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Abstract

Research has found that both flood magnitude and frequency in the U.K. may have increased over the last five decades. However, evaluating whether or not this is a systematic trend is difficult because of the lack of longer records. Here we compile and consider an extreme flood record that extends back to 1770. Since 1770 there have been 137 recorded extreme floods. However, over this period, there is not a unidirectional trend of rising extreme flood risk over time. Instead, there are clear flood-rich and flood-poor periods. Three main flood rich periods were identified: 1873-1904; 1923-1933; and 1994-2007. To provide a first analysis of what is driving these periods, and given the paucity of more sophisticated datasets that extend back to the 18th Century, objective Lamb weather types were used. Of the 27 objective Lamb weather types, only 11 could be associated with the extreme floods during the gauged period, and only 5 of these accounted for >80% of recorded extreme floods The importance of these five weather types over a longer timescale for flood risk in Carlisle was assessed, through calculating the proportion of each hydrological year classified as being associated with these flood generating weather types. Two periods clearly had more than the average proportions of the year classified as one of the flood causing weather types; 1900-1940 and 1983-2007; and these two

periods both contained flood rich hydrological records. Thus, the analysis suggests that systematic organisation of the North Atlantic climate system may be manifest as periods of elevated and reduced flood risk, an observation that has major implications for analyses that assume that climatic drivers of flood risk can be either statistically stationary or are following a simple trend.

Keywords

historical floods, trends, weather types, flood frequency, flood magnitude,

Introduction

Flood risk is becoming an increasingly important issue in North-West Europe in general and in the U.K. in particular. The aim of this paper is to assess the extent to which this is a systematic trend for a large river basin in North-West England and then to assess the extent to which the results obtained can be linked back to large-scale atmospheric forcing.

Severe flood events have been reported for the U.K. in Spring 1998 (Central England) (Horner and Walsh, 2000), autumn 2000 (Sussex and Yorkshire; Marsh and Dale, 2002; Kelman, 2001), autumn 2004 (Boscastle; Golding *et al.,* 2005; Roseveare and Trapmore, 2008), winter 2005 (Carlisle; Environment Agency, 2006), summer 2007 (Central and Northern England; Marsh and Hannaford, 2007; Marsh, 2008), autumn 2008 (Northern England; Wilkinson et al., 2010) and autumn 2009 (North-West England; Eden and Burt., 2010). It has been suggested that recent decades have seen more frequent and higher magnitude river flow extremes (Wheater, 2006) and that we are now in a flood rich period (Macdonald, 2006, Lane 2008).

The apparent increase in flood events, however, needs to be evaluated to assess whether or not it represents a long-term trend or simply shorter-term variability. Robson (2002) analysed both local and UK river flood series and found that there was an increasing trend over the past 30-50 years, emphasising that assumptions of stationarity in flood frequency analyses need to be questioned (Milly *et al.,* 2008). Furthermore, there seems to be a pattern and clustering of the worst flood events rather than a random occurrence (Wheater, 2006), perhaps related to shorter term climatic variability. Others have reached the same conclusion with respect to smaller regional datasets. For example, Scotland has seen an increased river flood frequency since 1988, with new maximum discharges recorded for many rivers, especially in the west (Black, 1995; Black and Burns, 2002; Werritty, 2002).

In relation to Europe, Brazdil et al., (2006) notes the large number of flood events throughout Central Europe in the last two decades; Rhine/Meuse in December 1993 and January 1995; Biescas (Pyrenees) in August 1996; Morova/Oder in July 1997; and the Elbe in August 2002. However, although many studies have investigated flood frequency (Kundzewicz and Robson, 2004; Radziejewski and Kundzewicz, 2004; Lindstrom and Bergstrom, 2004; Kundzewicz et al., 2005; Svensson et al., 2005), finding statistically significant general trends has been more difficult. This is likely to be a consequence of the low frequency of extreme events, meaning that long records are needed to have the required number of events to identify statistically significant trends. There are examples of historical flood records that suggest periods of greater flood occurrence than others. Barriendos et al., (2003) investigated the stationarity assumption for flood records in France and Spain. Mudelsee et al., (2006) constructed a 500 year flood record for the River Werra in Germany. Mudelsee et al., (2004) found that Europe experienced increased flooding frequencies in the 18th Century, which has been hypothesised to have been caused by the Late Maunder Minimum period. Macdonald (2006) found that this observation was not present in the UK. A possible explanation for this is that this period was cold and dry and saw an increase in the number of snowmelt and ice dam break flood events, which are more common in Central Europe than the UK.

These studies aside, there have been relatively few assessments of both the extent and timescales of flood clustering, and even fewer assessments of what might drive them. This paper explores the extent and timescales of flood clustering for a 2400 km^2 river catchment in northwest England, the River Eden at Carlisle, combining the shorter term gauged record with longer term historical data to construct a flood record for the last 240 years. It then tests the first hypothesis that the flood record can be divided into relatively flood rich and relatively flood poor periods.

The link between weather systems and hydrological flows, particularly extremes (floods and droughts) has been investigated by a few studies. Higgs (1987) investigated the link between weather types and floods for the River Severn at Bewdley, using a 101 year record. Zonal (Westerly) weather systems were found to be associated with the highest magnitude floods. Rumsby and Macklin (1994) studied the flooding frequency and magnitude of the River Tyne, considering weather types as a controlling factor. Major floods were found to be linked to meridional circulation (easterly weather types), while more moderate floods occurred in periods when zonal weather systems dominated (westerlies). A possible explanation for this was through the high amplitude waves associated with meridional circulations, which are linked to situations when high pressure cause blocking of depressions, leading to long duration, high intensity precipitation. A further study by Rumsby and Macklin (1996) compared the western Severn catchment, with the eastern Tyne catchment. The west of England is more susceptible to zonal precipitation (westerlies), while the north-east of England is in the rain shadow of the Pennines, so receives more precipitation from meridional (easterly) weather systems which absorb moisture over the North Sea. Grew (1996) used daily weather system classifications, unlike the previous studies which used monthly or annual categories, for 130 peak over threshold (POT) series in Scotland. Cyclonic, Westerly and South-Westerly weather systems were found to trigger flood events in Scotland. A similar approach was taken by Longfield and Macklin (1999) for the River Ouse in Yorkshire. Westerly, Cyclonic, Cyclonic Westerly and South-Westerly weather systems were found to have caused 79.7% of the floods in the flood record since 1875.

Expanding the spatial scale to include the weather types that cause floods in Central Europe has found that similar weather types are also important regionally. However, a different weather type classification is used in Europe, the Grosswetterlagen (Baur 1944), which has 30 classes under three main headings of zonal (westerly), mixed and meridional (easterly). Kastner (1997) found that only 5 of the 30 circulation types caused floods in Bavaria, while Petrow et al., (2007) found that 19 of the 30 caused floods in the Mulde catchment, Germany, in the 92 year period (1911-2002). Both these studies highlighted the importance of Westerly weather types (25% of Mulde floods), and identified the Vb circulation pattern as the most susceptible to causing floods in Europe (Mudelsee et al., 2004; Brazdil et al., 2005; Petrow et al., 2007). The Vb (van Bebber) weather type is a slow moving low pressure system, which moves northwards from the Gulf of Genoa, and therefore is characterised by a warm and moist air mass, which leads to high precipitation in the Alps. A continental scale study of 488 catchments in Europe by Prudhomme and Genevier (2010) found that the cyclonic westerly weather type occurred more frequently before and during a flood event than the annual average.

At a larger scale, the link between weather types and atmospheric processes and circulations has been investigated. For the UK, one of the most significant large scale atmospheric circulation indices is thought to be the North Atlantic Oscillation Index (Kingston *et al.,* 2006). This is a measure of the pressure gradient between the Icelandic Low and the Azores High (Hurrell and van Loon, 1997). It is often used as a measure of westerly weather systems over the UK and it has been found that Lamb weather types correlate well with the NAO, especially Anti-Cyclonic and Westerly weather types (Jones *et al.,* 1997). Wilby *et al.* (1997) identified four main phases of the NAO from pre-20th century to the mid-1990s: (1) pre-20th century when the NAO was near zero; (2) 1900-1930 when the NAO had a strong positive phase; (3) 1930-1960s when the NAO had a low positive index; and (4) 1960s to the mid-1990s when the NAO had a strong positive index (Wilby *et al.,* 1997). Since the mid-1990s, the strength of the positive NAO has been decreasing and the winter of 2010/2011 had the most negative NAO index in the 190 year record (Osborn, 2011). Hurrell (1995) found links between shifts in the NAO and changes in UK temperatures and precipitation totals. Bendix (1997) highlighted the importance of Westerly weather types and an enhanced North Atlantic Oscillation in causing floods throughout Central Europe. Fowler and Kilsby (2002) found a positive correlation between the NAO and the precipitation quantities in the west of the UK and a negative correlation in the east. However, the relationship does not seem to be that simple, with Wedgbrow (2002) finding a lag between the changing NAO index and the change in UK weather. This was hypothesised to be caused by either climatological memory effects, such as seasonal patterns, or hydrological memory effects, for example groundwater levels or antecedent moisture levels. Along with the weather type classifications, this index also has limitations for its use, as it represents complex multivariate interrelationships very simply (Kingston *et al.,* 2006). Thus, in this paper we focus upon weather types, not least because of the historical duration for which they are available. We use these to test a second hypothesis that the flood rich and flood poor periods identified in the historical record can be linked back as a first approximation to atmospheric forcing.

Methodology

The Eden Catchment and Flooding in the city of Carlisle

The Eden catchment comprises 6 major sub-catchments (Figure 1). The spatial annual average precipitation of the Eden catchment is 1,183 mm (SAAR 1961-

1990) (Environment Agency, 2008). The Eamont sub-catchment receives the highest rainfall per year with a spatial annual average value of 1,768 mm and local annual averages in excess of 2,800 mm in areas of high topography. The Petteril experiences the lowest rainfall totals with 942 mm per year, while the Lower Eden in the city of Carlisle receives approximately 800 mm every year. The spatial differences in average annual rainfall can be explained by the significant topographical variations within the catchment, with a total relief of approximately 950m. Although urbanisation has occurred in the Eden over the last three centuries (for instance, the population of the largest City, Carlisle, rose from 4,000 in 1750 to 71,773 in 2001), urban areas still only account for less than 1% of the catchment, implying that urbanisation is unlikely to be a major contribution to changing flood frequency at the catchment-scale. The vast majority of the catchment is rural and it remains an unresolved issue as to whether or not rural land management, as well as river and floodplain management, have contributed to changing flood frequency. Recent work (Beven *et al.*, 2008) has shown that such effects are likely to be very difficult to detect in historical records, not least because of natural climatic variability. Thus, whilst it remains a possible hypothesis for changing flood frequency, and may have contributed to those changes, it is likely that the primary driver of changing flood frequency is a climatic one.

Short Term Gauged Record

It was possible to obtain a recent gauged record of river flows for the Sheepmount gauging station in Carlisle (Figure 1) which opened in January 1967. Digital records begin in 1976 and the station is still operating. Here, event frequency and magnitude trends are analysed using peak over threshold (POT) and annual maxima (Amax) series respectively for two scales of high flow event. The number of events per hydrological year that exceeded the Q1 value (347 m^3s^{-1}), which was calculated from the digitised record for 1976-2007 was determined. This threshold was chosen to represent the full range of high flow events in the Eden, rather than restricting the analysis to just the overbank flood events. Analysis of the full event record will be referred to as >Q1 events. Events were identified that were independent of each other by requiring the time interval between floods to be three times the duration of the typical rising limb (Bayliss and Jones, 1993), calculated from an average of five flood events. This required events to be separated by a minimum of 4 days.

To provide information on a second scale of event, the Q1 events were also separated into high flows ($347m^3s^{-1} < Q < 500m^3s^{-1}$) and extreme flood events ($Q > 500\ m^3s^{-1}$). The extreme flood threshold was determined using a previous study by Smith and Tobin (1979) of long term flooding in Carlisle. Smith and Tobin (1979) calculated the return period of floods in the 1800-1970 period. The return period of the 1968 flood was found to be 42.75 years using the historical record, which is comparable to the 38.5 years calculated by the North-West Water Authority (Smith and Tobin, 1979). The discharge of events recorded in the British Chronology of Hydrological Events database and Smith and Tobin were found at Warwick Bridge (since 1959) and Sheepmount (since 1975) gauging stations (Black and Law, 2004). This allowed the short term gauged record to be comparable with the longer term record which was reported by Smith and Tobin (1979) and which was used in compiling the long-term historical extreme flood record.

Annual maxima series record the largest instantaneous flood peak in each hydrological year (Svensson *et al*., 2005). The major advantage of this approach is that data are easy to extract, but insignificant flows can be included in the record, if a year was particularly flood poor. Thus, the peak discharge of each POT event was also considered. Records were extended back to 1967 using the POT Hiflows database (www.environment-agency.gov.uk/hiflows).

Creating a longer term extreme high flow record

Past research has shown the risks of concluding the presence or absence of trends in short term gauged records. There have been several recommendations (Table 1) as to the minimum required record length, ranging from 10 to 50 years reflecting the problem that what can appear to be a trend in a short duration record may actually be shown to be fluctuation in a longer data record (Robson, 2002; Kundzewicz and Robson, 2004; Dixon et al., 2006) and be associated with spurious trends (e.g. Konrad and Booth, 2002). For instance, Hisdal *et al*. (2001), for a single station, found significant positive and negative trends in annual flood maxima as a 30 year moving window was applied to the record. Robson (2002) shows that shorter record lengths are more susceptible to edge effects, when periods that have several floods or few floods at the beginning and/or end of the record influence the strength of the trend. Hannaford and Marsh's (2007) benchmark dataset for UK records had an average length of 33.7 years reflecting the fact that much of the UK gauging station network was commissioned in the 1960s and 1970s (Lees, 1987).

Given the possibility that the 40 year record (1967-2007) is too short to reliably detect trends in the dataset, a longer timescale extreme flood record was constructed for the River Eden at Carlisle, using multiple sources of information. First, the British Chronology of Hydrological Events (Black and Law, 2004) was used. As of October 7th 2010, it listed 126 (some repeated) extreme flood records for the River Eden. For copyright reasons, records generally cover the period before 1931, although for the Eden, a record exists for the 1968 flood.

Second, newspaper reports from the Carlisle Patriot, Carlisle Journal, Cumberland News, Evening News and Star, and the Carlisle Directory were used to identify extreme flood occurrence. Some of the records give specific details, such as a quotation, while others just list the event and source. Third, extreme flood levels recorded on Eden Bridge in Carlisle by indentations with associated years indicate the peak flood water stage. Markings are present for the 1822, 1856, 1868, 1925, 1952 and 1968 floods. The level of the January 2005 extreme flood event was one metre higher than the highest previous mark. Such marks need to be assessed for their originality, by checking the age of the structure on which they are preserved (Brazdil et al., 2006). Eden Bridge was built in 1815 and consists of five long arches. Therefore all the epigraphic markings are thought to be legitimate. However, a limitation of using the flood levels is that the bridge width was doubled in 1932. This will have changed the conveyance of water downstream. Water levels are controlled by both discharge and conveyance, meaning that epigraphic markings are generally good at indicating a flood, but are less good at indicating the magnitude of the event.

Finally, Smith and Tobin (1979) ranked 49 major known extreme floods at Carlisle between 1800 and 1968 according to the approximate extent of flooding. This was an important source of information as it allowed the threshold for extreme floods to be standardised between the different sources and timescales of the floods. The British Chronology of Hydrological Events only recorded floods up until 1931, while gauged data starts in 1959 at Warwick Bridge and 1967 at Sheepmount (Figure 1). Smith and Tobin (1979) was used to fill the gap between 1931 and 1959. The threshold of 500 m^3s^{-1} was used at Sheepmount to make the short term gauged record comparable with the historical extreme floods recorded by Smith and Tobin (1979). The gauged record from Warwick Bridge was used to determine extreme floods between 1959 and 1976. The comparable flow at Warwick Bridge was calculated to be 460 m^3s^{-1}. Using these multiple sources of information allowed a robust record to be compiled, whereby multiple sources recorded the same event, along with single records allowing time periods to be filled. The extreme flood record was developed extending back to 1770. See appendix for a complete record of the extreme floods in Carlisle showing the source of the information. The reliability of the flood record increases with time due to better gauging and recording of events. However, it is believed that the record post-1800 includes most of the actual events. This is because multiple sources of information have been used to derive the record.

Atmospheric drivers of flood events

The UK's weather is determined by the position, origin and storm tracks of air masses. Atmospheric circulation systems can be classified (El Kadi and Smithson, 1992) and these have been used (e.g. Hess and Brezowsky, 1977; Yarnal, 1993; and Petrow *et al.,* 2007) to investigate the links between large scale atmospheric processes and regional weather and hydrology. In the UK, Lamb (1950; 1972) developed a weather type classification for 1861 to 1971. This is a classification based upon both synoptic pressure and direction of flow and so Lamb weather types describe the prevailing atmospheric pressure characteristics and hence indicate the presence and tracks of storms over a catchment. Lamb's original analysis resulted in seven classes (Westerly, North-Westerly, North-Easterly, Easterly, Southerly and Anti-cyclonic and Cyclonic) which were representative of weather systems over the whole of the UK. This subjective classification which relied on an expert basing a decision on a synoptic chart was developed by Jenkinson and Collinson (1977) to make the classification more objective. It has now been applied from 1881 to the present day. It is based upon the daily mean sea level pressure, which is used to indicate wind flow direction, shear vorticity and flow strength (Jones *et al.,* 1993). The Objective Jenkinson classification has 27 classes, sub-divided by direction (N, NE, E. SE, S, SW, W, NW), non-direction (Cyclonic, Anticyclonic), combined complex hybrid types (CN, CNE, CE. CSE, CS, CSW, CW, CNW, AN, ANE, AE. ASE, AS, ASW, AW, ANW) and unclassifiable (U). Jones *et al.,* (1993) found a strong correlation between the Lamb classification and the Objective classification.

There are several advantages to using a weather type classification to investigate multivariate climatological factors: (1) the classes are simple and easy to use; (2) the length of the record allows for long term trends to be investigated; and (3) they are based on physical linkages between the climate (large scale processes) and weather patterns (local scale). However there are several limitations in the use of these classifications (O'Hare and Sweeney, 1993). First, there is an issue regarding the balance between number of classes and ease of use. The seven Lamb weather types were thought to be too simplistic, so Jenkinson and Collinson (1977) added another 20 classes. This allowed the UK weather to be better represented but made the system more complex and harder to use. Second, some days experience multiple weather types, making them difficult to classify. The Objective Jenkinson system has an unclassified category, but this provides no information on the specific weather types experienced. Third, the UK also experiences different weather types in different regions. Questions have been raised over how representative of UK weather types these classifications are of the UK as a whole. Fourth, the Lamb weather type classification is subjective, although the changes made by Jenkinson and Collinson (1977) have made it more objective. However, Yarnal and White (1987) suggest that there are still problems in the use of objective classifications. Fifth, there are problems associated with assigning a daily weather type when climatological variables do not operate on daily timescales. Sixth, the relationship between weather type and rainfall totals is not always reliable and it has changed over the timescale of the record. Seventh, the classifications indicate direction of origin but not the specific region, which may differ considerable in their characteristics, including tropical, maritime, continental air masses. Also air masses from the same origin have different characteristics at different times of the year. Eighth, weather type classifications indicate large scale synoptic atmospheric processes and lack detail on meso-scale frontal and orographic systems, which cause a lot of the UK precipitation. Finally, the weather system classification scheme is inherently autocorrelated, as when one weather type becomes more frequent, others have to decrease in their occurrence. Despite the inherent limitations of the objective lamb weather type classification, it still allows the link between local catchment scale flooding to be linked to large scale atmospheric forcings over the historical period. The benefits of this relatively simple classification scheme is that it provides a daily summary of weather characteristics over a long time period, while more detailed datasets are constrained in record length.

The methodology used aims to identify links between the objective Lamb weather types and events of different magnitude (>Q1 events (high flows) and extreme floods) for the gauged period and consisted of the following steps. First, the objective Lamb Weather Type dataset was sourced (www.cru.uea.ac.uk/cru/data/lwt), which starts in 1880 and continues to the present day. The weather type on the day of each >Q1 event was extracted from the dataset, along with the weather classification on the previous two days. As the Eden is quite a large catchment (2400 km^2), the number of days of precipitation that result in a high flow or extreme flood events downstream may be more than just the day of the event. Grew (1996) stated that the number of days of precipitation is dependent upon the specific catchment characteristics, including area and gradient. The relative time between the peak flow in the Upper Eden (Kirkby Stephen) and the Lower Eden (Sheepmount), has a maximum lag of 34.5 hours, and a mean lag time of 12 hours. The delay between precipitation and a peak flow occurring, will increase this response time further. Longfield and Macklin (1999) devised a method using daily rainfall records to assess the number of days responsible for flood generation. The previous four days were included and each day given a weighting dependent upon the amount of rainfall. The objective Lamb weather type on the day with the most rainfall was taken as the dominant synoptic system that caused each event. However, we focus on the sequencing of weather types. In this study, the weather types on the previous two days as well the day of the event are assessed. First, each day is looked at separately; and second, the sequence of days is investigated.

Event generating weather types were then identified from this dataset, as the weather types that occur most frequently on days, and this was undertaken for both >Q1 and extreme flood events . The weather types that occur on >Q1 events were compared with those associated with extreme flood events. Trends in the extreme flood generating weather types are then investigated over the historical timescale by calculating the percentage of each hydrological year for the extreme flood generating weather types both individually and combined. The average of the 1880-2007 period was calculated, then the average was subtracted from each hydrological year. This means that positive values represented years which had a greater than the average proportion of the year with these extreme flood generating weather types, while negative values had less than the average. The cumulative was then calculated for the deviations from the average and can be plotted against time. This plot is a means of visualising the sequencing of flood-generating weather types. A period when the deviation is trending from negative to positive suggests a greater number of flood-generating weather types. The longer the period of this trend, the greater the length of the period when more flood-generating weather types have been present than average. If we imagine a flood-generating weather type as one that may, but that does not necessarily, produce a flood, then the longer a positive trend, the more likely it might be expected to identify a flood in the flood series.

Results

Gauged records

Figure 2a shows that the late 1960s and 1970s were relatively poor in terms of >Q1 flow events, with fewer than the average number of events per year every hydrological year except 1967-1968 and 1974-1975, which were the years with the most events in the whole of the record. Events >Q1 occurred in every year except 1995-1996, a year of hydrological drought. The Pearson's product moment correlation coefficient of the number of >Q1 events over time for Sheepmount is only 0.07, which is not statistically significant ($p=0.42$). Of the 138 >Q1 events since 1967, 31% were classified as extreme flood events. The largest number of extreme flood events in a hydrological year is four, and occurred in 1967-1968, 1981-1982 and 2003-2004. There are also no statistically significant trends in either non-extreme >Q1 (r=0.01 p =0.93) or extreme flood (r=0.19 p=0.22) events over the gauged period at Sheepmount.

Figure 2b shows the annual maximum flood for the River Eden at Carlisle (Sheepmount) and indicates a wider range in the magnitude of the annual maximum flood. The most extreme flood was in January 2005 with a magnitude of 1516 m^3s^{-1}, with other notable extreme floods in 1968, 1981, 1985 and 1995. Annual maximum flows which are below the extreme flood threshold we are using (500 m^3s^{-1}) are highlighted in grey (34% of hydrological years). The lowest AMax magnitude for Carlisle (Sheepmount) was 291 m^3s^{-1} in 1995-1996, although years without extreme floods seem to have occurred in the 1970s more than at present. A second, more robust approach used to assess the frequency and magnitude of extreme floods considers the magnitude of the events that exceed the >500 m^3s^{-1} extreme flood threshold (Figure 2c). However, there are also no statistically significant trends in this record. In conclusion, the short term records do not exhibit any statistically significant trends in either high flow or extreme flood frequency or magnitude for the River Eden at Carlisle. However, as Kundzewicz and Robson (2004) notes that a failure to identify significant trend does not necessarily mean that there is not one, especially given the relatively short duration of the record used here.

Historical Flood Record for Carlisle

Figure 3 shows the cumulative number of extreme floods (>500 m^3s^{-1}) since 1770. The periods on Figure 3 where the gradient of the line is steep indicate flood rich periods. Times when the line is flatter are flood poor. It appears that there are three flood rich periods over the past 240 years: (1) 1873-1904; (2) 1923-1933; and (3) 1994 onwards, each separated by periods which were relatively flood poor, which have been classified visually. The years with the most extreme floods are 1877 and 1891, with five recorded in these years. The period before 1850 has very few extreme floods, which may be due to the lack of evidence for them occurring, rather than a lack of existence. However, it is assumed that the largest events have been recorded. The magnitude of the largest events have been estimated by the Environment Agency (2006). Bankfull discharge at the Sheepmount station is 1434 m^3s^{-1}, and only the 2005 event exceeded this threshold. However, floodplain inundation occurred in all the events recorded in the British Chronology of Hydrological Events database, which has an approximate threshold of 500 m^3s^{-1}.

Weather types for instrumented period floods

Using the Objective Lamb Weather Types, it was found that 11 of the 25 weather types have caused extreme flood events in the gauged period (1976-2007 at Sheepmount), of which 5 (Cyclonic =27.3%, Westerly =15.9%, South Westerly =15.9%, Cyclonic South Westerly =6.8%, Cyclonic Westerly =15.9%) accounted for 81.8% of the extreme flood events (Figure 4). These results are similar to the findings of Longfield and Macklin (1999) for the Yorkshire Ouse Catchment, where four circulation types (W, C, CW and SW) accounted for 79.7% of all events (and the same 5 weather types caused 82.6% of flood events in the Ouse record). These particular weather types highlight the importance of both cyclonic weather types and weather systems from a westerly and south-westerly direction to both high flows and extreme floods occurring in

Carlisle. Cyclonic weather systems are likely to cover a greater spatial area and lead to a more coherent catchment response. Furthermore, as they are not prescribed a direction, this means that they are often blocked by other air masses, meaning they are stationary, resulting in a prolonged rainfall event. Several studies have found that these weather systems are of notable importance in accounting for precipitation in this region (Malby et al., 2007) and the UK in general (Sweeney and O'Hare, 1992). Figure 4 shows that the other objective Lamb weather types are not important in causing >Q1 events, with only 14 >Q1 events being caused by the other 20 weather types, 8 of which are extreme flood events.

Figure 5a indicates that the common weather types on the two preceding days are the same as the ones on the day of the event itself, for extreme events. However, the order of importance of the five dominant weather types is different for the preceding days than the day of the extreme flood itself. While cyclonic weather systems are the most common on the day of the event, weather systems from a south-westerly (38% on previous day, 25% on two days before) and westerly (20.4% on previous day, 25% on two days before) direction are the most common on the two preceding days. Cyclonic weather systems are less common on the days previous to an event occurring (15.9% on previous day, 9.1% on two days before). Furthermore, cyclonic weather systems from a westerly and south-westerly direction are also less common on the days prior to an event.

The sequencing of the weather types may also be important in causing extreme floods, as they control the antecedent conditions of the catchment. This has been assessed in terms of whether or not the previous two days and the day of the event were classified as an event generating weather type (C, W, SW, CW, and CSW). Table 2 shows that 47.7% of extreme floods have had event generating weather types on both the day of the event and the previous two days, while a further 27.3% of extreme flood events occurred on days with both the day of the event and the day before classified as an event generating weather type. Only one extreme flood since 1976 occurred when none of the three days were classified as one of the extreme flood generating weather types. No extreme floods occur in sequences where just the day of the event is an event generating weather type (1 0 0).

None of these analyses take account of the proportion of the year associated with each weather type. Therefore, Figure 6 shows the percentage of the 1976-2007 period classified as each weather type. Anti-cyclonic and cyclonic weather systems dominate, accounting for 20.7% and 13.8% respectively for the whole period and 21.1% and 13.0% respectively of the last 40 years. Weather systems from a south-westerly and westerly direction also have a high frequency individually, as well as for anti-cyclones and cyclones.

The likelihood of a particular weather system causing an event can be determined by dividing the number of events occurring on days of a particular weather type by the total number of days of the same weather type over the same period. Figure 7 shows that the most likely weather type to cause an extreme flood in Carlisle is the Cyclonic Westerly, with a 2.6% chance of an event occurring on a day with this weather system over the UK. This is because it is the least common of the event generating weather types over the

40 year period in terms of occurrence, but has still caused 7 events. Cyclonic synoptic events have a 0.7% chance of leading to an extreme flood occurring, as although most events occur on cyclonic days, these weather systems occur most often. .

Comparison of high flow and extreme flood event generating weather types

Figure 4 shows that ten of the objective Lamb weather types have occurred on days of high flows, and the same five weather types account for 93.6% of the days when high flows occur (Cyclonic =34.0%, Westerly =19.1%, South Westerly =17.0%, Cyclonic South Westerly =12.8, Cyclonic Westerly =10.6%) A Chi Squared Test showed that the weather types that cause extreme floods and smaller magnitude high flows are statistically similar (p=0.32). The weather types on the preceding two days are also similar for both high flows and extreme flood events (Figure 5a and 5b). This is significant because it means that weather types cannot be used to distinguish between the magnitude of the event that might occur: whether a high flow or an extreme flood. Furthermore, the sequencing of weather types show no significant (Chi Squared Test p=0.99) difference for events of differing magnitude, with high flows and extreme floods showing similar percentages for each sequence.

Weather types for the Historical Period

The relationship between weather systems and extreme flood frequency will now be investigated over a longer timescale. A few previous studies have looked into how weather type frequency has changed over approximately the last 100 years (Lamb, 1972; Jones and Kelly, 1982; Briffa, 1990; Sweeney and

O’Hare, 1992; Fowler and Kilsby, 2002; Malby et al, 2007). Many of these investigations reported a decrease in the number of westerly days since the 1950s, while cyclonic and anti-cyclonic weather systems have become more common since the 1980s. The focus here is those weather types found to produce most of the extreme flood events in the recent gauged period.

Figure 8 shows the cumulative number of extreme floods (>500 m^3s^{-1}) since 1880, superimposed upon the cumulative deviation of flood-generating weather types. The periods on Figure 8 where the gradient of the line is steep indicate flood rich periods. Times when the line is flatter are flood poor. In relation to flood-generating weather types, it is clear that there is a number of scales of variability. At the largest scale, there are two periods of generally positive trend, with the exception of short breaks in this trend: 1902-1938 and 1983-2007; before 1902 there was a dominant negative trend; and between 1938 and 1983 there were shorter periods of negative and positive trend. Thus, Figure 8 shows that flood-generating weather types are not randomly located in time but clustered into periods when there are generally more than average and generally fewer than average. The association between these weather type patterns and the cumulative flood record is interesting. For both the period 1902-1938 (until 1931) and 1983-2007, the cumulative flood records are weak positive exponentials suggesting that as the duration of generally positive deviations becomes longer, and the number of flood generating weather events in the positive sequence becomes greater, so there are more floods. This does not require a mechanism like land use change or groundwater recharge (which for the Eden is important but not that much so – the Base Flow Index is 0.498), but is a result of clustering of flood-generating weather types, which in turn increases the probability that one of these weather events becomes a flood, and so leads to an increase in the number of floods. Similar overall trends are shown in historical rainfall records (e.g. for Lockwood Reservoir; Fowler et al., 2002). Of course, it is also possible that the objective Lamb weather type classification misses some climatic signals, such as precipitation intensity or quantity, as it is only a broad categorical system.

Figure 9 shows the how the proportions of individual weather types per year change over time. Firstly, the Cyclonic-Westerly (Figure 9a) weather system does not vary significantly from the average, with only a range of 4.9% (0.6% to 5.5%). Also periods with more Cyclonic-Westerly weather systems do not correlate well with the periods of increased extreme flood activity in the Eden. The Cyclonic South-Westerly (Figure 9b) weather type varies by 4.7% (0.6% to 5.2%) and seems to match the flood rich and flood poor periods visually quite well. Pre-1918, the proportion of the year classified as a Cyclonic South-Westerly weather type decreased, while extreme flooding had a low frequency. Between 1919 and 1955, the proportion of the year categorised as Cyclonic South-Westerly increased, which occurred simultaneously with the 1923-1933 flood rich period. Since the mid-1950s to 2007, the proportion of Cyclonic South-Westerly types per year has stayed quite constant, although there has been a slight increase since the mid-1980s. The Cyclonic (Figure 9c) weather system has varied by 17.8% (5.5% to 23.3%) in terms of the proportion of the year classified as this weather type over the last 140 years. During the pre-1923 flood poor period, this weather type was decreasing in terms of the proportion of the year classified as it. It then increased during the 1923-1933 flood rich period. It has also increased since the mid-1970s, although specific years have had less than the average proportion of the year classified as cyclonic. The Westerly (Figure 9d) weather system has varied by 9.6% (5.2% to 14.8%) throughout the whole period. This weather system does not seem to match the flood rich periods well, with a decline in the proportion of the year of the westerly weather type since the mid-1990s, which coincides with the start of the flood rich period. Finally, the South-Westerly (Figure 9e) weather system has varied by 11.5% (3.6% to 15.1%). This weather type has the highest level of agreement with the extreme flood frequency, with the proportion of the year classified as south-westerly increasing from 1900-mid 1930s, falling significantly from 1960 to 1980 and then increasing again in the current flood rich period.

Discussion

If the latter part (post-1965, the start of the gauged record) of Figure 3 is analysed, then it could be concluded that there is a unidirectional trend of increasing extreme flood frequency in Carlisle, that starts with very few floods during the late 1960s, a rising number of floods until the early 1990s and a very rapid rise after that into the flood rich period from 1994-2007. However, when put into the historical period context, it becomes clear that there is not a unidirectional trend and that the period since 1994 has been flood rich, but so have other periods. Several other studies have identified flood rich and poor periods in historical flood records (Grew and Werritty, 1995; Werritty *et al.,* 2002; Macdonald, 2006; Macdonald *et al.,* 2006; McEwen, 2006). These examples, along with the River Eden, indicate that there are flood clusters throughout the historical period. However, a conclusion from Macdonald (2006) was that these flood rich periods are not nationally synchronous, which indicates that regional climatic variability and catchment specific characteristics are important in controlling flooding frequency. Possible reasons why flooding may not be recorded as regionally synchronous may be that; 1) there is an absence of extreme flood event recording in the documentary evidence; or 2) there are different causal mechanisms for extreme flood generation in different river catchments. However, it has been found that high magnitude floods can transcend catchment boundaries, depending on the precise forcing mechanisms and antecedent conditions. The 1771 floods occurred in both the Rivers Eden and Tyne (Macdonald (2006) and there were floods on both the River Severn and Trent in 1796. Furthermore, along with the flood event on the River Eden in January 2005, the River Tyne also exhibited flooding (Archer *et al.,* 2007a; 2007b). The storm event which caused this flooding extended from the 6th to the 9th January 2005 and affected Northern England, Southern Scandinavia, Germany and the Baltic Region (Carpenter, 2005).

The presence of flood rich and flood poor periods throughout the historical period has implications for the concept of stationarity. This assumption states that natural systems fluctuate within an unchanging range of values. However, as Milly et al (2008) stated it has been compromised by human disturbance, natural climate change and variability. They go on to say that the assumption of stationarity is dead and cannot be revived. Through analysing historical flood records, it could be concluded that stationarity in flood frequency has never existed, as floods have tended to cluster within certain periods separated by flood poor periods. Therefore, the range of behaviour of the system depends on the timescale over which it is analysed. If the post-1960 period is analysed without the context of the historical period then it could be concluded that the behaviour that we are seeing today is unprecedented. However if the whole period is analysed then it can be concluded that today's flood frequency is not out of the range of past flood occurrence, suggesting a more stationary behaviour. However, the presence of flood clustering means that there is a variable chance of a flood occurring in every year of the record. This raises a problem for flood frequency studies, as using short records will not capture flood variability (Bardossy and Pakosch, 2005), while using longer time series does not reflect stationary conditions, invalidating the assumptions of standard frequency analysis (Khaliq et al., 2006).

This study has highlighted the importance of cyclonic and westerly weather types, along with previous studies (Longfield and Macklin, 1999). However, a recent study by Macdonald et al., (2010) for Wales found that the link between westerly (SW, W, NW) weather systems and flood occurrence only is statistically significant for Northern Wales. However, there is no link between cyclonic weather types and flooding for Wales. Therefore, for Wales, weather types seem to be a poor predictor of flood frequency. This builds on the findings of Dixon et al., (2006) who found a strong east-west gradient in stream flow trends for western Britain. Possible explanations for why flood frequency and weather types can exhibit constrasting trends in different river systems may be the role of rain-shadows of orographic rainfall, the influence of oceans (distance) (Dixon et al., 2006) and catchment aspect. Macdonald (2010) explained these weak associations by commenting on the dataset limitations, with the need for concentration and distribution of the days of each weather type to be considered instead of just the annual totals. This has been addressed in this study by including the weather types occurring on extreme flood days and the preceding days and found that the sequencing of weather types is important in explaining extreme flood occurrence. It has been found that the same five weather types that occur on extreme flood days are also more likely to have occurred on the previous two days compared to the other objective Lamb weather types. However, it has been found that the likelihood of a certain sequence of weather types in causing an extreme flood is not significantly different to it causing a high river flow. This indicates that while weather types can be used as an indicator of how likely a high flow/flood is, they can not be used to predict the likelihood of an extreme event occurring in advance.

In addition, weather types and their link to flood risk has been investigated over longer timescales. Brazdil et al., (2006) states that knowledge of synoptic patterns for recent flood events can help explain past flood event occurrence. It is this assumption that this study has made, using the last 40 years to define extreme flood generating weather types and then looking at their frequency over the historical period. This study has established a possible link between the proportion of the year defined as an extreme flood generating weather type and extreme flood frequency. However, this analysis assumes that the weather types that cause extreme flooding has not changed over time. The weather types that have caused floods during the last three decades (1978-1987; 1988-

1997; and 1998-2007) have been analysed to assess this assumption. Figure 10 shows that the weather types that result in extreme floods have changed from the first decade, when two forms of anticyclonic weather type caused extreme floods (A, AS) to CSE and CS in the last decade. In terms of the high flow events, the importance of the cyclonic weather type has nearly doubled from the 1978-1987 to the 1998-2007 period. However, the dominant weather types (5 extreme flood generating weather types) have not changed over the 30 year gauged period. Furthermore, it has been shown that the weather types that cause both high flows and extreme floods have not changed statistically over the decades (ANOVA p= 0.816). Malby et al., (2007) found that for the Eden catchment, south-westerly and westerly weather systems contributed the most to the decadal precipitation totals. Furthermore, winter rainfall delivered by these weather systems has increased over the last 30 years. Specifically, the precipitation associated with each westerly weather system has increased between the 1970s and the 1990s for five rainfall gauging stations in the Eden catchment. The quantity of rainfall supplied by south-westerly weather systems was highest in the 1980s. Jacobeit et al., (2003) found that a broader range of circulation modes are important if studies are extended back into historical periods.

The periods of a greater proportion of the year than average of the five extreme flood generating weather types correlate with the flood rich periods. Furthermore, they match the periods identified by Wilby et al., (1997) as periods when the NAO was in a strong positive phase. Jones et al (1997) found a strong correlation between the NAO index and westerly weather systems, which is one of the extreme flood generating weather types. Wedgbrow (2002) found a lag between the changing NAO index and the change in UK weather. This was hypothesised to be caused by either climatological memory effects, such as seasonal patterns, or hydrological memory effects, for example groundwater levels or antecedent moisture levels. This study has also found a lag between the increase in the proportion of the year classified as one of the five extreme flood generating weather types and the increase in flood frequency. This would seem to be expected due to the "chain of causality" (Lawler et al., 2003) whereby the link between large scale atmospheric forcings, such as the NAO, are spatially scaled down to their catchment effects, through the weather types and the amount of precipitation which occur.

Conclusion

Various event frequency and magnitude indices have been used to investigate trends in both high flows and extreme floods. First, the gauged record at Sheepmount, Carlisle (1967-2007) was used to define the threshold of a high flow event, which was taken to be the Q1 value of 347 m^3s^{-1}. Extreme floods were defined by a threshold of 500 m^3s^{-1}, to allow compatibility with the longer-term Smith and Tobin (1979) study. The gauged record showed that, although the 1960s and 1970s seemed >Q1 event poor in comparison to more recent decades, there were no statistically significant trends over time. This was also the case when the non-extreme > Q1 and extreme records were considered separately. The annual maximum series showed that two thirds of years experienced an extreme flood. There were more annual maximum events which were less than 500 m^3s^{-1} (high flows only) during the 1970s than at present, although again these trends were not statistically significant. Multiple sources of documentary and epigraphic evidence were used to compile an extreme flood record from 1770 to 2007. This showed that extreme flood events have clustered in time, and three flood rich periods were defined as 1873-1904; 1923-1933 and 1994-2007.

The Lamb weather types that occurred on the days of extreme flood days (1976-2007) were extracted, and it was found that 11 out of the 25 weather types have caused extreme floods in the gauged period. Of these 5 have caused 81.8% of extreme floods. These were Cyclonic, Westerly, South-Westerly, Cyclonic-Westerly, and Cyclonc South-Westerly. It was shown that there was no statistically significant difference in the weather types that occur on days with either high flows or extreme floods. The same five weather types were more likely to occur on the previous two days before extreme flood events. The sequencing of weather types was also found to be important, with ~50% of extreme floods and high flows occurring after sequences of three days of the five event generating weather types. However, the sequencing of days was not statistically significant in determining whether an extreme flood or high flow occurred. This means that weather types cannot be used to distinguish between the magnitude of the event which might occur: whether a high flow or an extreme flood.

The proportion of each hydrological year of the five extreme flood generating weather types was calculated. It was found that there are two periods when the proportion of the year is less than the average for a sustained period; 1902-1938; and 1983-2007. These were shown to correlate with the flood rich periods, although a lag existed between the increase in the extreme flood generating weather types and flood frequency increasing. These periods also match with Wilby et al (1997) periods of a strong positive NAO index. Thus, the analysis suggests that systematic organisation of the North Atlantic climate system, which drives the weather types experienced by the UK, may be manifest as periods of elevated and reduced flood risk, an observation that has major implications for analyses that assume that climatic drivers of flood risk can be either statistically stationary or are following a simple trend.

Acknowledgements

Ian Pattison was funded by the Environment Agency and United Utilities as part of the EU Interreg IVB project ALFA (http://www.alfa-project.eu) and acknowledges additional support from Durham University and the Eden Rivers Trust. Two anonymous reviewers and the editor (Glenn McGregor) provided valuable and constructive comments on an earlier version of this manuscript.

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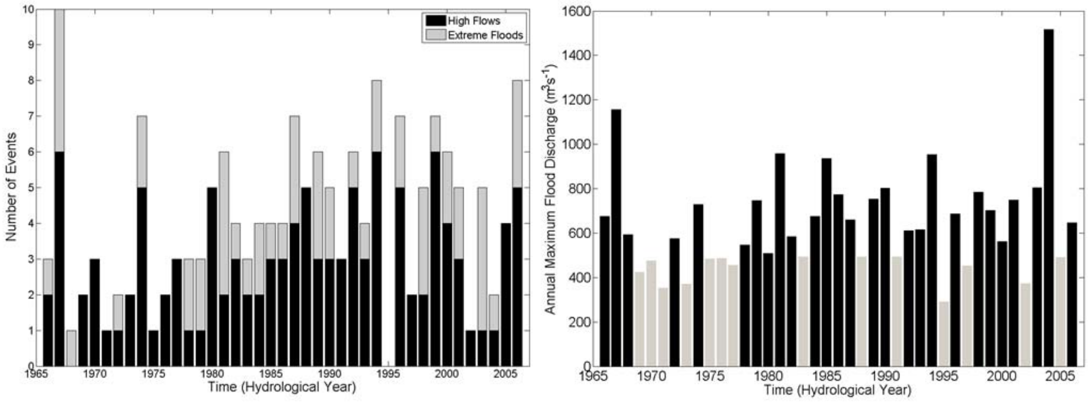
Figure 1 Map of the Eden Catchment



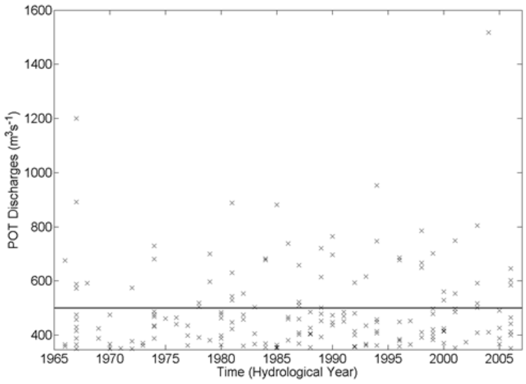


Figure 2 Gauged records from the Eden at Sheepmount in Carlisle (a) POT; (b) AMax; (c) Magnitude of POT events.

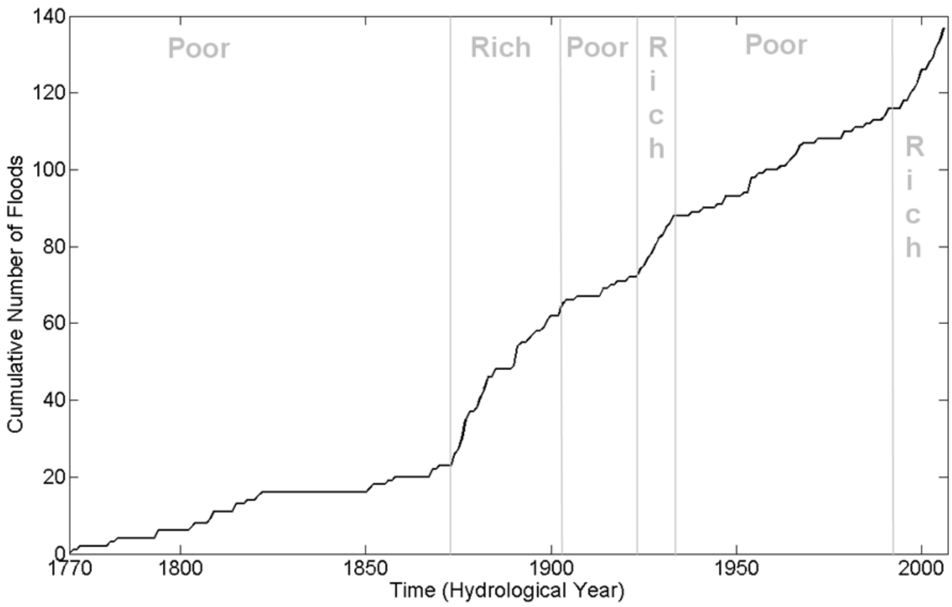


Figure 3 Cumulative number of extreme floods as a function of time

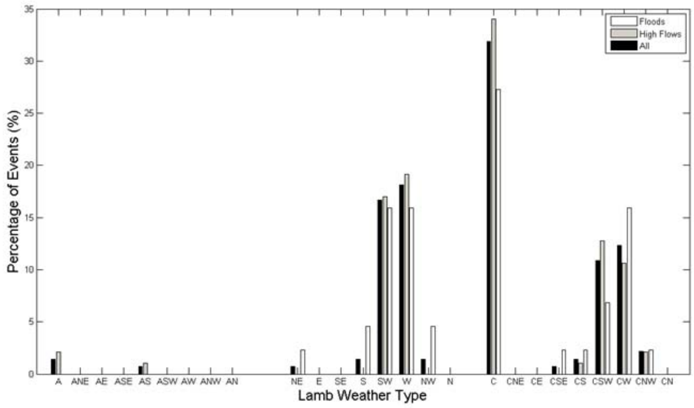


Figure 4 Percentage of floods since 1978 which have occurred on days of particular Lamb weather types.

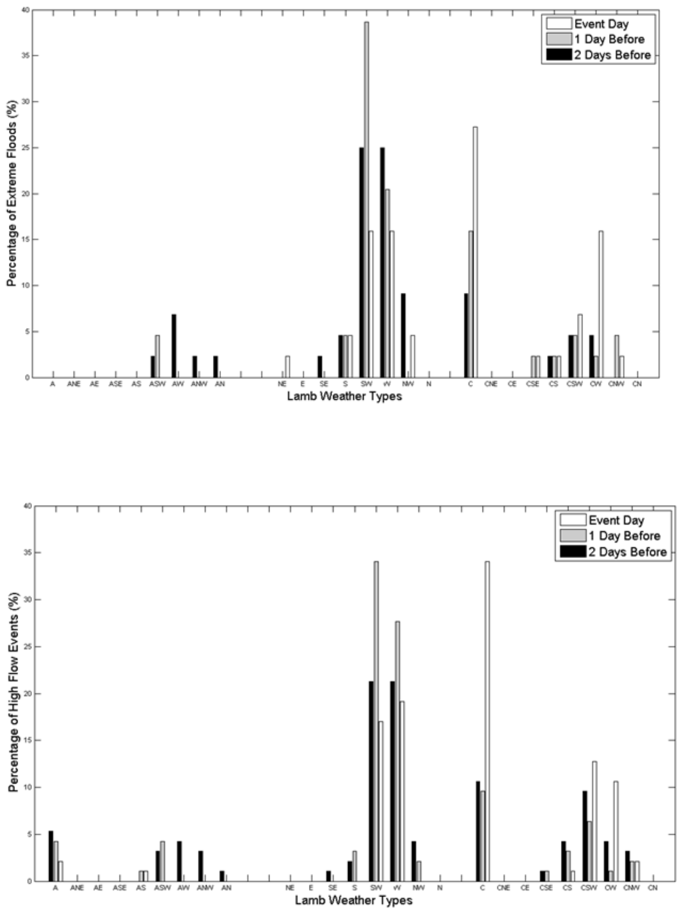


Figure 5 Percentage of floods which have occurred on days and preceding days of particular Lamb weather types a) high flows; b) extreme flood events

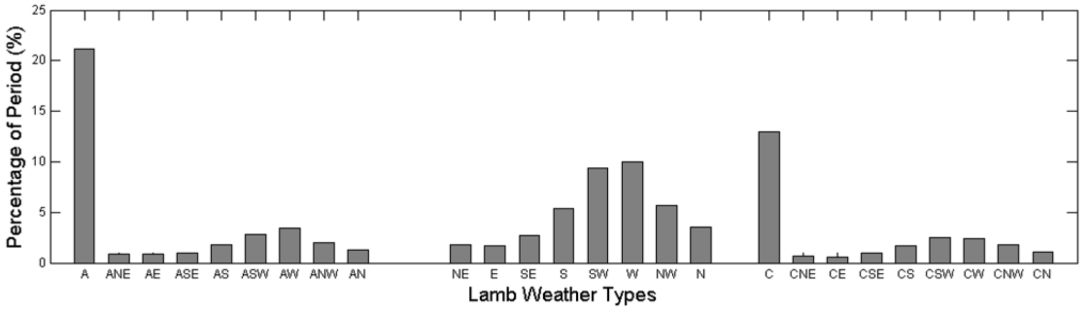


Figure 6 Percentage of the year classified as each Lamb weather type for the 1976-2007 period.

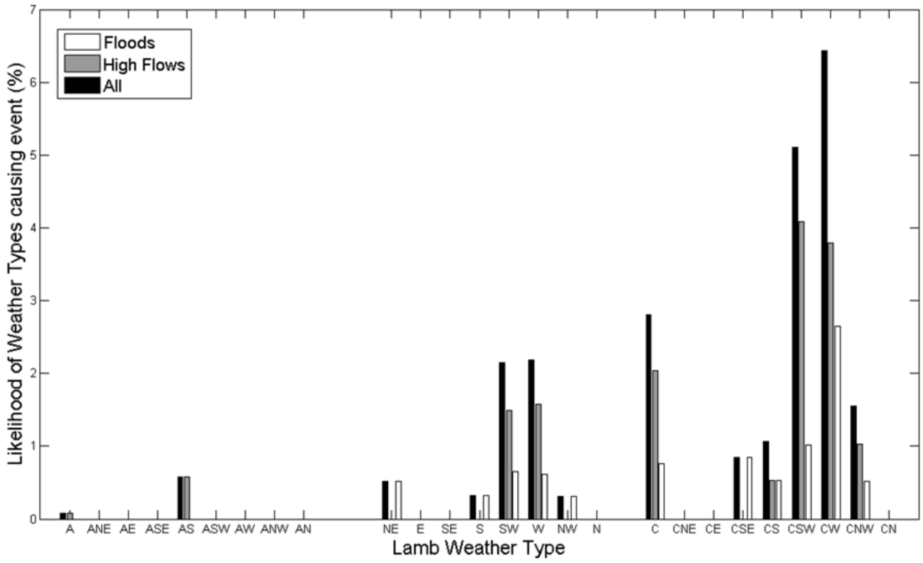


Figure 7 Probability that a day with a particular Lamb weather type will also have an >Q1 event occurring.

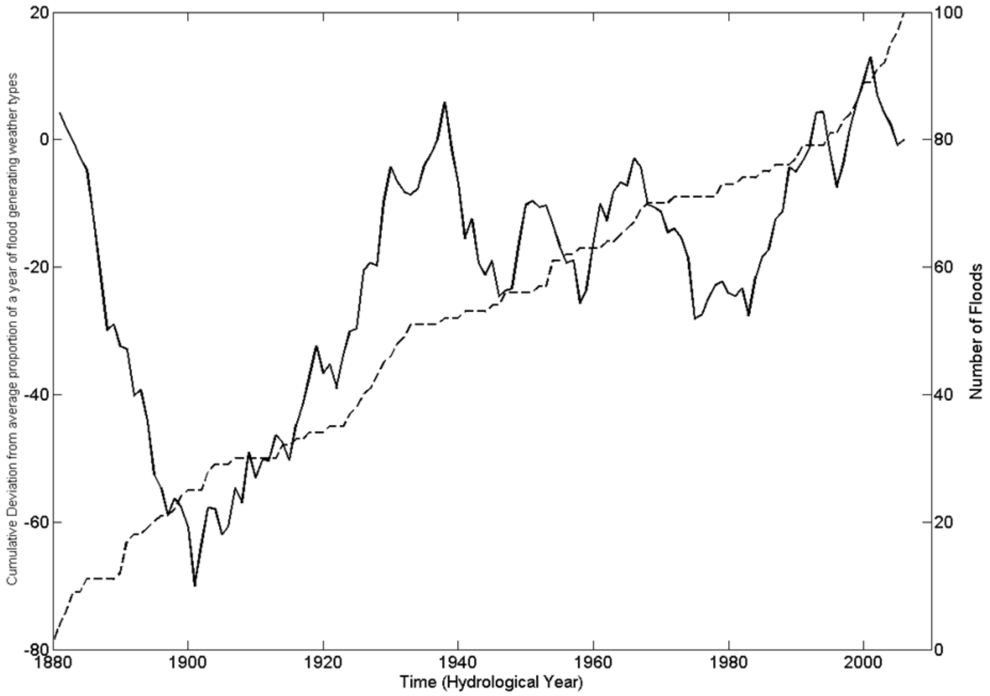
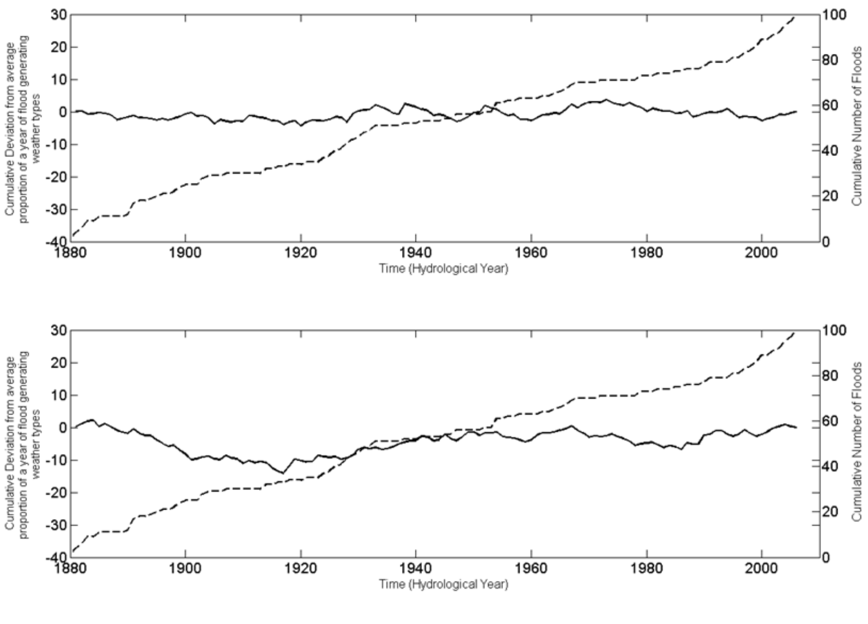


Figure 8 Plot showing how the proportion of the year classified as the five extreme flood generating weather types and extreme flood frequency have changed over time. (dashed line represents the cumulative extreme flood record, solid line represents weather types.)



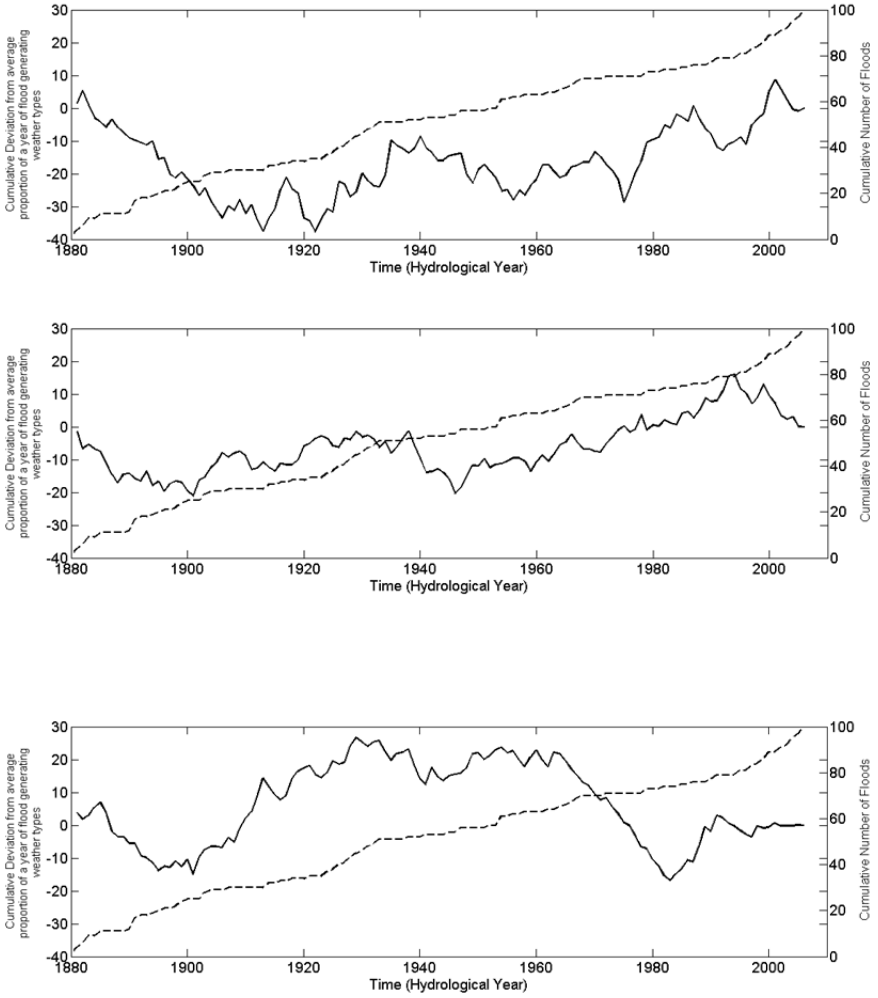


Figure 9 Plot showing how individual extreme flood generating weather types have changed over time a) CW; b) CSW; c) C; d) W; and e) SW. (dashed line represents the cumulative extreme flood record, solid line represents weather types.)

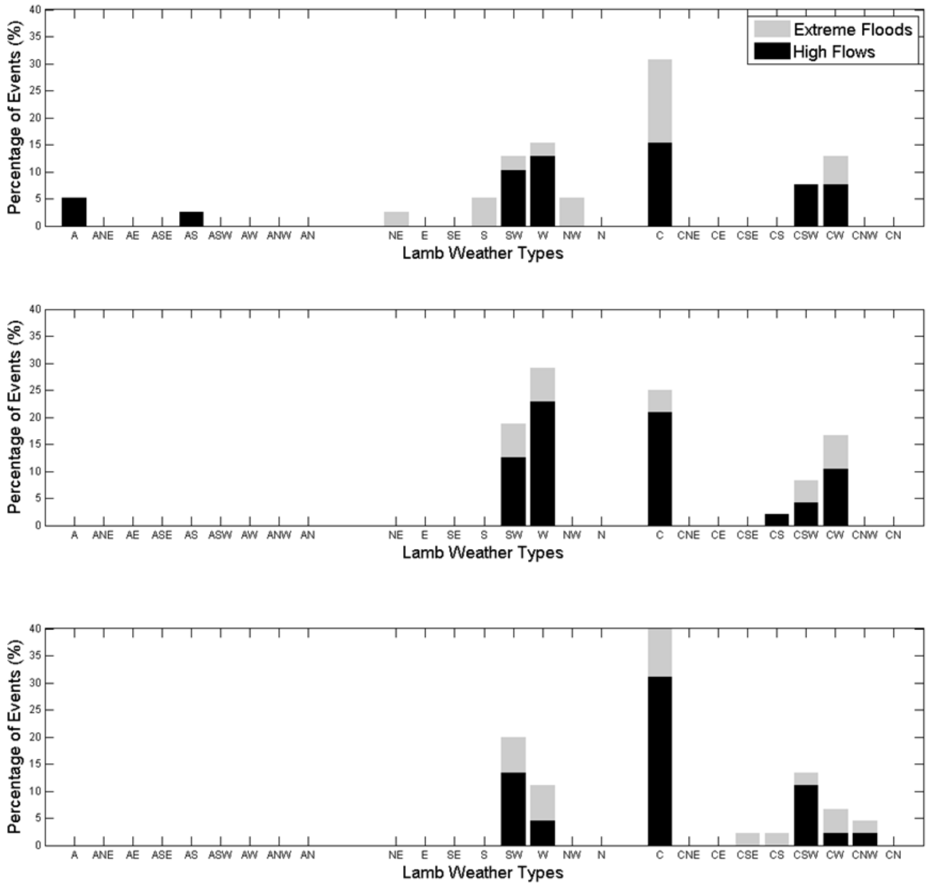


Figure 10 Percentage of floods since 1978 which have occurred on days of particular Lamb weather types. a) 1978-1987; b) 1988-1997; c) 1998-2007

Reference	**Record Length needed to identify trends**
Interagency Advisory Committee on Water Data 1982	10 years
Richter *et al*., 1997	20 years
Lettenmaier *et al*., 1994; Lins and Slack, 1999; Douglas *et al*., 2000	at least 30 years
Gan *et al*., 1991; Huh *et al*., 2005	at least 40 year records
Kundzewicz and Robson 2000; 2004	at least 50 years

Table 1 Summary of record length requirements from literature for identifying trends in flood records

Sequence	% of Extreme Floods	% of High Flows	% of All Events
1 1 1	47.7	53.2	51.4
1 1 0	27.3	21.3	23.2
1 0 0	0.0	8.5	5.8
1 0 1	6.8	10.6	9.4
0 1 1	4.5	3.2	3.6
0 1 0	2.3	1.1	1.4
0 0 1	9.1	0.0	2.9
0 0 0	2.3	2.1	2.2

Table 2 Percentage of events of each sequence (day of event, day before, 2 days before) of event generating weather types

1 = event generating weather type (C, W, SW, CW, CSW)

0 = day with another weather type

	BCHE	Newspapers	Epigraphic	Smith & Tobin	Warwick Bridge	Sheepmount
1771	Y					
1773	Y					
1781	Y					
1783	Y					
1794	Y					
1794		Y				
1803	Y					
1804	Y					
1808	Y					
1809	Y	Y		Y		
1809	Y	Y		Y		
1815	Y	Y		Y		
1815	Y					
1818		Y				
1821		Y				
1822	Y	Y	Y	Y		
1851	Y	Y		Y		
1852	Y			Y		
1856	Y	Y	Y	Y		
1858		Y				

1868	Y		Y	Y		
1868	Y					
1870	Y					
1874	Y					
1874	Y					
1874	Y			Y		
1875	Y	Y				
1876	Y					
1876	Y					
1876	Y					
1877	Y					
1877	Y					
1877	Y					
1877	Y					
1877	Y					
1878	Y					
1878	Y					
1880	Y					
1881	Y					
1881	Y					
1881	Y					
1882	Y					
1882	Y					
1883	Y					
1883	Y					
1883	Y					
1885	Y					
1885	Y					
1890	Y					
1891	Y			Y		
1891	Y			Y		
1891	Y			Y		
1891	Y			Y		
1891	Y			Y		
1892	Y	Y		Y		
1894	Y					
1895	Y					
1896	Y			Y		
1898	Y			Y		
1899	Y			Y		
1899	Y					
1900	Y					
1903	Y			Y		

1903	Y	Y		Y		
1903	Y	Y				
1904	Y					
1907		Y				
1914	Y			Y		
1914	Y			Y		
1916	Y			Y		
1918	Y	Y		Y		
1921	Y			Y		
1924	Y			Y		
1924	Y			Y		
1925	Y	Y	Y	Y		
1926	Y	Y		Y		
1926	Y	Y		Y		
1927	Y					
1928	Y			Y		
1928	Y			Y		
1929	Y	Y		Y		
1929	Y			Y		
1930	Y			Y		
1931	Y			Y		
1931				Y		
1932				Y		
1933				Y		
1933				Y		
1938		Y				
1941		Y		Y		
1945		Y				
1947		Y		Y		
1947		Y				
1952			Y			
1954	Y			Y		
1954		Y		Y		
1954		Y		Y		
1954		Y		Y		
1956		Y				
1958		Y				
1962		Y			Y	
1964		Y		Y	Y	
1965					Y	
1966		Y			Y	
1967		Y			Y	Y
1967		Y			Y	Y

1968	Y	Y	Y	Y	Y	Y
1972		Y			Y	Y
1979					Y	Y
1979					Y	Y
1982		Y			Y	Y
1985					Y	Y
1987		Y			Y	Y
1990		Y			Y	Y
1991					Y	Y
1991					Y	Y
1995		Y			Y	Y
1995					Y	Y
1997		Y			Y	Y
1997					Y	Y
1998					Y	Y
1999					Y	Y
1999					Y	Y
2000					Y	Y
2000					Y	Y
2000					Y	Y
2002					Y	Y
2002					Y	Y
2003					Y	Y
2004					Y	Y
2004					Y	Y
2004					Y	Y
2005		Y			Y	Y
2005		Y			Y	Y
2006					Y	Y
2006					Y	Y
2006					Y	Y