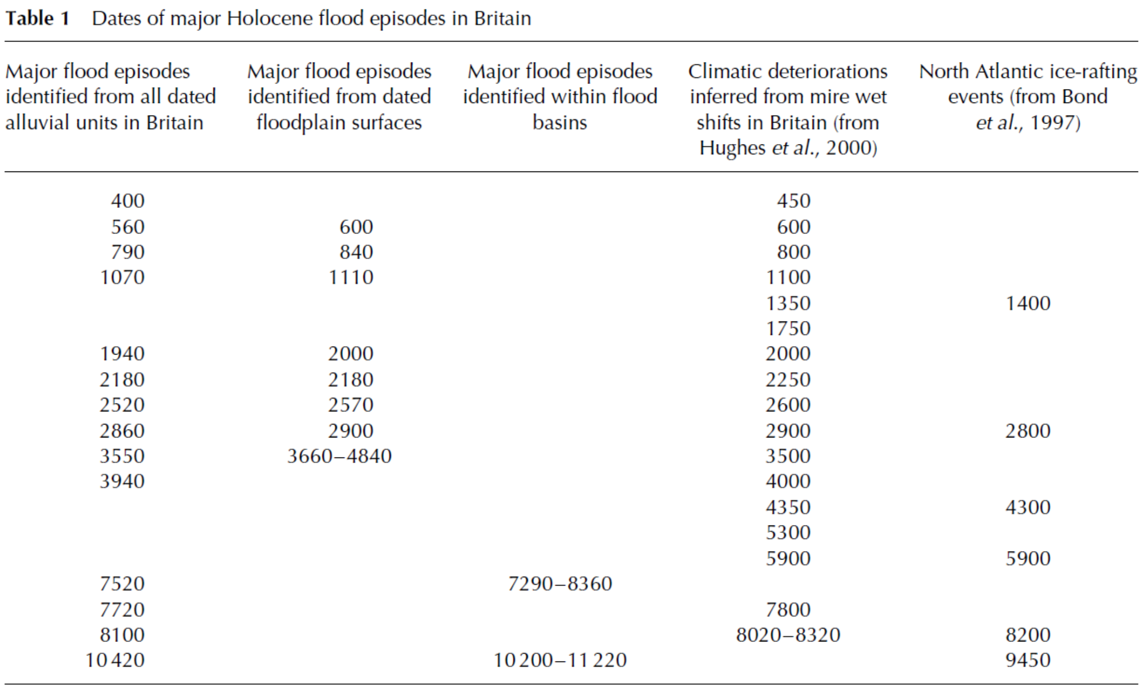

Table 1 Dates of major Holocene flood episodes in Britain

Major flood episodes identified from all dated alluvial units in Britain	Major flood episodes identified from dated floodplain surfaces	Major flood episodes identified within flood basins	Climatic deteriorations inferred from mire wet shifts in Britain (from Hughes *et al.*, 2000)	North Atlantic ice-rafting events (from Bond *et al.*, 1997)
400			450	
560	600		600	
790	840		800	
1070	1110		1100	
			1350	1400
			1750	
1940	2000		2000	
2180	2180		2250	
2520	2570		2600	
2860	2900		2900	2800
3550	3660–4840		3500	
3940			4000	
			4350	4300
			5300	
			5900	5900
7520		7290–8360		
7720			7800	
8100			8020–8320	8200
10 420		10 200–11 220		9450

Table 1 from Macklin and Lewin (2003).

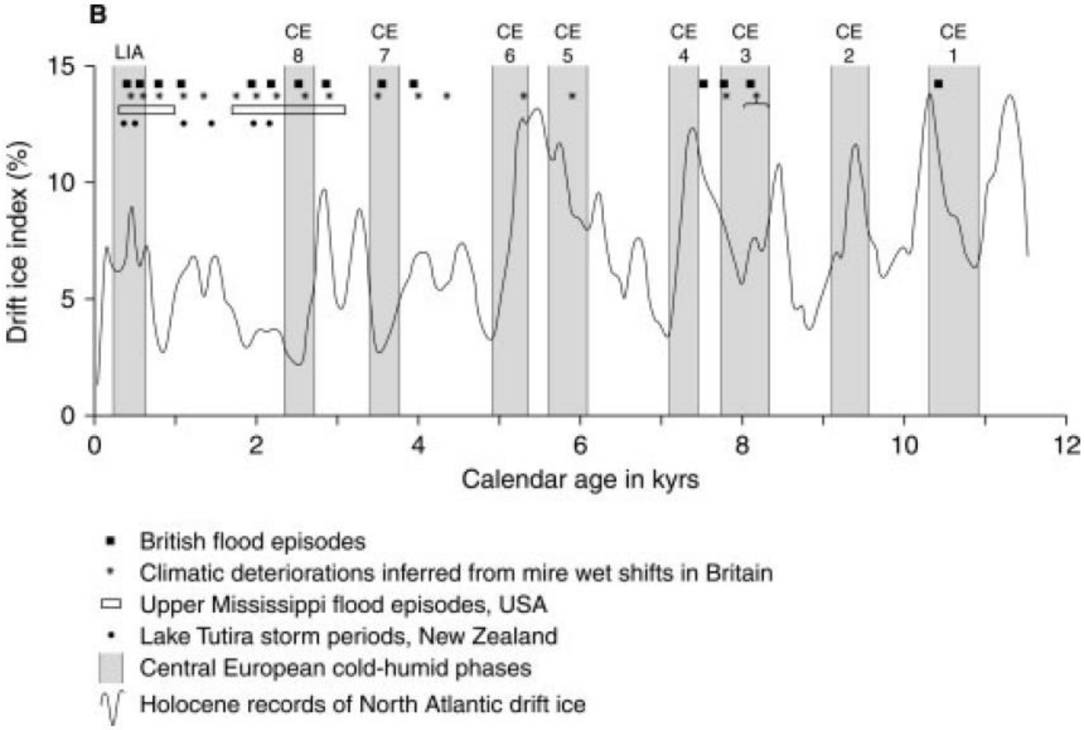

Figure 2 from Macklin and Lewin (2003). Comparison of British Holocene flood episodes with proxy climate records for Britain, Central Europe and the North Atlantic. Well-dated storm periods for Lake Tutira, New Zealand and flood episodes in the upper Mississippi basin, USA are also plotted towards the top of the diagram. 'LIA' and 'CE' refer to the Little Ice Age and the Central European Cold-Humid Phases.

Section 3: The record of historical weather events

As shown in Sections 1 and 2 , geomorphological and sedimentological data have been used to extend the palaeoflood record (Kochel and Baker, 1982; Baker, 2000; Jones et al., 2010; Benito and O'Connor, 2013). While the pre-historical flood record contains sedimentary evidence for extreme floods, the historical record (i.e. since historical observations and records) shows clear and verifiable evidence for larger events than have occurred in recent decades, and this section reviews some of this evidence.

It should be noted that historical weather events can be further subdivided into those measured using instrumental data, those that have been observed, inferred from proxy data, and those events identified using anecdotal records. Of these, the instrumental record is likely to have the highest accuracy and precision in terms of date of occurrence, magnitude and location; but even this is variable in terms of the spatial density and temporal frequency of certain measurements.

Research on the flood histories of central European rivers from the 16th to 19th centuries has shown that local floods have developed from convection storms; those floods affecting multiple catchments over large areas were clustered in winter and often associated with the breakup of frozen rivers and snowmelt from alpine catchments.

In central Europe one of the most famous, and largest, precipitation and flood event of the last millennium occurred in July 1342 (Herget et al., 2015 and Figure 3) in what is now Germany. Given its size, it is often termed the hydrological worst-case scenario. The flood started on July 19th and lasted 3 days. At its peak the flood level was 8.8m above the river gauge at Frankfurt and this represented a reconstructed discharge of 4300 m^3/s. This compares with recent mean discharge at Frankfurt of 194 m^3/s and the highest measured value of 2010 m^3/s, and was much higher than recent catastrophic floods on the Danube, Elbe and Oder in 2002, 2005 and 2013.

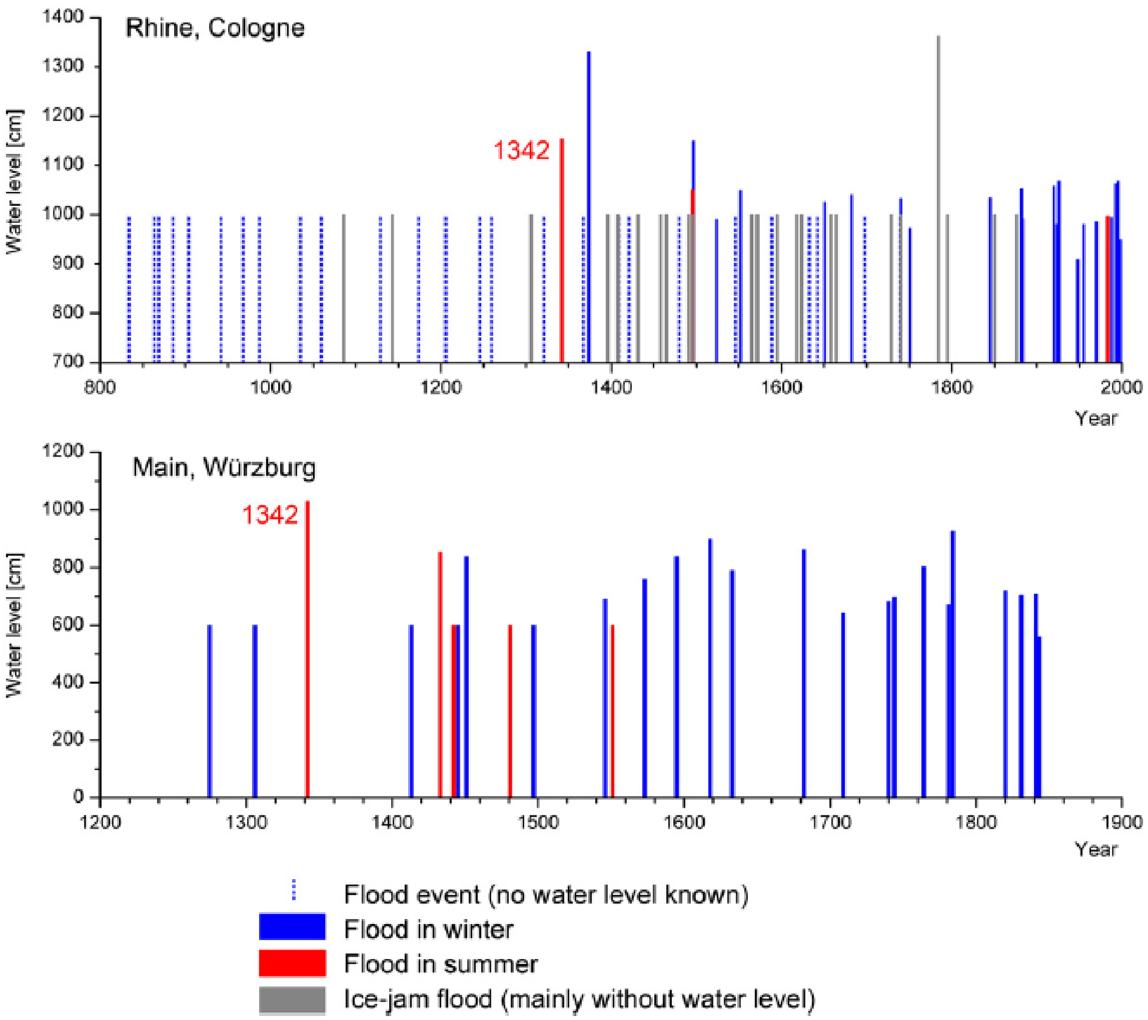

Figure 3. Flood depths of the Rivers Rhine and Main (Herget et al., 2015).

Section 4: Extreme events in the instrumental period (19th century to present)

Recent research (Blöschl et al., 2020) has attempted to assess the significance of recent large floods across Europe in the context of flooding over the past 500 years. They used a compilation of published and unpublished flood series, documents and newspaper archives from 103 river reaches in Europe from 1500-2016 AD and identified 9,576 floods, with 8,954 of these having information on the season that the flood occurred.

Blöschl et al. (2020) showed that the past 30 years was separated from past floods by a 90 year 'disaster gap' - a period with few large floods - and that this recent period was amongst the most flood-rich episodes in Europe over the past 500 years. They subdivided flood-rich periods into 1560-1580 (in western and central Europe); 1760-1800 (in most of Europe); 1840-1870 (in western and southern Europe) and 1990-2016 (in western and central Europe).

The timing of recent floods has changed; 41% of past Central European floods and 42% of interflood periods occurred in the summer. However, 55% of recent floods have occurred in the summer and this contrast is assessed as being statistically significant. The timing of past floods appears to support much of the fluvial palaeoflood literature from the British Isles, which stresses the role of rain on snow events in the Little Ice Age as driving historical and earlier events.

In the UK, Macklin and Rumsby (2007) show that timing of the largest floods in upland catchments (the most flood sensitive) since the second half of the twentieth century has correlated with the negative mode of the NAO index (as defined by Jones et al., 1997 and Osborn, 2005). During these times weaker westerlies and slow moving weather patterns over the North Atlantic prevail. Most of these floods developed by localised, intensive convection storms in summer and during anticyclonic conditions, or in association with slow-moving (e.g. Yorkshire Dales 1986 flood) or near-stationary fronts (e.g. Lake District 1995 flood).

This raises two important issues for assessment of extreme floods. First, there is a clear pattern in the palaeoflood record of times when floods are concentrated in periods of wet, stormy conditions (e.g. Macklin and Lewin, 2003; Foulds and Macklin, 2016) associated with positive NAO conditions; and also times when floods are associated with negative NAO conditions and with convective storms. The latter include the floods of 1952 on Exmoor (Kidson, 1953), Forest of Bowland in 1967 (Duckworth, 1969), the Cairngorms in 1978 (McEwen and Werritty, 1988), Caldwell Burn, Dumfries in 1979 (Acreman, 1989), the Howgill Fells in 1982 (Harvey, 1986), the

Northern Pennines (Carling, 1986) and Southern Uplands (Acreman, 1991) in 1983, the Yorkshire Dales in 1986 (Newson and Lewin, 1991) and the Lake District in 1995 (Johnson and Warburton, 2002), as well as the more recent 2004 Boscastle and 2005 Helmsley events (references in Macklin and Rumsby, 2007).

Second, this association of floods with both negative and positive NAO conditions, means that flood risk assessments cannot be based upon modelled NAO behaviour. In addition, frequency of extreme floods is also variable regionally, even when the NAO sign does not vary. For instance, between 1920 and 1970 there was an increase in extreme floods in the North Pennines and Yorkshire Dales, but no increase in the Brecon Beacons and the Lake District. This correlates with a phase of negative NAO during the late 1950s and early 1970s (Jones et al., 1997).

In summary, the fluvial record of extreme floods from the British Isles suggests that:

- extremely large floods have occurred in the past, at times when the human impact on the climate was likely minimal;
- these large floods occurred during times when the NAO was in its positive or negative phases, so attribution of these events cannot be made to specific weather types and there is also spatial variability (c.f. Wrzesiński and Paluszkiewicz, 2011); and
- these floods may be larger than floods seen in recent decades (see also section 5).

Recent work on palaeofloods has implications for our understanding of the recent record. While past flood events have only rarely been reconstructed from lake sediments, Chiverrell et al. (2019) developed a continuous 558-year long time series of flood events from Bassenthwaite Lake in the English Lake District, which captures the runoff from a 300km2 catchment (Figure 4). The research demonstrated, first, that floods occur in clusters and this probably represents shifts in atmospheric circulation. This is significant because extreme flooding is often associated prolonged rainfall events of moderate magnitude onto already saturated ground, rather than discrete, extreme events. In other words, clustering of rainfall might well produce extreme floods. Second, Chiverrell et al. (2019) showed that the most extreme floods (the top 1% in the record) in their data series occurred between 1990 and 2018. This is significant because much of the flood record from fluvial systems in the UK suggests that floods were much more extreme in the past. Reconciling these differences is likely to be extremely important for licensees of nuclear and other infrastructure sites and regulators. Third, they estimate that the damaging 2009 flood was the largest in the 558 year record and had a recurrence interval of 1:2200 year, larger than the recurrence interval estimated using the shorter-duration gauge record (1:1700 year). From this they argued that developing flood frequencies from short-gauge records that captured such clustered floods would produce recurrence probabilities that are too frequent, and over-estimate flood risk. Of course, the opposite is also true and the use of short-gauge records to produce flood frequencies should be viewed with considerable caution when that observational record coincides with flood-poor time periods. Finally, they attributed the clustering of recent floods to warm Northern Hemisphere temperatures and a positive phase of the Atlantic Multidecadal Oscillation (AMO).

However, an important methodological caveat should be mentioned. In this research the palaeoflood record was generated using particle size distribution data of lake sediments from the lake cores, with the assumption that particles size reflects flood magnitude. However, the sedimentary record might give erroneous flood magnitude results (even if flood frequency is accurate) as the particle size signature might just reflect remobilizing channel and floodplain sediments as channels shift and incise during high-discharge events.

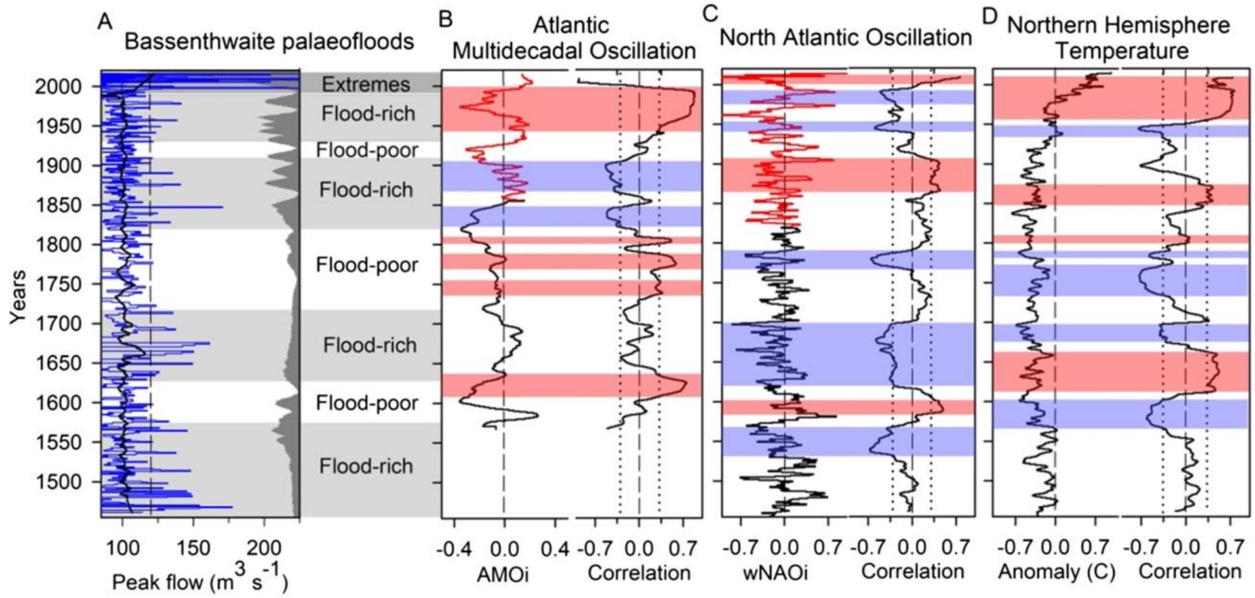

Figure 4 (from Chiverrell et al., 2019). A. Time series of raw (blue) and smoothed (black) river flow series (m3 s-1) reconstructed from core BASS-2016, showing the modelled age probabilities for flood layers (>115m3 s-1), with flood-rich periods and episodes of extreme flooding.

B. Indices for Atlantic Multidecadal Oscillation (AMO) (left: measured series in red, reconstructed in black) (Cook et al., 2002) and a Pearson correlation co-efficient series (right) relating the AMO and the smoothed Qmax series. Vertical lines (pecked) show zero correlation and the 99% significance limits. Shaded rectangle zones highlight periods with significant positive (red) and negative (blue) correlation.

C. The same as B except for indices of winter North Atlantic Oscillation (wNAO; Gray et al., 2004).

D. The same as B except for reconstructed Northern Hemisphere Temperatures (NHT; Shi et al., 2013).

The HANZE Database

The Historical Analysis of Natural Hazards in Europe (HANZE) database is a compilation of 1564 damaging floods in Europe between 1870 and 2016 (Paprotny et al., 2018a; see also Paprotny et al., 2018b). It also provides information on exposure to climate hazards for 37 European countries covering around 70% of Europe’s population at 100m resolution. It is made up of two components. First, HANZE-Exposure is a database of gridded data on metrics such as land use, population and wealth indices between 1870-2020. This allows damage from any specific event to be derived with a defined spatial extent. Second, HANZE-Events contains quantitative data on the timing, location and consequences of natural disasters, and these data are supplemented by economic data to assess monetary losses. At present the natural hazard data only record floods between 1870 and 2016.

The floods included in the database required data to be available for the event, and to include at least one of four statistics: area flooded, fatalities, people affected and losses. If no fatalities occurred or people were missing, then at least one of the other statistics were required to ensure inclusion. Not included were floods that only affected a small part of a region, with no fatalities and fewer than 200 people affected. Also not included were floods associated with inadequate urban drainage, those caused by dam failure and not triggered by meteorological events, and those associated with geological events such as tsunami and glacier-related floods. A list from the HANZE database of damaging floods that have impacted the UK is available at https://doi.org/10.4121/collection:HANZE.

The HANZE database has been used in a number of ways. For instance, Paprotny et al. (2018b) showed that there has been an increase in the numbers of people affected by flooding since 1870 (corrected for changes in flood exposure) and in annually inundated area. They also showed that under-reporting of small floods has a large impact on the observed trends (and this is a clear bias in such data sets especially as data before around 1970 are regarded as likely to be incomplete). This under-reporting means that the yearly number of flood events has shown a much smaller increase compared with uncorrected data series, and that it might have declined since the mid-twentieth century (see Figure 5).

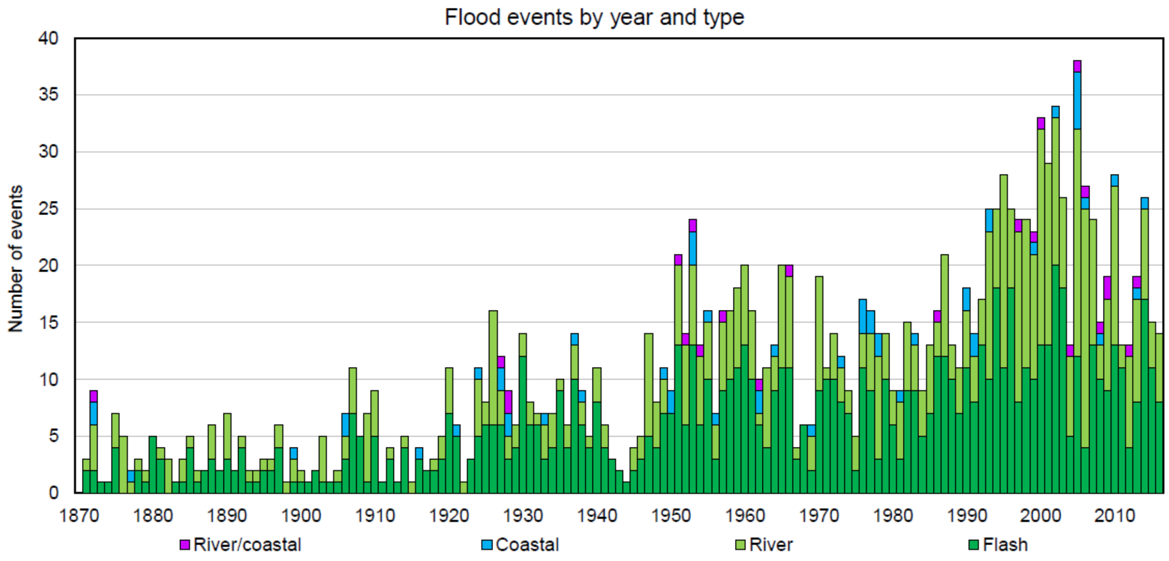

Figure 5. European flood events by year and type (HANZE database).

Extreme High Temperatures

It is shown (e.g. Rahmstorf and Coumou, 2011) that the observed global number of heat records of mean monthly temperatures is significantly higher than that expected in a stationary climate (see also Benestad, 2003). Daily record highs in Australia and the US are at least twice as large as would be expected in a stationary climate (Meehl et al., 2009; Trewin and Vermont, 2010). In addition, Wergen and Krug (2010) show that an increase in the number of daily temperature records is consistent with a systematic increase in the mean temperature (i.e. consistent with AGW). Coumou et al. (2013) showed that the number of record-breaking heat extremes has increased by around 5 times that expected in a stationary climate, with the increase in record events, particularly since the 1980s, and concentrated in continental interiors.

Long-duration heat records are those that last for several weeks or months and are most destructive for human health and ecosystems. In Europe, they include the heatwaves of 2003 and 2019, which also affected the UK. The August 2003 heatwave caused around 15,000 extra deaths in France (mainly of elderly people and those with pre-existing medical conditions) and about 70,000 deaths across Europe (Mitchell et al., 2019). About 70% of the heatwave-related deaths in Paris have been attributed to AGW (Mitchell et al., 2016).

In summer 2019 western Europe experienced another record-breaking heatwave. Towards the end of July temperatures of more than 40°C were recorded for the first time in several countries and over 4 days. The heatwave over 3 days had a return period assessed as 50-150 years, and in France and the Netherlands this was about 100 times higher than expected in a stationary climate (World Weather Attribution, 2020). Comparing the 2003 and 2019 heatwaves is difficult, as the relationships between mortality and temperature may not have been the same in the two events, given advances in medical science and heat mitigation schemes (Mitchell et al., 2019).

However, the 2019 heatwave was more extreme than climate model projections under current forcings (Seneviratne et al., 2006; Figure 6). This could be because the physical parameterisation of soil-moisture feedbacks is inadequate, especially in mid-latitude areas such as central Europe, or because the climate system is more sensitive to forcings than our estimates suggest.

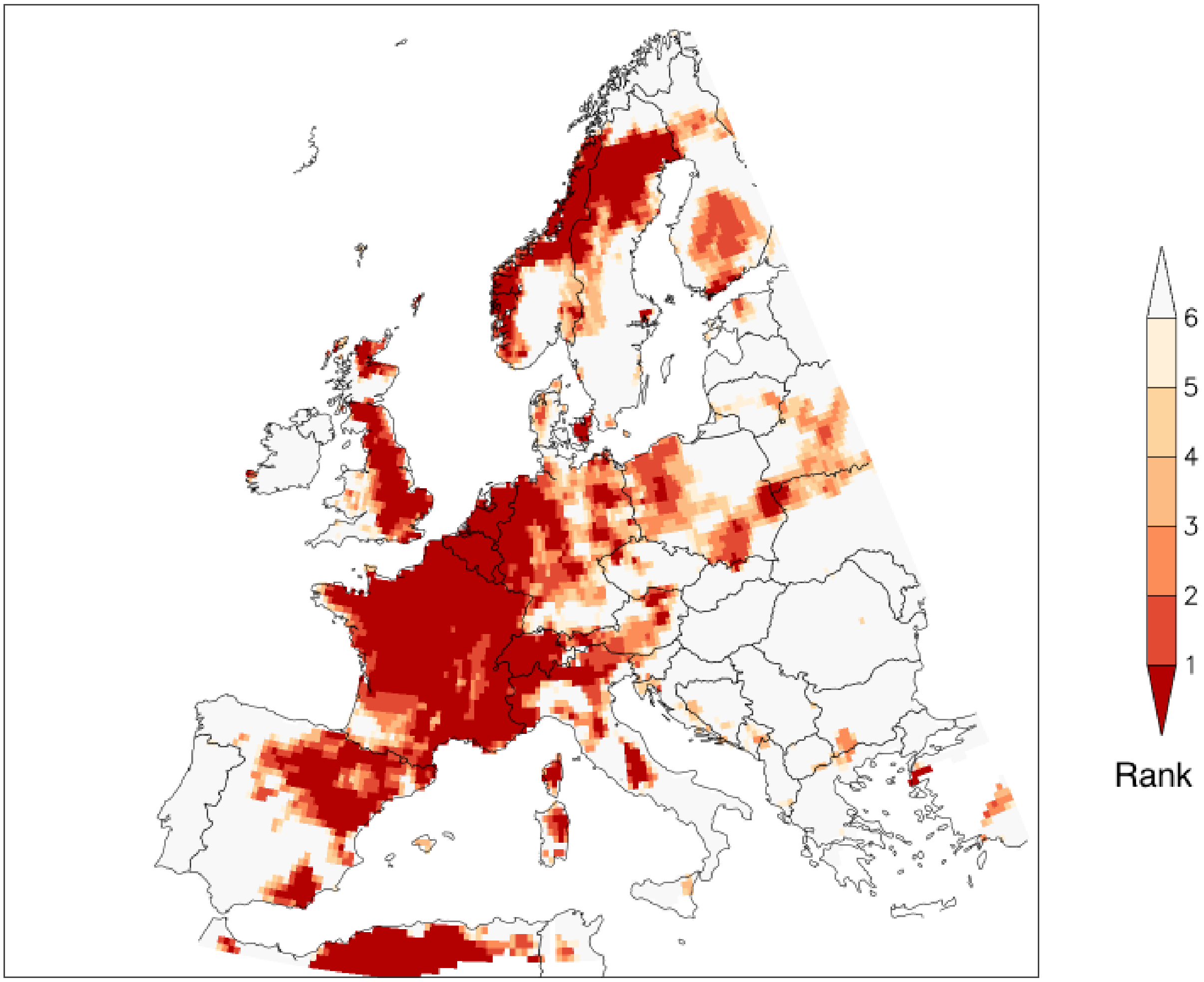

Figure 6. (from Mitchell et al., 2019). Rank of annual maximum temperatures observed in Europe in 2019 compared to 1950 –2018.

The heatwave in late July 2019 produced the warmest temperature recorded in the UK of 38.7 °C at Cambridge Botanic Garden, which exceeded the 38.5°C recorded at Faversham, Kent on 10 August 2003 (UKMO 2019). The heatwave was more intense and more widely felt than previous heatwaves and this is shown in Figure 7, which compares the 2019 event with similar extreme events in 2006, 2003 and 1990.

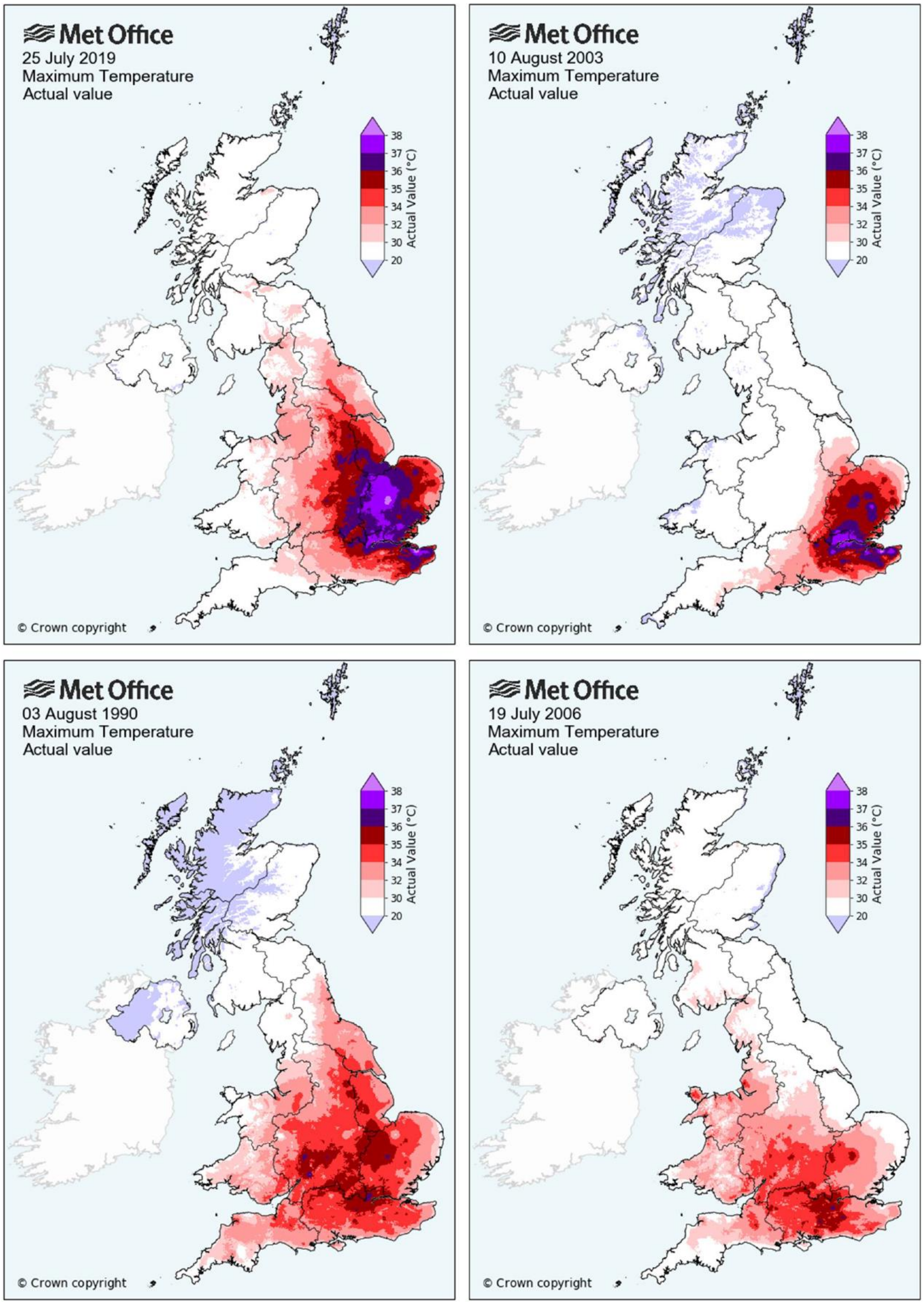

Figure 7. Daily maximum temperatures on 25th July 2019, 10th August , 3rd August 1990 and 19th July 2006 (UKMO, 2019).

Extreme low temperatures

These are considered unlikely in a warming world. However, since the Intergovernmental Panel on Climate Change 3rd Assessment in 2001 a cool spot in the North Atlantic south of Greenland has been observed, and this represents a long-term cooling trend in this region. 2015 was the coldest year in this region since 1880, even though this was globally one of the warmest years in the instrumental record. Caesar et al. (2018) argue that this reflects a weakening of the Atlantic Meridional Overturning Circulation (AMOC; which is a current-driven system that regulates heat transfer in the Atlantic by transporting heat northwards). This might presage cooler temperatures for parts of the North Atlantic if this slowdown continues.

Extreme precipitation

In the UK, most extreme climate or weather events of interest to the ONR and licensees are those producing damaging floods and/or storm surges.

For extreme rainfall (and therefore floods) there are clear physical reasons why rising Global Mean Surface Temperature (GMST) would produce a rising trend in the statistics (Trenberth et al., 2003). Changes in saturation water vapour pressure is described by the Clausius-Clapeyron relationship and is seen as a good predictor of extreme rainfall intensities. Water vapour increases by about 7% per °C of atmospheric warming. However, the relationship between rising temperature and precipitation is clearly non-linear. Convection precipitation increases with temperature exceed the rate given by Clausius-Clapeyron (e.g. Berg et al., 2013; Lehmann et al., 2015) compared with frontal precipitation, and this may have implications for predicting the effects of damaging high precipitation effects, especially if there is a trend to more convective storms.

Lehmann et al. (2015) used observational data sets between 1901-2010 to show that the global number of record-breaking rainfall events was 12% higher post-1981 than that expected in a stationary climate. This rainfall anomaly peaked in 2010 with 88% more events than expected. They conclude that this pattern is consistent with that expected in a warming world.

Previous work on precipitation change in response to warming temperatures have failed to assess the regional responses. A recent paper that does attempt this is by Blöschl et al. (2019). They used statistical modelling of river discharge observations from 3738 gauging stations over the period 1960-2010 to show that the spatial pattern of European floods has changed considerably over the past 50 years. They show that climate change has increased floods up to

+11.4% per decade in northwest Europe (including the UK) and led to a decrease of −23.1% per decade in southern and Eastern Europe. This suggests that understanding the regional responses to climate change might be extremely important for infrastructure developers; and further that sub-regional climates might be equally variable.

Given recent damaging floods, this simple reading of the relationship between the Clausius-Clapeyron relation and atmospheric water vapour has led to assumptions by some academics and many policymakers that recent large floods have been ‘caused’ by AGW. However, as the section on past flood events has discussed, this attribution narrative is not as robust as some researchers have argued. Partly this is caused by the relatively short nature of the observational record and partly by the misunderstanding of how floods develop.

The pattern of rainfall over the UK shows several characteristics. First, analysis of rainfall data between 1868 and 1968 in the British Isles (Rodda et al., 2009) shows that the maximum number of extreme events of 100mm and above in the record occurred in November. Second, rainfall totals above 150mm per event occurred mainly in the summer months (associated with convective storms) with a secondary peak in November and December, probably associated with extreme cyclonic conditions. For example, in summer 1989, the Halifax convective storm produced 193mm in less than two hours (Acreman, 1989). This was associated with a combination of strong urban heat island and sea-breeze convergence (Thielen and Gadian, 1997) and could be taken as an indication of possible precipitation events in a warming climate. However, the lack of long-term instrumental records makes it difficult to respond to such questions with confidence.

Flood records integrate rainfall totals and timing, and catchment characteristics. Because of this inter-dependence, some large rainfall events may not produce damaging floods, and conversely some floods may be produced by modest rainfall. In section 4 we have seen how the extensive record of flood events from fluvial systems in upland British Isles differs somewhat from the spatially more restricted record from lake sediments. The fluvial system in all upland regions of England and Wales discussed by Macklin and Rumsby (2007) showed a clear reduction in the frequency of extreme floods during the second half of the twentieth century, and especially since the 1970s. They argued that the occurrence of extreme flood events towards the end of the 20th century may have been at its lowest “since the end of the nineteenth century and possibly since the first half of the eighteenth century” (Macklin and Rumsby, 2007). However, recent years in the UK have seen a number of extremely large flood events, and this might herald a new upturn in flood risk.

It should also be added that recent parts of the flood record from Central European Rivers suggests that land-use changes have played an important role in affecting river flooding and have contributed to the non-stationarity observed in such data sets (e.g. Toonen, 2015). In contrast to recent assessments using climate models, it appears that recent changes in flood frequency variability is not exceptional when compared with the flood behaviour of the past 500 years in Europe. If this view is taken, the conclusion is that recent UK floods have not been caused by anthropogenic climate forcings. In that case there is the potential for extremely large floods in future as the climate system continues to warm.

21st century extreme rainfall and floods

There has been a cluster of extreme floods since the turn of the Millennium (e.g. Golding et al., 2005; Jones et al., 2013). Chiverrell et al. (2019) suggested that this cluster was unusual in their 558 year record of flood events from Cumbria. However, the absence of other high-resolution long-term records means that we cannot yet test this assertion. Chiverrell et al. (2019) argued that these floods are associated with warmer Northern Hemisphere temperatures and a positive AMO, although others have suggested links with the north and west Pacific ocean temperatures (e.g. Huntingford et al., 2014; Kendon and McCarthy, 2015).

2000

The 2000 ‘Millennium’ floods in England and Wales damaged 10,000 properties and caused insured losses of around £1.3bn. The floods occurred during probably the wettest autumn experienced in England and Wales up to that date since records began in 1766 (Pall et al., 2011). The authors used an ensemble of climate models to develop a probabilistic attribution framework to demonstrate that anthropogenic greenhouse gas emissions substantially increased the risk of flood occurrence by between 20-90%. Similar work using climate model ensembles to analyse the 2013/14 England floods showed that anthropogenic warming increased the number of January days with westerly flow, with the amount of water vapour in the atmosphere increasing the likelihood of extreme precipitation (Huntingford et al., 2014; Schaller et al., 2016). A clear caveat to such work using model assessments of precipitation and flooding, is that the palaeoflood records from the UK and more widely shows that extreme large floods have occurred in the past when anthropogenic forcing was much lower than present. As a result, developing flood risk strategies based on approaches from climate modelling should be approached with caution.

2005

The January 2005 flood affecting northwest England was associated with a cyclonic south-westerly airstream. This generated a near stationary weather front across northern England and southern Scotland that contributed heavy rainfall (<180.4 mm) across Cumbria with an estimated return frequency of <200 years (Stewart et al., 2012), resulting in an estimated peak flow of 219 m3 s-1 on the Derwent (Portinscale) (Miller et al., 2013).

2009

In November 2009 a similar near-stationary weather front over Cumbria produced heavy rainfall for 36 hours in the region (Miller et al., 2013). A UK 24 hour rainfall record was set at Bassenthwaite catchment in the Lake District (316 mm, Recurrence Interval ~1,862 years) (Stewart et al., 2012), with other upland regions receiving more than 400mm of rainfall in 72-hours. The peak flow into Bassenthwaite was estimated as 402 m3 s-1 for the River Derwent, with a single-site return period of 228 years (95% confidence limit of >40 and <50,000) (Miller et al., 2013; Wong et al., 2015). Chiverrell et al. (2019) estimated that the resulting 2009 flood was the largest in the >558 year Bassenthwaite flood record.

2013/14

During the UK winter of 2013/14 an exceptional clustering of vigorous storms was driven by the North Atlantic jet stream, which was about 30% stronger than in recent decades (Slingo et al., 2014; Christidis and Stott (2015). This may have been the stormiest season over the UK since 1871, with the highest value of cyclone counts (Wild et al., 2015). This produced the highest total rainfall averaged across the UK since 1931 (estimated from the HadUKP observational dataset). Other data sets (e.g. National Center for Environmental Prediction and National Center for Atmospheric Research (NCEP–NCAR) reanalysis4) suggest that this was the wettest season since the beginning of the record in 1948.

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[4] *https://psl.noaa.gov/data/gridded/data.ncep.reanalysis.html*

2015

During winter 2015 a succession of severe storms brought extreme rainfall and flooding to a number of regions in western and northern parts of the UK. This period has been called “one of the most extraordinary hydrological episodes witnessed in the UK in recent decades” (Barker et al., 2016). December 2015 was the wettest month in the instrumental record and the winter (December-February) was the second wettest in the series since 1910. The winter was exceptional because of the spatial scale of the flooding and its duration, and also because it followed closely on from the severe 2013/14 winter.

The largest event in 2015 was Storm Desmond, from 4-6 December, when northwest England was affected by exceptionally heavy rainfall. Honister Pass experienced record 24 hour rainfall (341.4mm), as did other regions in the northwest, and a 48 hour rainfall record of 405 mm was achieved at Thirlmere. It is assessed that these had a return period of around 1,300 years and a 0.08% probability (Barker et al., 2016; Burt, 2016; Parry et al., 2013; Chiverrell et al., 2019).

Chiverrell et al. (2019) summarise the damages caused by the floods. In 2009 economic damages reached £276 million and rose to £1.6 billion in 2015.

Causes of extreme rainfall

The likely cause of extreme rainfall in winter months is Atmospheric Rivers (ARs); over summer these are less important and extreme precipitation is generally caused by convection cells. While ARs have been studied for some time (e.g. Namias, 1939) and originally called Tropospheric Rivers (Newell et al., 1992) there is little recent work on ARs as they apply to the UK, so the text from the ONR Expert Panel on Natural Hazards (2018b) is adapted:

> *Precipitation types in the British Isles are strongly seasonally dependent. In winter, about 70% of the precipitation in the British Isles is associated with the development of extra-tropical cyclones. Important contributors to extreme winter precipitation are ARs. These are narrow lower troposphere atmospheric structures, usually 10^2 km wide and 10^3 km in length (Dacre et al., 2015). They form a component of the warm conveyor belt found in mid-latitude storms and are characterised by a strong low level jet and produce filamentary bands of air transporting large amounts of water vapour (typically with vertically integrated water vapour of more than 2.5cm liquid equivalent) and with maximum wind speeds higher than 10 m/s. They have been shown to be responsible for*

> *extreme winter flooding in the UK (Lavers et al., 2011; 2012) and associated with the 10 most extreme UK storms since the 1970s. All these floods developed from an AR plume oriented SW-NE.*

Enhanced moisture transport occurs in a narrow band ahead of the cold front of an extratropical cyclone within the cyclone's warm sector. Heavy precipitation occurs when this system encounters significant orography (e.g. along the western coast of the British Isles) and produces 'seeder-feeder' precipitation where high-level precipitation falls through low-level, mesoscale orographic stratus clouds (Browning, 1990), thereby enhancing precipitation intensity. Such prolonged winter precipitation is associated with lengthy, vigorous, quasi-stationary cold fronts (some 103 km in length), and commonly lasts several days.

In contrast, there is little evidence to show that summer precipitation is dominated by Ars, with fewer than 20% of summer extremes having been associated ARs. Most summer rainfall is short-term in nature, with extreme flood events produced by strong convection, often in combination with thunderstorms and, more rarely, supercell thunderstorms.

A better understanding of the future evolution of ARs would help in managing flood and snowfall risk to nuclear facilities. The success of future long-term projections of trends in ARs will depend on better modelling of the behaviour of baroclinic-wave activity in the Atlantic (Ulbrich et al., 2009), and better parameterisation of cloud properties. However, increased future flooding is very likely as continued atmospheric warming will lead to increased atmospheric water vapour content, which is governed by the Clausius-Clapeyron moisture-temperature relationship (Held and Soden, 2006).

Lavers et al. (2013) used Coupled Model Intercomparison Project (CMIP) Phase 5 models to project an increase in the frequency and magnitude of ARs in the North Atlantic, with a doubling of AR frequency by 2074-2099 under the Representative Concentration Pathway (RCP) emissions scenario RCP8.5. Modelling at shorter timescales is undertaken using numerical weather prediction (NWP) models. Currently, these are not able to model the position and timing of the landfall of ARs well, although they show better skill at modelling the presence of ARs (Wick et al., 2013). Modelling using higher resolution climate models (e.g. Coordinated Regional Climate Downscaling Experiment (CORDEX)) does not appear to have been done.

Some very significant rainfall totals associated with ARs may not have been captured by past meteorological records because they were not dense enough spatially. As a result, historical data have the potential to mislead analysts concerning the frequency of these events. Accordingly, large departures from mean conditions should be assumed to be likely to occur occasionally during the lifecycle of major infrastructure projects, such as nuclear sites.

Extreme winds

These are associated with extreme storms, localised tornadoes and also ‘meteo-tsunamis’, which are anomalous high-magnitude events.

Allan et al. (2009) looked at the record of autumn and winter extreme storms over the 20th century. The storms in the autumn season, October-November-December (OND) (see Figure 8) during the 1920s was the most active decade in the record, followed by the 1990s. Severe winter storms (January-February-March) are clustered in the 1920s, 1980s and 1990s (see Figure 9). They also looked at the relationship between the NAO and autumn and winter storms in the region and showed that the strongest NAO relationships occurred during 1970–1990 and 1940–1960, with a weaker correlation in the 1920s–1940s, and effectively no correlation in 1950–1970. This should be borne in mind when assessing the likely relationship between NAO and flood events in the British palaeorecord. They suggest a possible link between El Nino Southern Oscillation (ENSO) in the Pacific Ocean and OND storms over the British Isles.

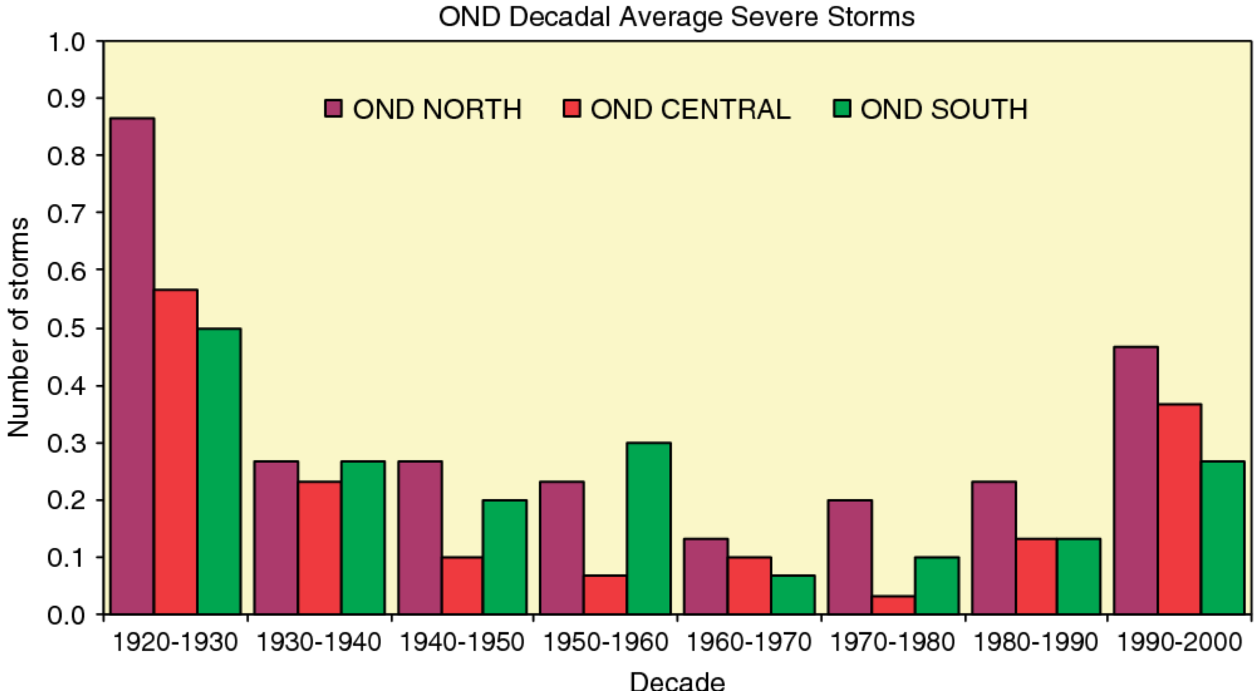

Figure 8. Decadal average autumn storm frequency over different regions of the British Isles for October-November-December (OND).

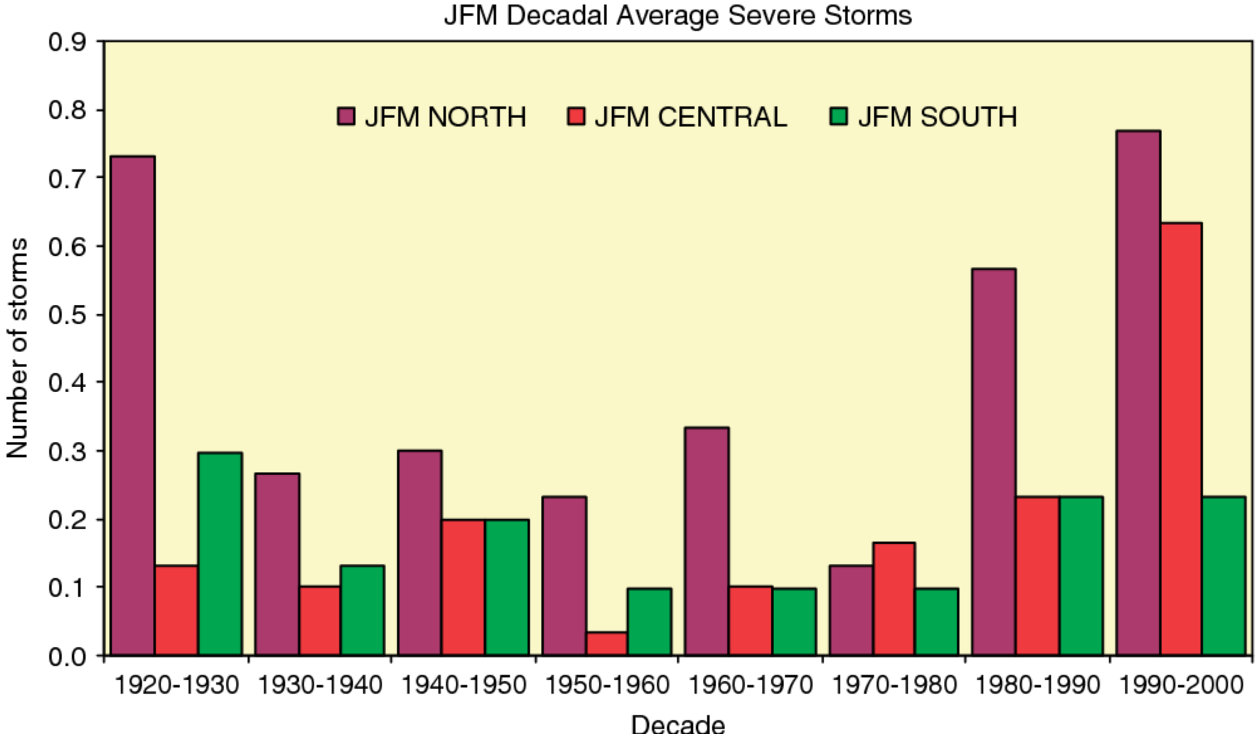

Figure 9. Decadal average winter storm frequency over different regions of the British Isles for January-February-March.

Extreme storm surges

The coastline of the UK has been affected by severe storms. The Great Storm of 1703 (Wheeler, 2003) caused widespread flooding in the Somerset Levels, with the loss of hundreds of lives and caused one ship to be washed 15 miles inland. Lamb (1991) estimated the wind speeds were 150 Knots (~165mph). A paper by Bryant and Haslett (2007) suggested a tsunami affected the Bristol Channel in 1607, but this has been identified as a storm-surge event in the British Geological Survey (BGS) catalogue. Haslett and Bryant (2009) discuss the issue of meteorological tsunamis. These are waves that possess the characteristics of tsunami (long wavelength and long periods), but which have a likely meteorological origin, probably developed by convective cells or squall lines associated with resonance with ocean waves. These waves grow in height as they shoal in shallow water and therefore may impact inland. They are known from various studies globally, including in Japan, the Mediterranean and the Baltic. The authors argue that "…*these large waves are not presently accounted for in the coastal defence strategies of the region. Sea walls are typically constructed up to the height of known historical storm surges, but allowance is not made for large, super-posed waves. As a result, such waves present a potential hazard, one that was associated with considerable damage and loss of life in the past*" (Haslett and Bryant, 2009). They conclude that such waves are poorly modelled compared with storm surges.

Compound events

While weather events individually may cause impacts, spatial and/or temporal combinations of weather events may magnify these impacts. Clearly extremes of weather combinations can produce extreme impacts, and these are often ignored by risk assessments analysing weather events as individual components. As a result, there are relatively few studies that assess the risk and consequences of compound climate or weather events, even though there are clear physical reasons why such events might be combined (although see Granger, 1959; Mantz and Wakeling,1979; Thompson and Law, 1983). For instance, low pressure cyclonic atmospheric systems are likely to produce high rainfall and consequently high-river discharge, at the same time as producing storm surges that can slow or block river discharge into the sea and cause inland flooding.

However, the pattern and timing of combination events is highly variable. For instance, it might be assumed that there is a clear relationship between timings and locations of sea surges, river discharge and precipitation over the UK as similar physical processes drive these metrics. However, the strongest correlation between these variables occurs between river flow and sea surges on the east coast of Scotland, north of the Firth of Forth (Svensson and Jones, 2004). As discussed, high winter precipitation in the UK is associated with cyclones passing to the north of Britain, producing high-precipitation totals along the westerly and south-westerly airstreams. Any orographic enhancement is therefore likely on the northern coast of Scotland, with the east coast of England being in a rain-shadow and with low levels of river flow. In addition, high-river flows along western coasts (associated with rain-bearing westerly winds) would not occur with extreme storm surges, as these are particularly generated in the North Sea. Using climate and weather data, they estimate that a weather variable exceeding a certain return period is associated with a c.20% chance of the other variable exceeding the same return period.

A recent analysis of Compound Events (in this case called Compound Flooding (CF)) used the HANZE database discussed earlier to identify 24 CFs around European coasts (Bevacqua et al., 2019; Figure 10). In the UK these included the 2014 Avon flood in Bristol (Bevacqua et al., 2017). They used daily maximum values of the superposition of storm surges (including waves) and astronomical tides, and storm and wave projections using hydrodynamic models forced with ERA-Interim reanalysis data for present climate (1979-2014). Climate projections were based on data from six CMIP5 global climate models (GCMs) run for present (1970–2004) and future climate (2070–2099).

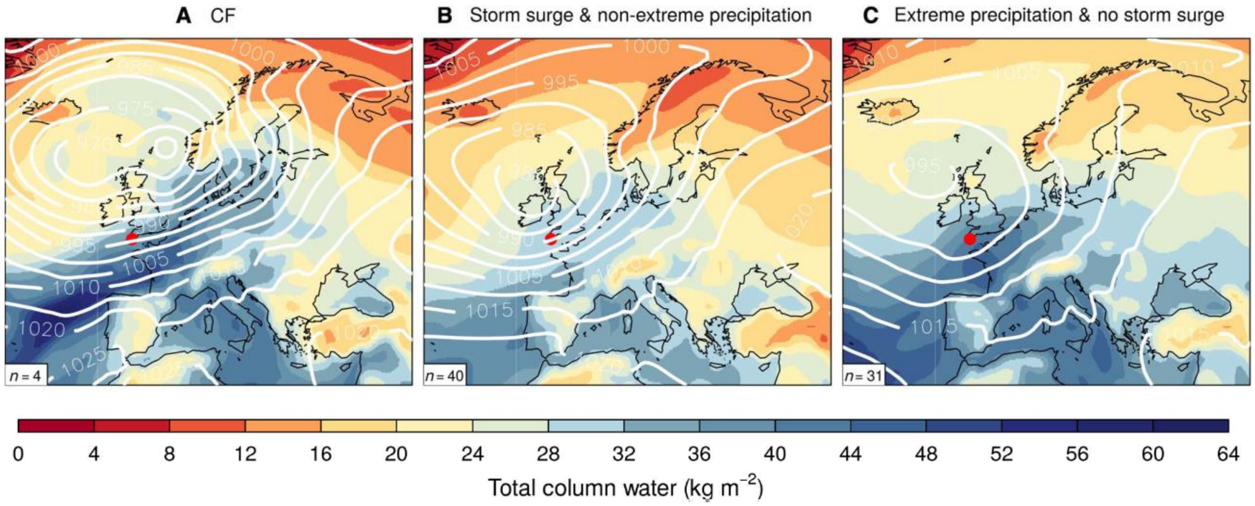

Figure 10. Synoptic weather conditions driving extreme events. Composite maps of sea level pressure (hPa, in white) and total column water fields computed over days where extreme events (>99.5th percentile) occurred in Plymouth indicated by the red dot (based on ERA-Interim data, 1980–2014) (from Bevacqua et al., 2019).

These projections show that CF will increase, particularly along western British coasts, northern France and the east and south coasts of the North Sea (see Figure 11). The proportion of coasts with return periods below 6 years will increase by 3% now to 11% by the end of the century. Places where return periods will be below this value include the Bristol Channel and the Devon and Cornwall coasts.

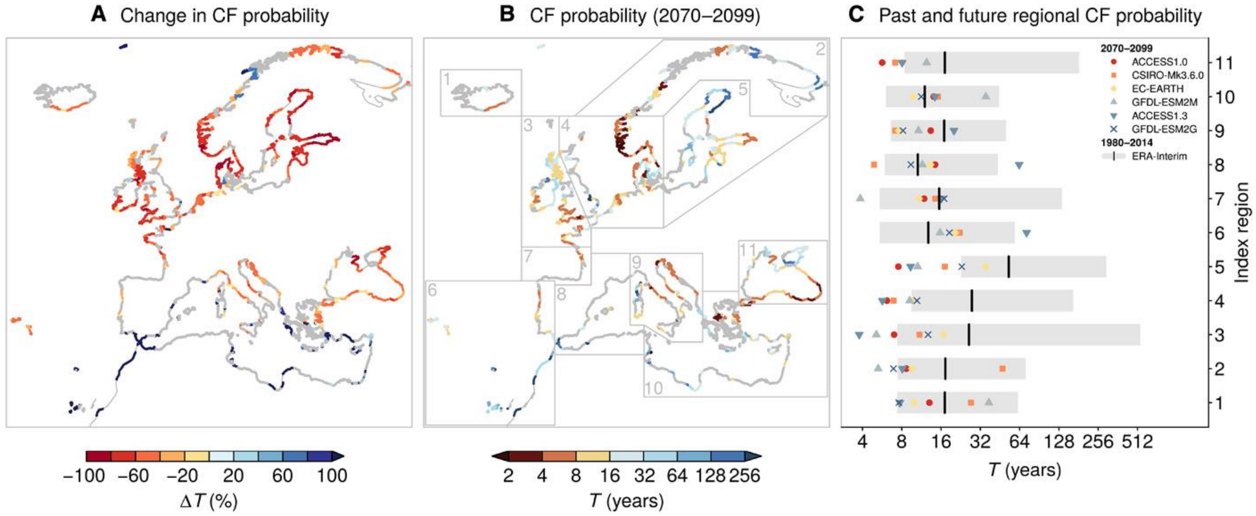

Figure 11. (from Bevacqua et al., 2019). Future probability of potential compound flooding (CF).(A) Multimodel mean of projected change (%) of CF return periods, between future (2070–2099)and present (1970–2004) climate. (B) Return periods for the future (2070–2099). Grey points indicate locations where only four or fewer of six models agree on the sign of the return period change (three or less of five models in the Black Sea). Areas of grey points in (A) and (B) are slightly different, as the former are computed taking into account the past period (1970–2004) and the latter the period (1980–2004. (C) Median value of CF return periods over regions defined in (B) for past [1980–2014, based on ERA-Interim] and future (2070–2099) climate, separately for individual models. For ERA-Interim, grey shading illustrates the sampling uncertainty 95% range

Bevacqua et al. (2019) conclude: “*Estimating the coastal flooding risk is essential for policy-making, disaster risk reduction, and engineering practices. At the moment, the CF hazard is usually omitted in coastal flooding risk analyses, implying that sea and river flooding are considered as independent phenomena*”.

Interpretation

How we interpret 21st century trends in climate, weather and some extreme events such as floods depends critically upon the methodology and approach employed. From one perspective an anthropogenic fingerprint on the climate and weather is clear and detection and attribution studies show that climate variability has emerged from the natural noisiness of climate data (i.e. there is a clear difference seen between forced versus unforced variation). This is the perspective taken by most researchers in the case of extreme high temperatures and droughts; and by many researchers on extreme flooding.

From another perspective, current observed climate and future projections do not capture the variability that the palaeoclimate record reveals, and therefore in some instances the anthropogenic fingerprint cannot be identified in the recent observed record. This latter point is made most forcefully in the case of extreme floods.

Clarifying these points is crucial if we are to produce clear guidance for climate risk assessments for infrastructure development.

Section 5: Discussion of the methodological and technical issues for understanding extreme weather events.

This review has outlined some of the methodological and technical issues surrounding the understanding of extreme weather events in the British Isles. This section discusses the use of climate models and climate projections of extreme events, and ends by highlighting the challenges that remain.

Climate modelling is the only way to obtain predictions of future extremes and to develop projections. As part of the move towards the new CMIP6 climate projections, the World Climate Research Programme (WCRP) Grand Challenges programme has identified weather and climate extremes as being a key area to focus research (e.g. .Sillmann et al., 2017). An improved prediction of extremes, especially those of short duration, can be made if the processes and climate drivers behind them are understood in more detail (e.g. Chan et al., 2016). WCRP argue that both large-scale circulation and small-scale feedback processes are drivers of extremes, and should be the focus of future research. They also argue that there is a discussion between researchers about how to better understand extreme climate and weather events; do you put resources into increasing the resolution of climate models to better understand important small, scale processes such as convection, or is it more useful to run multiple ensembles of models that already exist?

Schaller et al. (2016) provide an example of the latter approach. They used distributed computing methods to produce an ensemble of over 134,000 simulations of weather under forced and unforced conditions. They ran a Regional Climate Model (RCM; HadRM3P) within HadAM3P forced with prescribed sea-surface temperatures (SSTs) and sea-ice concentration. The RCM covers Europe and the Eastern North Atlantic Ocean, at a spatial resolution of about 50 km.

Schaller et al. (2016) modelled the Southern England storms of 2013/14, which had caused around £450 million insured losses. The exercise showed that warmer atmospheric temperatures increased the amount of water vapour the atmosphere could hold (in agreement with theory and observations), but also produced a small yet significant increase in the number of January days with westerly flow. Both of these changes in the atmospheric state increased extreme precipitation. They used hydrological modelling to assess flow of the River Thames under these conditions and this demonstrated that extreme 30 day average river flows and daily peak flow would increase as precipitation events moved to longer duration (greater than 10 days).

Similar attribution arguments about the 2013/14 winter over the whole of the UK were reported by Kay et al. (2018).

The focus on attribution is a major area of current research and is an area where there is clear disagreement between climate modellers assessing flooding extremes and palaeoflood specialists who use geomorphological, sedimentological and historical proxy data to extend the flood series. While we can detect a climate event (or set of events), detection of a climate signal does not necessarily give us insight concerning its causes. For this, we need to undertake attribution studies where we assess the existence and significance of individual drivers of climate change. “Attribution is the process of establishing the most likely causes for a detected change with some level of confidence. We seek to determine which external forcing factors have significantly affected the climate, where external forcing factors are agents outside the climate system that cause it to change by altering the radiative balance or other properties of the climate” (Stott et al., 2010).

Detection and attribution are used to distinguish between forced variability and unforced variability in a system; in other words differentiating between systems whose behaviour is being driven by external changes in the climate compared with behaviour of that system when driven only by variability exhibited within the climate (Stott et al., 2004). Detection and attribution studies can be focused on trends in weather or climate, or on individual events. To develop detection and attribution for extreme weather events, we need to have at least the data showing a clear and substantial record of extreme events before the time that greenhouse gas (GHG) forcing drove the climate outside of natural variability, compared with a record of extreme events under a GHG-driven climate.

To attribute contemporary climate change to human emissions of GHG, we need to show that the observed warming is consistent with such forcings in rate and pattern, and inconsistent with other drivers (e.g. Hegerl et al., 2006). There is now evidence that anthropogenically-forced climate change can be detected at very small temporal scales (annual to daily; Sippel et al., 2020). Formal detection and attribution of the forced signal on climate relies on the presence of spatial patterns (called fingerprints) that reflect the expected physical climate response to an external forcing (such as GHG emissions). They used a regression method to distinguish between climate noise and signal at daily levels, reanalysis and model data to argue that the climate change signal can now be identified at daily levels.

There are two general ways in which detection and attribution studies have proceeded: those using observations of data sets, and those using climate models. Observation-based approaches attempt to identify trends in data that exceed some metric associated with natural variability and are especially useful in assessing changes in systems that are poorly modelled. The presence of ‘hockey-stick’ patterns in climate data or impacts are used to assess the unusual changes in earth systems in recent decades compared with changes in the past. Such approaches use some aspect of GHG-forcing history as a ‘baseline’ with which to compare the event or system change of interest. IPCC Assessment Report 5 (AR5) Working Group 1 (WG1) (2013) show that the rate of increase in radiative forcing from GHG is very likely at levels not seen for 10,000 years, and studies detailing the climate responses to this includes multiproxy analyses of late Holocene climate (e.g. Mann et al., 1999; Mann and Jones, 2003).

Model-based attribution contrasts observed changes in the metric of interest (e.g. surface-air temperature) with modelled expectation of the metric under conditions of forced and unforced variability. However, there are several issues that complicate attribution studies. The most important is detection uncertainty. We know, for instance, that the observational record of extreme weather is uncertain with uneven spatial and temporal records. These uncertainties can be reduced by employing different but complementary records of weather behaviour (e.g. observational records with sedimentological data) or by attempting to estimate the magnitude of observational uncertainties.

Hegerl and Zwiers, (2011) develop this point by suggesting that favouring observational data over model outputs is able to directly avoid explicit assumptions about the shape and timing of the expected response but does require other assumptions to be adopted. These include the assumption that the response to forcing is instantaneous. In Section 1 we have discussed the issue of model uncertainties that complicate model assessments of climate variability.

Recently, UK Climate Projections 2018 (UKCP18) have developed several approaches to better understand extreme rainfall over the UK. These include high resolution model projections at 12 km model, which can be compared directly with projections from EURO-CORDEX, and Ultra High Resolution Projections at 2.2 km creating sub-daily projections. The latter projections will be used to explore quantitatively the climatology of localised heavy rainfall in summer and potential improvements in modelling the diurnal cycle. At 2.2 km the climate model is able to represent convection without the need for parameterisation, thus undoing a key, long-standing uncertainty. The 2.2km resolution in UKCP18 will provide sub-daily data and these can be used to generate time-series analyses.

In UKCP18 the H++ scenarios have been maintained for both time-mean sea level and storm surge changes. These are portrayed as plausible, high-end scenarios and, whilst seen as highly unlikely, cannot be ruled out.

While numerical climate simulations are the only method for developing projections of future climate, this report has argued that these projections may not capture the weather and climate variability that has occurred in the past, and therefore they are unlikely to prepare us for highly variable future weather and climates. Future climate and changes may lie outside of the model projections and this will have important policy implications. The research on ‘tipping points’ in the climate serves to underline this point.

Challenges that exist in better understanding extreme weather and climate include:

- A better recognition that the recent past during which instrumental data have been collected can be seen as a relatively benign period of UK climate, which is likely to be unrepresentative of parts of the Holocene. This means that extrapolation from such data sets may not capture the increased risk of future extreme events. This also calls into question whether attribution arguments are robust; can we really say that the 2000 ‘Millennium’ floods would have been very unlikely to have occurred in an unforced climate (Pall et al., 2011) when the palaeoflood record suggests that such floods are not that unusual over the longer term?
- EVA based on short data sets (see Brown et al., 2014), which may have been collected in a ‘benign’ climate, may bias the assessments of future weather and climate risk. Such data sets have only been collected from a short period of the Holocene, and from a small region of the Northern Hemisphere. A wider spatial and longer temporal view might strengthen our view of climate and weather extremes. This report has investigated the use of geomorphological, sedimentological and other proxy data of extreme events (mainly flooding) and argues that developing these would extend the temporal range of flood magnitude and frequency analyses might help enormously if information on both event timing and magnitude can be secured.
- Extending the palaeoflood record could provide reliable estimates of rare floods (potentially with annual exceedance probabilities of 10^{-6}) for infrastructure such as

nuclear power-plants (O’Connor et al., 2014). In certain environments the geological record of large floods is preserved for thousands of years and could be used to explore the context of recent floods and future flood projections (Benito and O’Connor, 2013; Benito et al., 2015).

- More research on atmospheric variability (including atmospheric rivers) is required. While this will be hampered by the absence of proxy records with high temporal and spatial resolution, understanding this will support current detection and attribution studies.
- Better understanding the limits of our statistics, especially where data sets are short and synthetic data may not reflect climate and weather variability.

Section 6: Conclusions

The location of the British Isles in the North Atlantic and at the junction of important centres of air masses has made it especially sensitive to extremes in weather and climate. Understanding these and their variability is the focus of much research and is of interest to policymakers and planners involved in developing climate-resilient infrastructure and policies. We make three conclusions:

- First, this paper has shown that unforced climate variability over the British Isles region has been high in the past (and this might also be the case in many other regions of the world) and probably higher than much previous research has suggested. This is most likely the case for flooding, where the palaeoclimate and palaeoflood record shows that recent floods are probably not extremely large when considered in their long-term context. This means that the views from some detection and attribution studies suggesting that recent UK floods would have been unlikely to have occurred in an unforced climate are probably erroneous. We argue that this means that long-term studies of extreme weather and climate events are important if we are to better understand the context within which recent extremes have occurred.
- Second, we show that uncertainties in climate modelling are large and this means that detailed resolution of the past and future behaviour of extreme weather and climate events is not achievable at the resolution required for infrastructure planning at the site scale. Despite this, progress can be made if we make use of a better understanding of past climate and weather extremes in combination with detailed assessments of the physical drivers of future climate impacts.
- Finally, great progress is being made in our understanding of the physical links between mid- and high-latitude climate change, the drivers of these and causal relationships between these and this has the potential to increase our forecasting ability of extreme events.

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