University of Reading

Department of Meteorology

Extreme Rainfall and the Relationship to Summer Flooding Events in the UK

Maya Balasubramanyam

A dissertation submitted in partial fulfilment of the requirement for the degree of MSc Applied Meteorology

26th August 2014

Abstract

Daily rainfall data from the UK Met Office raingauge network was analysed to identify summer (June, July, August) extreme rainfall events in five regions in England and Wales. These regions were selected for their importance to the insurance industry, in particular relating to caravan sites and holiday homes which are prone to flooding. The data was first processed in order to remove any errors and to fill in any missing gaps in the observational time series prior to analysis. The data was then analysed by excluding all rainfall events which fell below a pre-determined threshold in order to identify extreme rainfall events within the five regions. It was found that many flooding events could be identified by using a threshold of 60mm of daily rainfall, but that it would be necessary to analyse hourly rainfall data in order to identify the shorter and more highly localised convective events which sometimes fell below this threshold and that are associated with summer flooding. The data was then analysed using the in2extremes software to produce return value plots for each raingauge and average return values for each of the five regions were calculated. Because of the relatively short time series of rainfall data it was found that the uncertainty in return values for return periods of over 50 years was very high, reducing confidence in the results for higher return periods. A preliminary analysis of the atmospheric conditions of a selection of summer flooding events identified a range of processes which could lead to flooding. An important part of any future work into the analysis of summer floods would be the collection and analysis of hourly rainfall data which could then be compared with historical flood records in order to identify the shorter duration convective events.

Acknowledgements

My thanks and gratitude to Richard Allan and Adrian Champion for their invaluable advice, support and feedback during the course of this project, and to Tom Philp from Catlin for providing an interesting and informative insight into the insurance industry.

Also, to my husband and three children for putting up with my continued absence and the lack of proper food whilst I completed this dissertation – a huge thank you.

Contents

1. Introduction

The UK is particularly vulnerable the destructive forces of flooding events because of its high population density and concentrated infrastructure. This liability is further amplified by the increasing amount of construction taking place on flood plains, leading to a sizeable number of properties being at risk. Although much work is being carried out by local councils in conjunction with the Environment Agency to protect susceptible areas, damages from recent flooding incidents are high; it was estimated that the summer floods of 2007 resulted in record losses of approximately £4 billion (Environment Agency, 2010). The magnitude of loss was partly due to the fact that these particular floods hit many town and city centres causing major losses of income and business, as well as structural damage to both commercial and residential properties. £3 billion of these losses were reported to be insurable and were paid out in over 165,000 flood insurance claims (Chatterton et al, 2007). It is therefore unsurprising that insurers have a vested interest in assessing the probability of the occurrence of future extreme rainfall events and in developing a greater understanding of the subsequent risks.

The industrial partner for this project, Catlin Group, is a global speciality property and casualty insurer and reinsurer who have an interest in the risk analysis of flooding events around the UK. Insurance companies often depend on catastrophe and risk modelling companies such as Air Worldwide and RMS (Risk Management Solutions) who provide risk modelling software and consulting services for the analysis and prediction of future catastrophic events including those caused by flooding. In order to tailor the analysis to their specific requirements, Catlin Group is partnering this project with a view to gaining a greater understanding of the risks posed by extreme rainfall events in specific locations around the UK.

Evaluating flood risk is an exceptionally complex task as there are numerous variables which affect the probability of a flood occurring and its magnitude at any given location, with summer flooding being more difficult to interpret and forecast than winter flooding due to the short duration of many of the events and the highly localised nature of the rainfall. The focus of this project is the extreme rainfall and flooding events which take place during the months of June, July and August.

The project can be divided into the following four areas:

- **To identify extreme rainfall events using observational daily raingauge data from the UK Met Office network of raingauges in order to establish rainfall time series' for specific locations across England and Wales:** One of the most challenging parts of this process is to characterise the rainfall events and to establish which events should be defined as extreme. There are four main factors that could give rise to flooding. Intensity of rainfall, duration of rainfall, the ground moisture content and the response of the catchment to rainfall (Hand et al, 2004). This project is concerned more with the meteorological conditions responsible for flooding, than the hydrological conditions. Therefore the main focus will be on the rainfall intensity and duration, although some attention will be paid to the ground conditions in case studies of specific floods.

- **To analyse the probability distribution of extreme rainfall events and determine return periods for specific locations using extreme value theory:** This is achieved by the use of the in2extRemes package which is part of the R software of UCAR (UCAR, 2012).

- **To investigate the relationship between extreme rainfall and summer flooding using historical flood records:** Not all extreme rainfall events produce flooding, and conversely a flood sometimes occurs from a relatively low amount of precipitation. It is therefore important to compare the results obtained in the first two sections of this project with historical flood records which are drawn from numerous sources such as journals, newspapers and online databases.

- **To investigate the atmospheric conditions prior to and during summer flooding events:** By combining the results obtained in the earlier sections of the project with atmospheric reanalysis data, identification of patterns in the state of the atmosphere prior to and during extreme rainfall events are considered.

2. Background

2.1 Rainfall in the United Kingdom

A study of rainfall patterns in the UK is complex and demanding because of the diversity of topography and the numerous air masses bringing a range of weather systems to the country. The West of the UK is typically wetter than the East because of the higher ground and the exposure to extra tropical cyclones bringing moisture from the Atlantic. This is particularly true during the winter months when rainfall is dominated by frontal systems bringing moisture from the West. This pattern can be seen clearly in Figure 2.1, where the number of rainfall events exceeding 10mm/day is greater in the hillier North and West of the Country than the flatter East and South which is sheltered by the orography in the West.

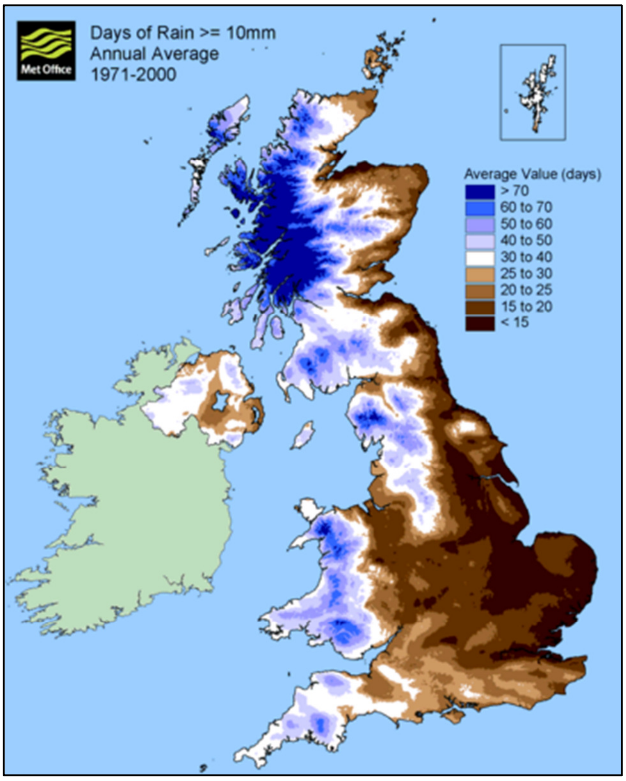

Figure 2.1: *Number of days per year with 10mm or more rainfall. .Met Office (2011)*

2.1.1 Winter Flooding

Winter flooding events can often be attributed to deep low pressure systems generating large fluxes of water formed from the convergence of atmospheric water vapour. They are typically large scale events that can be forecast often several days prior to their arrival in the UK. The frontal rain associated with winter flooding can span many hundreds of kilometres and can last for several hours or even days, causing the ground to become saturated and rivers to flood. The strong winds and low atmospheric pressure of an extra tropical cyclone can also cause dangerous coastal flooding from storm surges.

Atmospheric Rivers (Lavers et al, 2011) are a key feature of winter flooding events. This phenomenon is attributed to a flux of water transported in long thin ribbons in the warm conveyor belt of an extra tropical cyclone as shown in Figure 2.2, causing significant precipitation events which often lead to flooding. If mountainous regions cause the moisture laden air to rise and the water vapour to precipitate, the intensity of the rainfall is further increased. The seeder-feeder mechanism, whereby rainfall from higher level clouds 'seeds' lower level orographically produced cloud resulting in an increase in rainfall intensity from the low level cloud, is also an important process which can lead to flooding in hilly areas. During this process, rain falling from high altitude synoptically produced seeder cloud sweeps through the lower level feeder cloud. As the raindrops fall through the lower level cloud they grow, by coalescing cloud drops and hence increasing the intensity of the rainfall in the region.

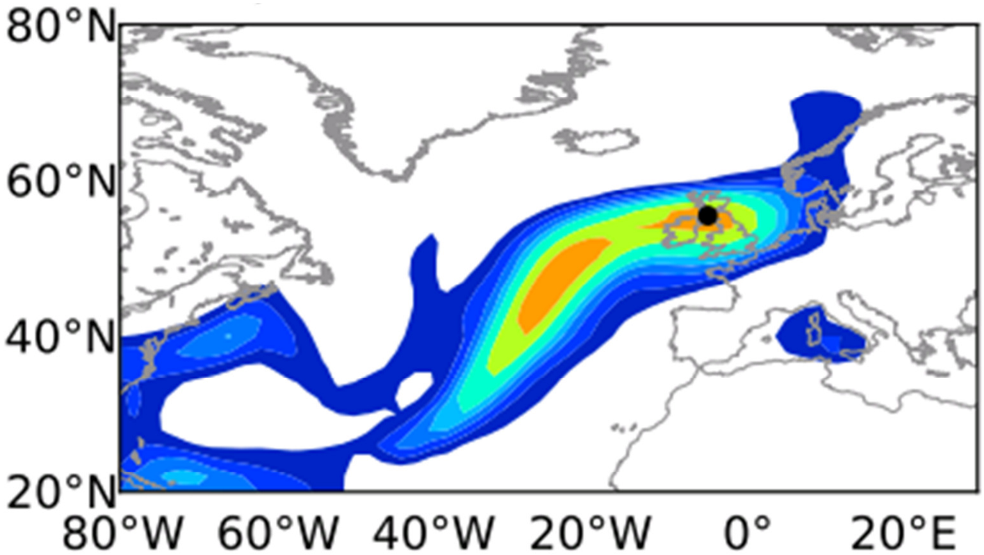

Figure 2.2: *Integrated Water Vapour Transport (in $kgm^{-1}s^{-1}$) using 20th Century reanalysis dataset for 10th December 1994, prior to 11th December 1994 flood in Scotland, showing atmospheric river. (Lavers et al, 2012)*

2.1.2 Summer Flooding

Floods caused by convective storms are typically summer events and are notoriously difficult to simulate because of their limited spatial scale relative to the model grid size (Kendon et al, 2014).

They can have a spatial scale of the order of tens of kilometres, rather than the scales of several hundreds of kilometres associated with frontal rainfall. This leads to uncertainty in the prediction and forecasting of convective rainfall because of the need for very high resolution models. A convective storm producing an extreme rainfall event which results in summer flooding is generally caused by heavy rainfall over a short period of time which can cause torrents of water through urban areas and river beds. This type of flash flooding is particularly sensitive to not only the intensity and duration of the rainfall, but also to the antecedent soil conditions and the response of the catchment under investigation (Hand et al, 2004). Towns are often susceptible to this type of flooding because of the large amounts of concrete and inefficient drainage (Sanderson, 2010). It is often even more destructive than winter flooding, because the rapidity of the event does not allow time for preparation, large amounts of damage can be sustained in a very short space of time.

Many summer flooding events have been analysed in great detail (Almond, 2013, Sibley, 2012, September, 2007); however the atmospheric conditions of particularly the earlier floods have not always been studied. Now that the tools and techniques for reanalysing meteorological conditions have developed it is possible to revisit some of the extreme rainfall events which produced the summer floods in the earlier part of the 20^{th} century for further analysis using reanalysis data, in order to gain a greater insight.

2.1.3 Seasonal Distribution of Extreme Rainfall Events

Figure 2.3 (Hand et al, 2004) illustrates the proliferation of extreme rainfall events in June, July and August when compared with rest of the year using a method of extreme event selection defined by the Flood Studies Report II (1975). See section 3.1.2 for further details of method used to identify and classify extreme rainfall events. It can be seen that the summer rainfall events are mainly, but not exclusively convective. The convective events tail off during October and November and there are no convective events during the period from January to April, as convection requires insolation. The winter events are fewer in number and are predominantly due to frontal systems.

It is worth noting that many of the frontal events during the summer months produced extreme precipitation because of convective storms embedded within the frontal system. The summer frontal events themselves tend to be fairly weak and are often incapable of leading to flooding, but as they are often the trigger for a cluster of convective events, they play an important role in summer flooding.

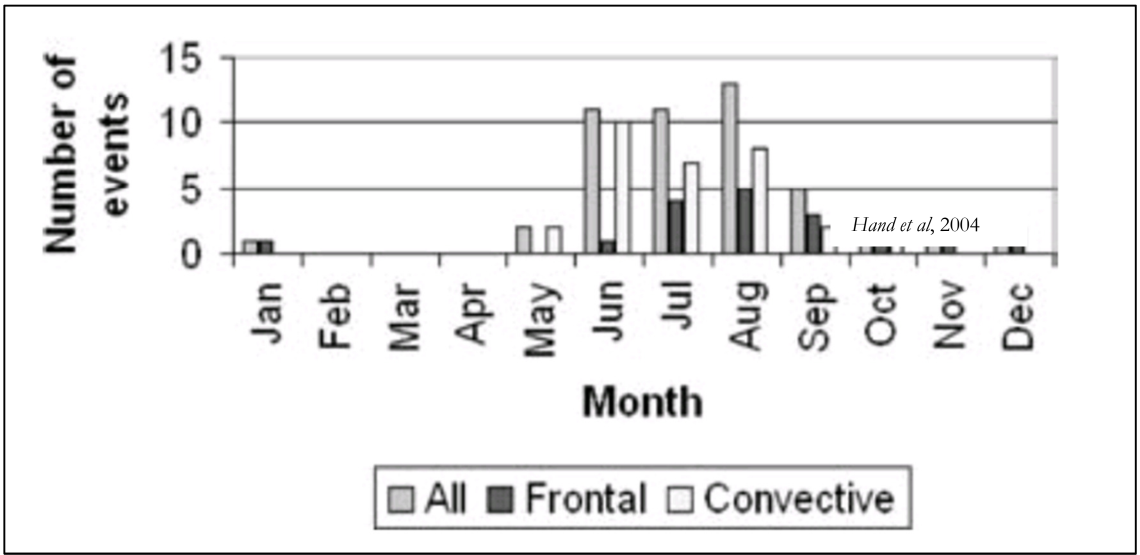

Figure 2.3: *Distribution of extreme rainfall events by month and by type. Data comes from a list of 50 of the most extreme rainfall events from 1900 – 2004 Hand et al (2004).*

2.1.4 Studies of Flooding Events

Many of the extreme flooding events to have impacted the UK have been studied in great detail with analysis of not only the rainfall data, but also the atmospheric conditions at the time. Notable summer flooding events which have been investigated are the Boscastle flood of 2004 (Golding et al, 2005), the summer flooding events of 2012 (Almond, 2013) and the Norfolk floods of 1912 (Brooks, 2012).

As mentioned earlier, the 2007 summer floods led to massive socio-economic losses and have been studied in depth from both a meteorological and a hydrological perspective. The larger scale global patterns which led to the highly destructive summer floods of 2007 were also investigated by Blackburn et al (2008). This study concludes that the flooding was caused by events which produced high rainfall totals over a period of days, but did not show that high daily rainfall rates were associated with convective thunderstorms. This was an unusual summer event caused by slow moving cyclonic systems which led to persistent rainfall due to the ascent within the cyclone rather than due to the deep convection that is often associated with summer events. The air was not particularly moisture laden as sea surface temperatures around the UK were anomalously low, therefore the atmospheric river mechanism (Lavers, 2011) did not apply. The persistence of the rainfall in this particular case was accounted for by a stationary upper level trough which stalled over the UK. Similar upper level conditions can explain several of the severe Autumn flooding events however this type of weather pattern is quite unusual for the summer months.

The large numbers of highly localised summer flooding events which are often reported less well in the media than larger scale flooding events have not been as well documented and are therefore less well understood. However, one such event, the West Surrey thunderstorm of August 2006, which was analysed by Mayes (2007), concluded that a cold pool of air over the continent was the cause of instability when the temperatures across Surrey rose, generating around 935 J/kg of CAPE (Convective Available Potential Energy). The exact location of the heavy rains was then determined by a study of the local topography.

The role of CAPE in convective events is of great importance and is a useful quantity to analyse when investigating these events (Riemann-Kamp et al, 2009). It is defined to be is the amount of energy a parcel of air would have if lifted a certain distance vertically through the atmosphere. Another way of describing this would be to state that CAPE is the positive buoyancy of an air parcel and is therefore a good indicator of the atmospheric instability at that point. This makes it a very useful predictor of severe weather produced by convection. In the large plains of the US where tornados are common CAPE can exceed values of $5000Jkg^{-1}$, however in the UK, values of over $1000Jkg^{-1}$ would be considered to be high.

2.2 The UK raingauge network

The UK has one of the densest networks of raingauges in the world, with nearly 4000 raingauges taking hourly, daily and monthly rainfall measurements. The coverage is greatest in and around London and across the Midlands, with Wales having the lowest raingauge density. Around 50 raingauges have a data record which spans over 100 years with some dating back to the 1880s, although there are often large blocks of missing data. Over 1500 raingauges have records which span 30 years or more. Figure 2.4 shows the current network of weather stations in the UK however there are also a number of stations not shown here which measure rainfall only, in order to increase the density of the network.

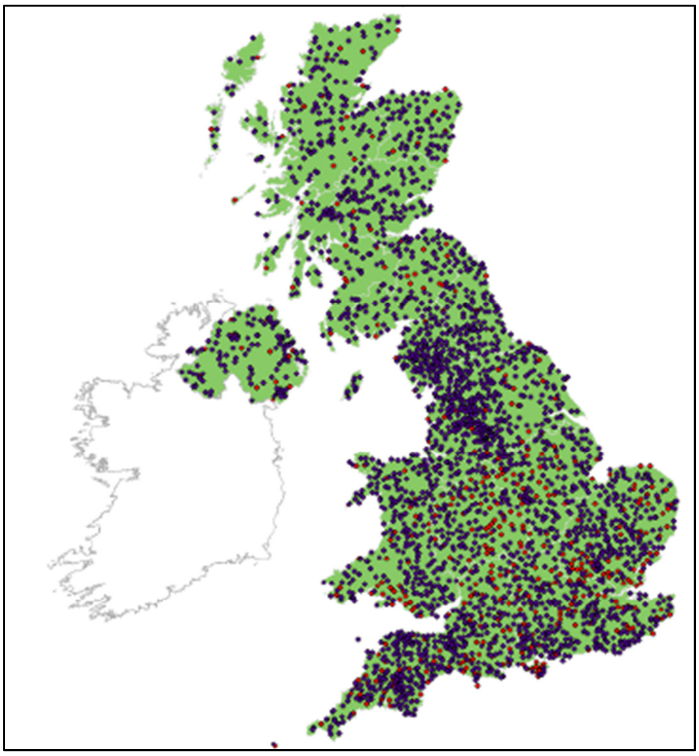

Figure 2.4: *Distribution of UK raingauges (Image courtesy of the UK Met Office)*

Rainfall data from the UK Met Office network of raingauges, obtained from the British Atmospheric Data Centre's MIDAS (Met Office Integrated Data Archive System), was used in this project to build up a profile of the rainfall history for a number of different locations in the UK. Observations were taken from the WADRAIN (Water Authorities Daily RAINfall) stations within this network, which transmit daily precipitation amounts from observations which are recorded predominantly by a 5 inch raingauge, with rainfall accumulation measurements being recorded to the nearest 0.2mm. A tipping bucket raingauge is the type of gauge which has been used for many years by the UK Met Office for automatic rainfall measurement and is the most widely used. All measurements are quality controlled by the Met Office although there are sometimes difficulties with missing data or equipment failure and the quality of data can vary from region to region.

Figure 2.5 shows that there are a large number of stations which are no longer operational. This is often because a weather station is closed and relocated to an alternative location which may be just of few kilometres or even metres away, so it is sometimes possible to use the two sets of data to form a continuous time series.

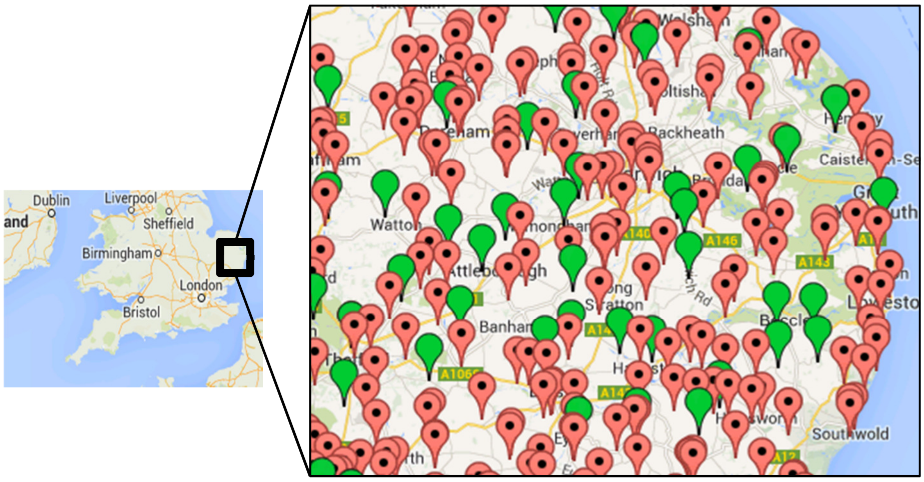

Figure 2.5: *Distribution of rain gauges across an area of East Anglia, showing the density of raingauges. Green markers represent raingauges currently in use, red markers represent raingauges with are no longer operational, but for which data is available. Image taken from British Atmospheric Data Centre website (http://badc.nerc.ac.uk)*

2.3 Extreme Value Theory

Extreme Value Theory is a statistical method which was developed to calculate the stochastic behaviour of a process at either very large or very small values. Extrapolation techniques are used to estimate the probability of events that are beyond the limits of those which have already been observed. It is used widely in a number of disciplines such as the financial industry, engineering and hydrology as well as in meteorology

When fitting a probability distribution to a set of events, the tail end of the distribution is often modelled incorrectly as shown in Figure 2.6. It is often the case that the model underestimates the extreme events, leading to an error in this part of the distribution. This could be because, by definition, there are fewer data points in the tail and models are generally chosen to fit the part of the distribution with the greatest observation density. Extreme Value Theory uses theoretical techniques to model only the tail end of the distribution and aims to achieve a more accurate fit.

Before a distribution can be calculated a method of selecting extreme values from the data set must be established. The two commonly used methods are the block maxima method and the Peak Over Threshold method.

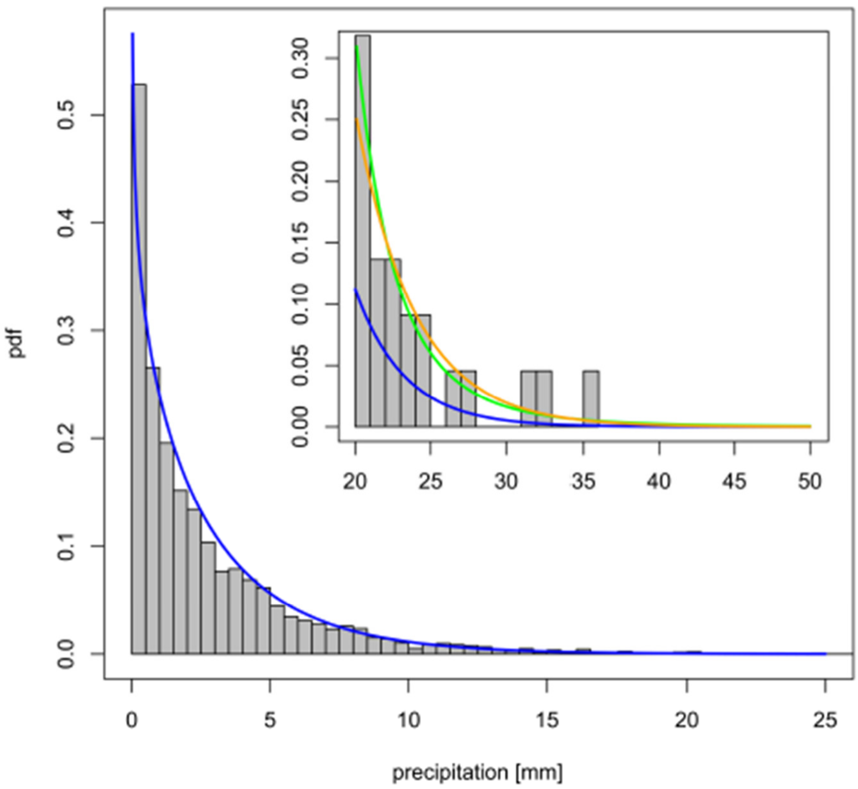

Figure 2.6: *Probability distribution of a set of observations. Inset shows that the distribution tends to underestimate extreme events, therefore it is necessary to use a separate distribution for this part of the data set. The blue line represents the normal distribution. The green and orange lines in the inset represent distributions calculated using extreme value distributions (Maraun, 2014).*

2.3.1 Block Maxima Method of Data Selection

The observation period is divided into blocks of equal width as shown in Figure 2.7, and the maximum data value within each block is extracted for analysis. This method can however miss some of the extreme observations and retain some of the lower value ones, and hence does not always make best use of the data available. This would be particularly true when sampling rainfall data, as the extreme events are not necessary evenly distributed throughout the observation period. The block maxima method may be useful if, for instance, there is a periodicity in the data which leads to, for example, yearly maxima.

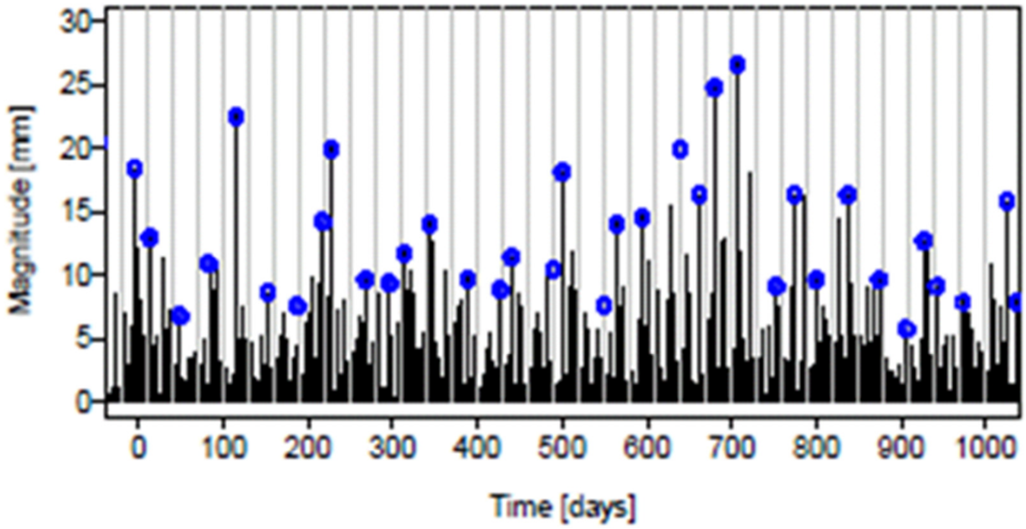

Figure 2.7:*Block maxima method for extraction of extreme events. The events identified by the blue circles are the maxima in each block, however is can be seen that some of the extreme events are not identified by this method if, for example, two high observation lie within the same block. If all the observations in a particular block are low, then a low value will be extracted from the dataset and used to calculate the probability distribution. Maraun (2014)*

2.3.2 .Peak Over Threshold (POT) method of data selection

A suitable high threshold is chosen and all observations above the threshold are retained for analysis. In this way, all extreme values are utilised. The choice of threshold level alters the probability distribution of the data, so it is important to choose a value which extracts only events which can be deemed to be extreme, but also allows there to be a sufficient number of observations with which to construct a probability analysis. This method of data selection seems more appropriate for the type of data being analysed in this project.

2.3.3 Probability Distribution

The two most widely used families of probability distribution used for extreme values analysis are the General Extreme Value (GEV) and the Generalised Pareto Distributions. The Generalised Pareto Distribution (GPD) is more commonly used when using a POT data selection method and was therefore chosen for this investigation. A comparison of GEV and GPD is carried out as part of an investigation into rainfall classification by Jones (2014) and the merits of the use of GPD for rainfall analysis is presented.

Usually, an empirical cumulative distribution function is used for the regions where there are many available observations and the GPD is used only for the tail. It is specified by three parameters, location μ, scale σ which is a measure of the spread of the distribution of the function and shape ξ. The following theorem outlines the main GPD result (Coles, 2001).

If X_1, X_2, ……. are a sequence of random independent variables which have a common distribution function F, let

$$M_n = \max\{X_1, X_2 \ldots\ldots\ldots X_n\}$$

For large n, the probability distribution function is given by

$$P_r\{M_n \leq z\} \approx G(z)$$

Where z is a variable in the non-degenerate function, G and

$$G(z) = exp\left\{- \left[1 + \xi\left(\frac{z - \mu}{\sigma}\right)\right]^{-\frac{1}{\xi}}\right\}$$

for μ, σ > 0 and for ξ.

For a large enough threshold, u, the probability distribution function for the POT distribution of (X – u) for X > u is given by,

$$H(y) = 1 - \left(1 + \frac{\xi y}{\tilde{\sigma}}\right)^{-\frac{1}{\xi}}$$

where $\tilde{\sigma} = \sigma + \xi(u - \mu)$

2.3.4 Threshold Selection for GPD

Too high a threshold will lead to a high variance in the resultant distribution, because there will be too few observations with which to estimate the distribution. Too low a threshold will produce a distribution with a bias, therefore it is necessary to find a balance between bias and variance when choosing threshold levels. It is usual to adopt a method whereby the lowest possible threshold which provides a reasonable approximation to the limit model is used.

One method of estimating the threshold level is to calculate a mean residual life or mean excess plot. This is a plot of threshold value against the mean excess i.e. the mean value of X_i – u. If this plot, for $u > u_o$, where u_o is some high threshold is a straight line, this indicates that the threshold does not produce a distribution with too many points, i.e. the bias is not too great.

The second method of selecting a suitable threshold is to fit a GPD to a range of thresholds and look for stability in the shape parameter, ξ. If a GPD with shape parameter ξ and scale parameter σ_{u_o}, is the correct distribution for a high threshold u_o, then if the threshold is increased further, so that $u > u_o$, the excesses will be a GPD with shape parameter ξ and scale parameter

$$\sigma_o = \sigma_{u_o} + \xi(u - u_o)$$

This leads to a modified scale parameter

$$\sigma^* = u_o - \xi u$$

Therefore if excesses X_i - u are modelled for $u > u_o$ using a GPD, both σ^* and ξ should be constant as the threshold is increased.

3. Data and Methodology

3.1 Rainfall Data

Following consultation with Catlin group, a number of locations in the UK were identified which would be of interest for analysis. The main reason for the choice of locations is the presence of a number of caravan sites and holiday homes which are prone to flooding. It would therefore be useful to understand the risks and probabilities of flooding events occurring in these areas, particularly during the summer tourist season, in order to assist with the pricing of insurance. After taking Catlin's requirements into consideration, it was decided to focus on the areas shown in Figure 3.1, all of which have suffered from flooding events in the past. The size and shape of each area under investigation was determined by taking into account the local topography and by finding a region which is fairly homogenous, so that any variations in rainfall across the region would be determined predominantly by the state of the atmosphere at the time of the observations.

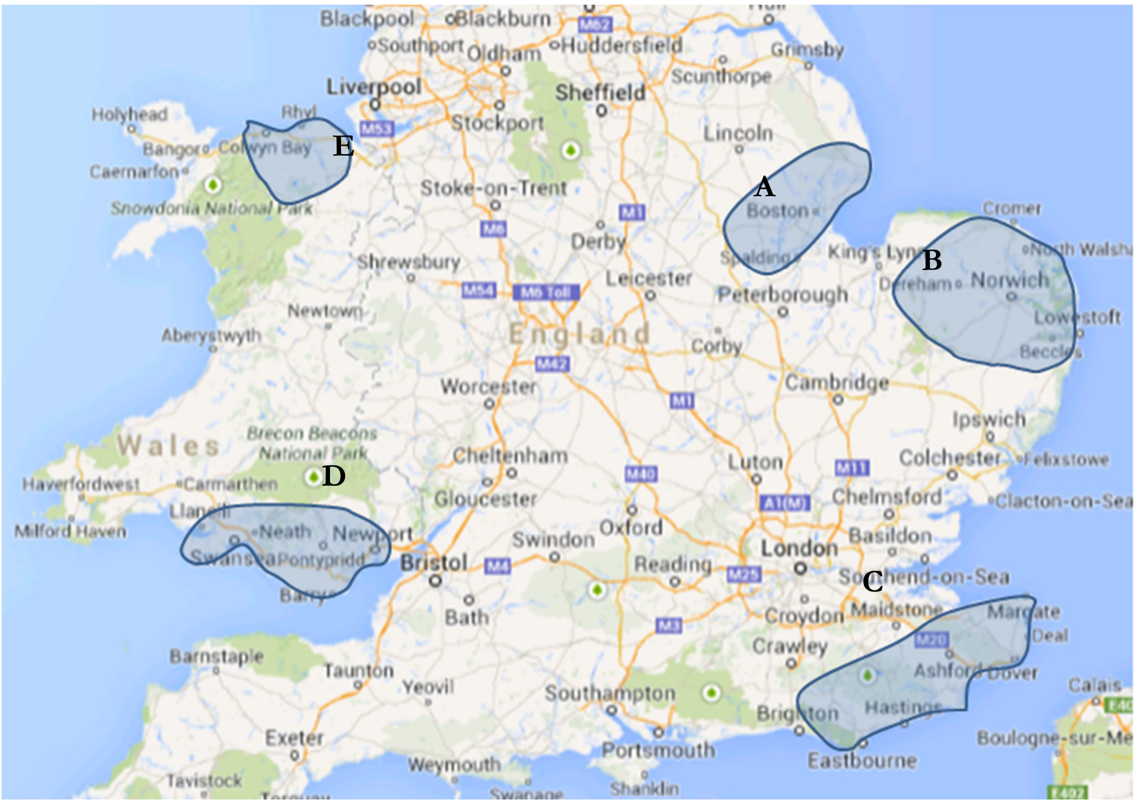

__Figure 3.1:__ Areas selected for investigation of extreme rainfall events.

Apart from meeting Catlin's requirements, the five regions chosen provide a diverse selection of location and topography, by covering both the East and West coasts of the UK and by presenting areas with both flat and hilly terrains and a range of river catchments and soil types.

Region A: This coastal region in the South East of Lincolnshire is in a flat part of the country with very few obvious raised topographic features. The nearest major river is the Trent which does not pass directly through the region, but there are many smaller rivers and tributaries within the area. Several of the towns and villages have been prone to flooding in the past. Flash floods are not uncommon and the coastal town on Skegness has also suffered from coastal flooding.

Region B This area is also fairly flat, but contains a network of rivers and waterways, the Norfolk Broads, to the East of Norwich and towards the coast at Great Yarmouth. Flash flooding has been experienced at several locations, with the town of Norwich being affected on several occasions.

Region C: This region covers the Kent coastline and inland areas. The main rivers in this region are the Medway and the Stour which, along with their tributaries cover much of the area. Apart from the Kent Downs which run through the centre of the region, most of this area is fairly flat. There do not appear to be large numbers of floods recorded in this region. Whether this is due to a lack of historical records or to a lack of flooding is unclear at this point.

Region D: Trecco Bay and the surrounding area is located to the south of the hilly area of the Brecon Beacons National Park and has a predominantly hilly landscape. It is bordered to the East by the River Severn, with the main rivers within the region being the River Usk at Newport and the Rivers Taff and Ely at Cardiff. Although there is some indication of summer flooding, the most severe floods in this area appear to be during the winter months.

Region E: This region around the coastal town of Rhyll contains many minor rivers and streams. The main river in this area is the Clwyd which enters the sea at Rhyll. The region is covered by low lying hills with the more mountainous Snowdonia National Park lying to the West, just outside the area under investigation.

3.1.1 Daily Rainfall Data Collection

It was found that to collect data from all the raingauges in each region was beyond the scope of this project. Therefore ten raingauges were identified in each region, shown in Figure 3.2, and daily rainfall data obtained from the British Atmospheric Data Centre (http://badc.nerc.ac.uk/) was collected and processed in order to obtain a time series of observations for all selected raingauges.

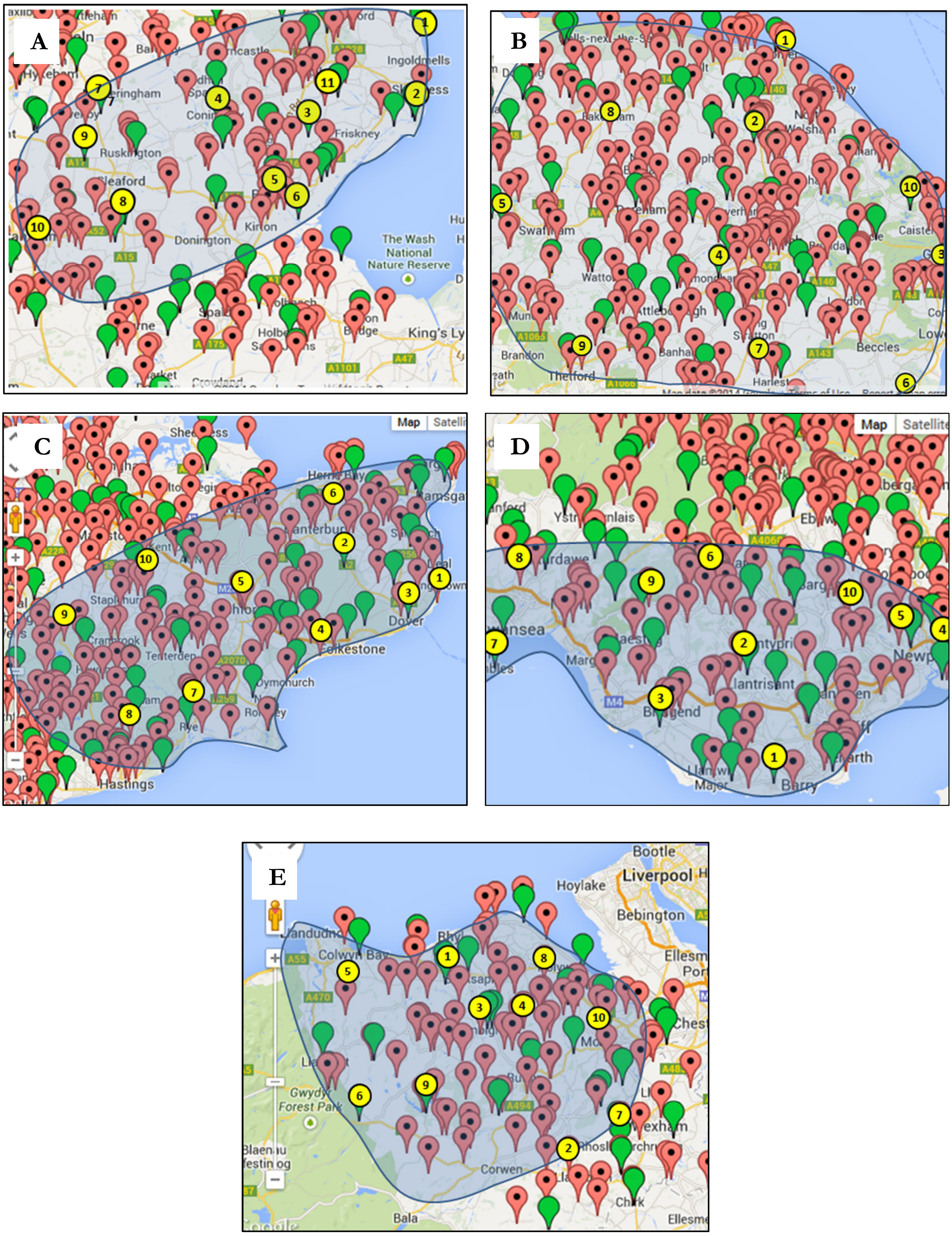

Figure 3.2: *Ten raingauges in each region chosen for detailed analysis.*

The selection of the raingauges was based on their spatial distribution and quantity of available data.

It was found that the observational data often contained gaps of a few days or weeks, which impedes statistical analysis. In the instance when a raingauge was located in an area with sparse coverage and had no neighbouring raingauges, there was no way of overcoming this problem and it was necessary to simply work with the longest available time series of observations. There have been many approaches used to fill in the missing data from time series. The commonly used kriging (Jeffrey, 2001), or more complex methods such as the Artificial Neural Network models (Kim and Pachepsky, 2010; Khorsandy, 2011) have been proposed to reconstruct the gaps is precipitation databases. However simpler methods (Tardivo and Berti, 2013) including a linear regression method, an inverse distance weighted method and a nearest neighbour method have been proven to be effective and are suited to the data under analysis in this project.

The simplest method is the 'nearest neighbour' method, which aims to find the station with the highest correlation to the target raingauge within a given search radius. Tardivo et al (2013) used a radius of 15km and a minimum Pearson correlation threshold of $r = 0.5$, but because of the high density of UK raingauges and the highly localised summer precipitation events, it was decided to use a radius of 10km. Any gaps in the data from the target raingauge are then simply filled with data from the closest raingauge to meet the correlation threshold requirement.

This is certainly not the most accurate method of filling in missing data, although for a very dense network of raingauges such as is found in the UK, accuracy is substantially increased (Serrano, 2009). Methods which use several surrounding raingauges with weighted coefficients would improve accuracy however it was decided to use the simplest method for the purpose of this project.

The main problem with any method of precipitation data reconstruction for extreme events is that if a highly localised extreme event is missing from the target raingauge, there is no way of reconstructing this using data from the surrounding raingauges.

Although daily rainfall data was collected for all raingauges in the areas shown, ten gauges were selected in each region for detailed analysis as shown in Figure 3.2. These raingauges were chosen by selecting those with the longest time series' of data and by aiming to achieve a good spatial distribution across the target region. Temporal coverage was very dependent on location.

For example, Region E in North Wales has very little rainfall data from before 1961, whereas the raingauges in Region A, Lincolnshire, can sometimes provide data from before 1900 until the present day. The details of the selected raingauges with start and finish dates for the observations is given in Appendix A.

3.1.2 Identification of Extreme Precipitation Events

Determining the precipitation threshold when identifying extreme events across a region is a subjective process and the choice of a sensible threshold level varies considerably depending on location. In the UK, average annual rainfall varies markedly across the country, so it is reasonable to assume that precipitation thresholds for extremes will also vary with location. Ideally, the threshold for an extreme event should be determined for each individual location because of the limited spatial scale of summer convective events. However, for the purpose of this project this is not a practical method of analysis, so a fixed threshold was used for initial analysis.

An alternative method for extracting extreme precipitation events is the percentile method whereby all events above a particular percentile of the observational values are classed as extreme. This method was also implemented, in order to give a threshold specific to each region.

An analysis of historic flood data provides an indication of the lowest rainfall values above which flooding could occur. Figure 3.3 (Hand et al, 2004) which shows the duration and rainfall amounts of 50 flooding events from 1900 onwards, indicates that flooding events can occur with as little as 50mm of precipitation, although it is important to note that this amount falls in approximately half an hour. This method of classification was derived from a method set out in the Flood Studies Report II (1975) which uses a criteria for event selection established by making use of the point rainfalls as the 'maximum' falls possible for durations of less than 1 hour, and the one in one hundred year return period for durations greater than one hour (Hand et al, 2004).

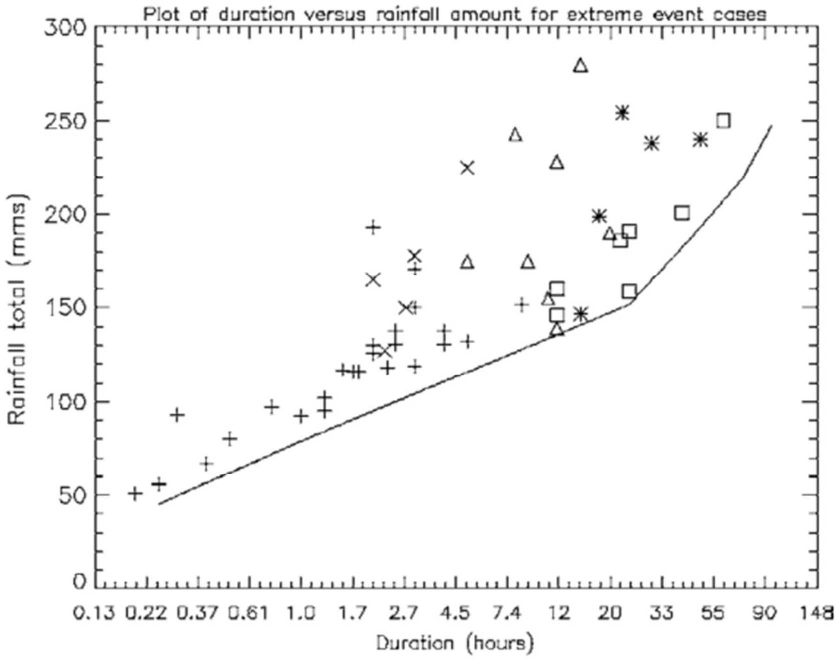

***Figure 3.3**: Top 50 flooding events from 1900. + indicates convective event, Δ indicates frontal event. Solid line indicates lowest threshold for extreme event classification - classification determined from Flood Studies Report records of maximum rainfall amounts (Hand et al, 2004)*

This project only makes use of daily rainfall data, rather than hourly or sub-hourly data which makes the identification of extreme precipitation challenging for summer rainfall events, as many events last only a few hours and the duration of the precipitation is a large factor in deciding whether or not the event should be classed as extreme. Unfortunately, obtaining high quality hourly records was problematic and not considered practicable within the scope of this project. 50mm of rain falling over 30 minutes may be enough to produce a flood, but the same quantity of rain falling over 24 hours is unlikely to produce a similar flooding event. It is therefore necessary to identify extreme events by first examining flood data and then comparing this data with rainfall data in order to gain an insight into the rainfall levels required for flooding to occur in various locations.

3.2 Historical Flood Records

Historical flood records come from a diverse range of sources. Some of the more descriptive sources of data can often provide insightful information into the nature of flooding which is not present in more quantitative flood information.

Interestingly, it is more difficult to find comprehensive flood records for more recent years than for floods which occurred in the first half of the 20th century. Older records tend to be more qualitative in nature and documented in greater detail which often leads to a greater understanding of the exact location of the flood and the subsequent damage incurred. For example, this written report of the 1937 Lincolnshire floods in the Yorkshire Post reports:

" Electricity supplies in the north of Lincolnshire have been cut off, road and rail traffic held up, streets flooded and people trapped in their houses following the worst thunderstorm Lincolnshire has experienced for many years. Damage, to the extent of thousands of pounds, was done by this storm, the main streets being under water in some places to a depth of over two feet. About 17h. the sky darkened and there was violent thunder and lightning followed by torrential rain and a gale. Visibility was reduced to a few yards, the headlights of cars failing to penetrate the falling rain to any appreciable distance. A landslide occurred on the South Park embankment of the main line from Lincoln to Grantham and the line was impassable. The River Witham overflowed in several places, one place nearby being flooded to a depth of four feet. The Foss Dyke near Lincoln rose five feet in an hour. Trees fell in two roads, holding up traffic and breaking down telephone lines. Over 500 lines were dislocated by the storm.

The following report refers to the 1931 flooding event and gives details of tides, locations of the worst flooding etc.

"The point of maximum rainfall appears to have been immediately south of Boston and the worst flooding occurred in the Borough and the parishes of Skirbeck Quarter, Wyberton, Frampton and Kirton. Flooding elsewhere in the district was of a temporary character and the land surfaces were generally clear by the afternoon of the 9th, although the main drains and rivers were swollen. The floods in and surrounding the Borough were intensified by a neap tide which closed the automatic drainage sluices for a long period. For instance, the flood doors at Black Sluice, at the outfall into the River Witham, were closed from 8h. 45m. until 15h. 25m. and low lying streets were flooded in places to a depth of four feet."

Much of the data used in this project from before 1966 was collected from *British Rainfall* which has proved to be an invaluable source of information. This is a Met Office publication which is has been produced every year from 1900 until 1966. The sections on heavy rainfall provide dates and locations of extreme rainfall events and comments on the areas in which flooding has occurred. The *Met Office monthly weather report* (http://www.metoffice.gov.uk/archive/monthly-weather-

report) and *Roger Brugge's UK weather diary* (*http://www.met.rdg.ac.uk/~brugge/diary.html*) were also invaluable and concise sources of information , particularly for more recent events.

The journals *Weather* and *The Journal of Meteorology* give accounts of more recent flooding events and local and national newspapers contain information on the more extreme floods, often with eye witness accounts which are useful in identifying the nature of the flood damage.

The British Hydrological Society's *Chronology of British Hydrological Events* (www.dundee.ac.uk/geography/cbhe) is a database which was launched in July 1988 to cover all hydrological events. It aims to improve access to historic information by relying on contributors to draw on sources such as newspapers, diaries and published accounts of major hydrological events. It contains over 6000 entries and has been a useful source in identifying some of the smaller events which are not covered in journals. Many of the events recorded in this database are from personal records and, whilst they make very interesting reading, it is sometimes difficult and time consuming to filter the relevant information as can be seen from the following record of the floods in South Wales in July of 1907.

The Thunderstorms of July 21st and 22nd, 1907 1907 July 21/22 Mr J.S.Masterman was quoted "It is extraordinary what an amount of rocks and trees the infant Senny has uprooted ... the flood was about 4p.m., on Sunday July 21st. There was a big thunderstorm up there on the 20th and 21st, but the flood that nearly swept away the little farm of Llwyn Llydan, the highest in the glen, only lasted an hour.--- as a boy who lives there told me ..... The Gihiyrch stream is the chief feeder of the new Swansea [Cray] reservoir. The chief man among the reservoir keepers told me that the cloud-burst tore great rents in the hillside near the source of the Gihiyrch, and the stream carried such a lot of stuff into the reservoir that Swansea could not drink it. For three weeks the Usk was so foul from the overflow of the reservoir that they could not fish. Then they got the reservoir people to flush the river with the clearer water from the surface of the reservoir (it seems the regular covenanted supply comes out at a lower level) and so things got right. The Usk, however, above the junction of the Cray and the Senny remained clear all the time. Therefore the cloud-burst must have been concentrated on a very limited area near Bwlch y Duwynt.

From the sources above, summer flooding events which took place in the selected regions in England and Wales since 1900 were identified. Maximum rainfall observations, rainfall duration and any indication of the type of weather system producing the flooding events were noted when applicable.

This information was then compared with the raingauge data in order to find the relationship between flood events and extreme rainfall events. Any, floods which were identified in the historical flood record, but were not picked up by the extreme rainfall data were also noted.

The following sources proved to be the most useful in identifying past flooding events:

1860 – 1899	Symons British Rainfall
1900 – 1966	British Rainfall
1953 -	Weather
1844 -	Journal of Meteorology
1091 -	Chronology of Hydrological Events
2001 -	Roger Brugge's UK weather diary
1884-1993	Met Office Monthly Weather Report
	National Newspapers
	Local Newspapers

Table 3.1: *Useful sources of historic flood data*

3.3 Atmospheric Reanalysis Data

Atmospheric reanalyses are considered to be a best estimate of the historical state of the Earth's atmosphere. The data used to analyse the antecedent atmospheric conditions to flooding events was collected from NOAA's 20th century reanalysis product. This is a global gridded reanalysis product, which assimilates meteorological and oceanic observations into Numerical Weather Prediction model output to produce an atmospheric data set between 1871 and 2012, with a resolution of 2x2 degrees. Mean sea level pressure (MSLP), vector wind at 950mb, CAPE (Convective Available Potential Energy) and atmospheric precipitable water were determined to be the key parameters for this investigation. All reanalysis images are provided by the NOAA-ESRL Physical Sciences Division, Boulder Colorado (http://www.esrl.noaa.gov/psd/).

Although alternative reanalysis datasets which assimilate satellite data and atmospheric soundings in addition to the surface observations used in the NOAA 20th century reanalysis may achieve greater accuracy, in order to maintain consistency between events which take place over a long period of time it was decided to use the NOAA product for all observations. Compo (2011) provides a review of the product outlining some of its strengths and weaknesses.

The results of the investigation into the atmospheric conditions surrounding flooding events is presented in chapter 6.

4. Analysis of Rainfall Data

4.1 Daily Rainfall Observations

An examination of the raw daily rainfall data showed that the majority of data from the selected stations contained a significant number of missing observations and only a few raingauges yield a time series of continuous data which is long enough to perform a statistical analysis. Figure 4.1 shows the available data for each of the raingauges identified in section 2.5. Although many of the weather stations have been collecting rainfall data since 1900, daily rainfall data collection is less common than monthly data collection, with daily rainfall observation becoming more common in from the 1960s onwards.

In addition to the difficulty with missing observations, it was found that there were several issues with data quality control which needed to be corrected prior to analysis.

Errors in the raw data were as follows:

- During certain time periods the data consisted of observations only on the first of every month, leading to a large number of gaps in the observational data series. It was also found that there were periods of time when there was a spike in the data on the first of every month. There errors could be due to either monthly rainfall data being incorporated into the daily rainfall data series, or could possibly be attributed to a test data signal being transmitted on the first of the month. This was corrected by removing the data observation when a spike, defined as an observation greater than 300mm/day, was found on the first of any month (the highest daily rainfall observation to date in the UK is 270 mm http://www.metoffice.gov.uk/climate/uk/extremes/#rainfall). Of course this led to the problem of a break in the time series and if an extreme event happened to fall on one of the days on which an observation was removed, then this event would be missing from the data. An alternative solution would be to simply remove all readings from the 1st of every month, with the risk of losing an extreme event observation.

- Obviously erroneous readings, such as daily rainfall observations of over 600mm/day were found in the raw data. Obviously incorrect observations were infrequent – around one every 50 years – but of course there could be other errors which are not identifiable by inspection alone. Excessively high observations which do not appear to coincide with a historical rainfall event were removed from the data series by using the same threshold of 300 mm/day.

- The raw data often contained multiple observations per day within the daily rainfall data. In order to correct this problem it was decided to take the maximum value for that day and to ignore all other readings which plausibly could be readings taken at earlier times during the day.

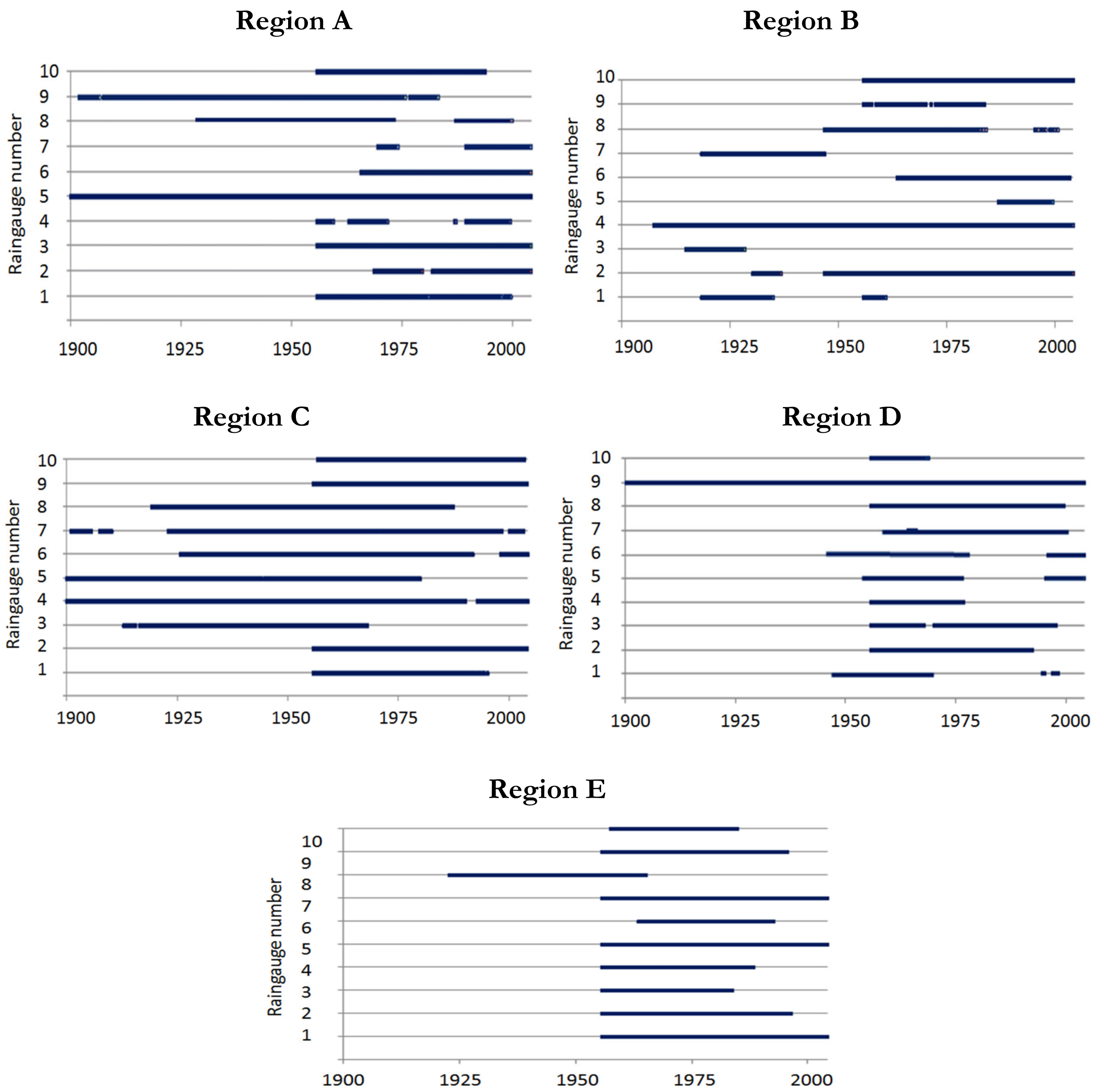

Figure 4.1: *Graphs show the time periods for which data is available for each of the selected raingauges from 1900 - 2014. Gaps in the blue lines indicate that no data is available for this time period. The vertical axis gives the raingauge number which corresponds to the numbers shown in Figure 3.2*

From 1961 onwards there is an increase in the number of raingauges producing daily rainfall data, particularly in the Welsh regions D and E, but as can be seen from Figure 4.1 there are still many gaps in the observations. Note that many of the time series shown appear to be complete, but the smaller gaps of a few days rather than a few months are not visible in the plots.

4.2 Establishing Continuous Time Series of Rainfall Observations

Figure 4.2 shows one of the selected raingauges (gauge 4, Region A) along with the surrounding raingauges which were used to fill the gaps in the observations using the method described in section 2.5. This particular raingauge is in a location which has a high density of weather stations (6 stations within a 10km radius), whereas is some parts of the country, such as Wales, there are far fewer gauges therefore it becomes more difficult to obtain a continuous time series of daily data which spans several decades. The South East of the UK has a raingauge density of approximately 3 raingauges in every 10 square kilometres, whereas in Wales the density drops to around 1 raingauge in every 10 square kilometres.

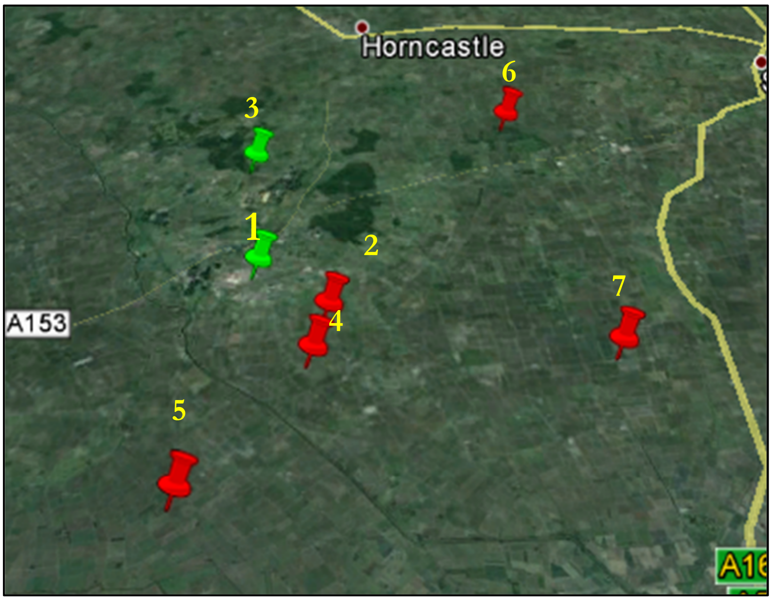

Figure 4.2: *Stations within a 10km radius used to fill in missing observations of the chosen raingauge (Raingauge 4, Region A). The 'key' raingauge is labelled number 1. The surrounding raingauges are numbered in ascending order according to their distance from key raingauge. The green pins indicate gauges at currently operating weather stations, whereas the red pins indicate weather stations which are no longer in use.*

The availability of daily rainfall data for each of the raingauges identified in Figure 4.2 is shown in Figure 4.3, with gauge number one being the key raingauge under investigation. The correlation, r, between the overlapping data for the key raingauge and each of the surrounding gauges was calculated and the data with the highest correlation was used to fill the gaps in the observations of the key raingauge.

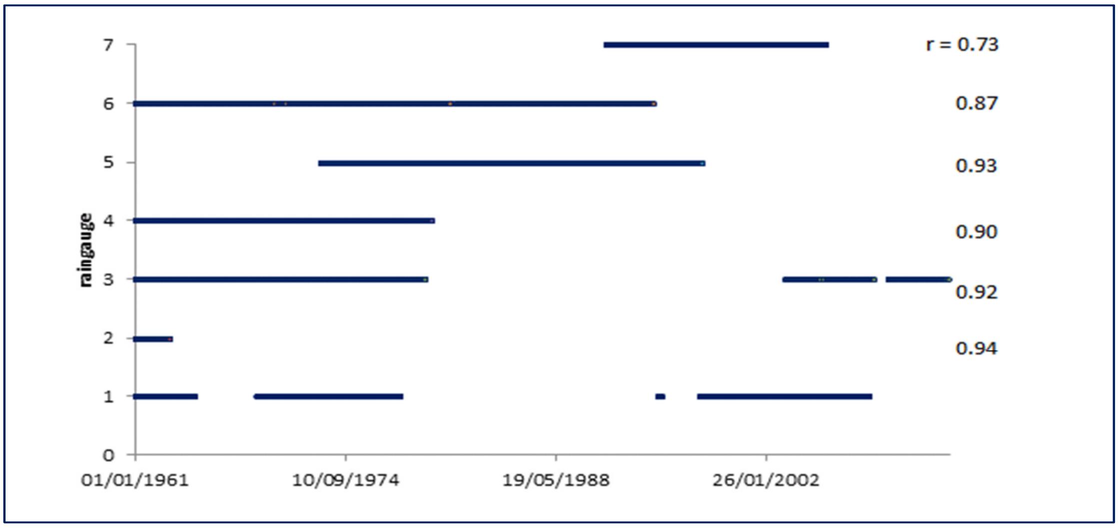

Figure 4.3: *Raingauge 1 is the key raingauge. Raingauges 2-7 are the surrounding raingauges used to fill in the missing data. r is the correlation coefficient for each gauge when its data is compared with data from the overlapping time periods from raingauge 1.*

Despite seeing a high correlation between the key raingauge and the surrounding raingauges, the high spatial variation of rainfall in the summer means that this method of producing continuous time series could result in data which contains a bias being used to fill the gaps in the data. These biases could arise because one of the surrounding gauges is, for example, sheltered by topography and therefore receives less rainfall than the key raingauge despite its proximity.

In the case where there is data available from 2 or more of the surrounding raingauges for a particular date, the observations from the raingauge which exhibits the highest correlation with the data of the key gauge, rather than the nearest raingauge, is used to fill the gap in the time series.

By applying this technique to each of the chosen raingauges it was possible to obtain continuous daily rainfall data observations for periods of at least 48 years for all but 5 of the 50 selected raingauges, where there was insufficient data available due to the low density of raingauges in the areas. The 5 raingauges were all located in the Welsh regions D and E where it was possible to construct a continuous series of data spanning 35 years. It was possible to obtain a time series of continuous observations of 112 years for 2 raingauges in Region A and 2 raingauges in region B.

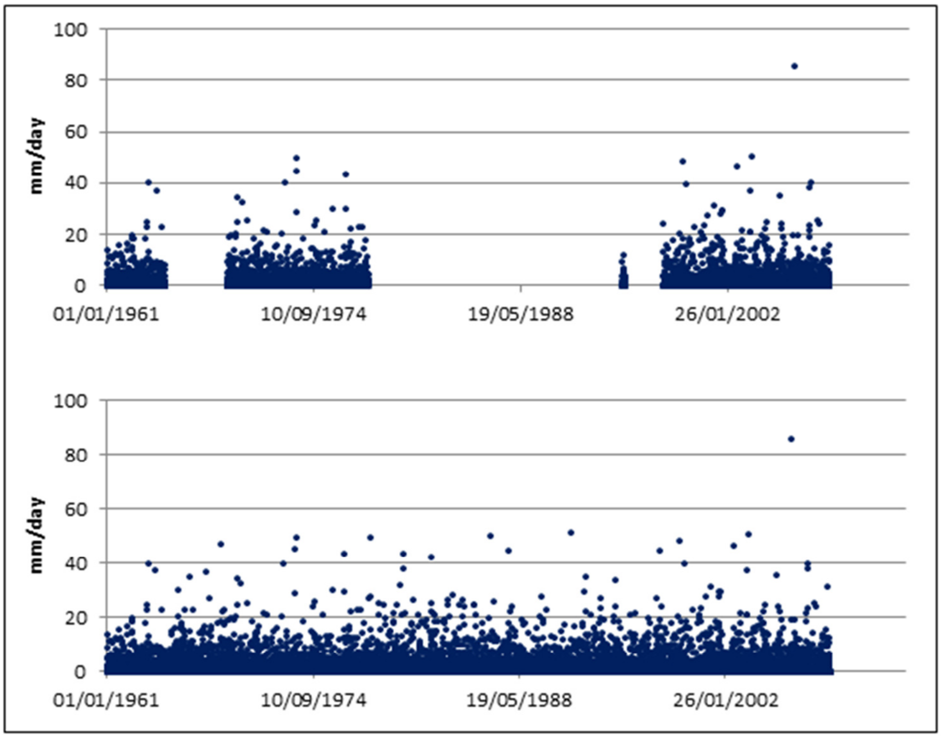

Figure 4.4: *Daily rainfall observations for raingauge 4, Region A. The upper plot shows the raw data taken directly from the raingauge readings. The lower plot shows the time series with the gaps filled by data from surrounding raingauges from 1961 – 2009, giving a total time span of 48 years of continuous rainfall data.*

4.3 Application of Thresholds to Rainfall Time Series

It was decided to use an initial threshold of 60mm/day of rainfall for all regions and to investigate all events which lie above this threshold. A lower threshold for flooding events of 50mm/day which was identified by Hand (2004) allows short duration extreme rainfall events of typically less than 30 minutes to be included. It was found that if this threshold was used, a large proportion of the events identified were not flooding events and without hourly rainfall to determine the duration of the event it was difficult to analyse these low intensity rainfall events, which may potentially be flooding events if the rain fell over a short time period. The threshold of 60 mm/day will of course lead to the exclusion of some of these very short events, but it also allows all events above the threshold to be investigated, as the numbers are of a more manageable size.

Events were identified by first taking the maximum daily rainfall across all the selected raingauges within each region, and then applying the 60mm threshold to these maximum values. This data was then compared with historical flood data in order to identify the events which led to flooding as opposed to those which were simply heavy rainfall events.

Although many summer flooding events are caused by short intense rainfall, it is useful to also look at extreme rainfall events which span a period time greater than 24 hours. By calculating the 3 day and 5 day running averages for each selected raingauge it was possible to identify those longer rainfall events which are possibly frontal in nature. There was no obvious method for choosing thresholds for the extraction of extreme 3 and 5 day events, so arbitrary choices of 40 mm/day for 3 day events and 30 mm/day for 5 day events were used as a starting point.

Figure 4.5 show the daily, 3 day and 5 day events in each region which exceeded the chosen thresholds. When interpreting figure 4.5 it must be remembered that the number of raingauges in regions D and E before 1961 was very low, accounting for the scarcity of events identified during this period. Regions A, B and C have relatively better coverage from 1900 – 1961, but the quantity of available data improves in all regions after 1961.

The region with the least number of extreme events is Region C, the East Sussex/Kent area. This does not necessarily mean that this is the driest region, but rather that its rainfall events may be more moderate than in other parts of the country. Regions D and E in South and North Wales receive the largest numbers of 3 and 5 day events, indicating that as expected, the Western part of the UK suffers from more frontal extreme rainfall, as well as large numbers of daily extreme events. It can also be seen that in these two regions most of the daily extreme rainfall events which exceed the 60mm/day threshold are actually associated with longer lasting rainfall events. This is to be expected in this hilly region on the West Coast, which is exposed to frontal systems bringing longer rainfall events. It is important to note, however, that it is possible that flooding events may have occurred with daily amounts of rainfall which fall below the 60mm/day threshold. This will be investigated by a study of historical flood records to find any localised flooding events which have not been identified by the threshold method.

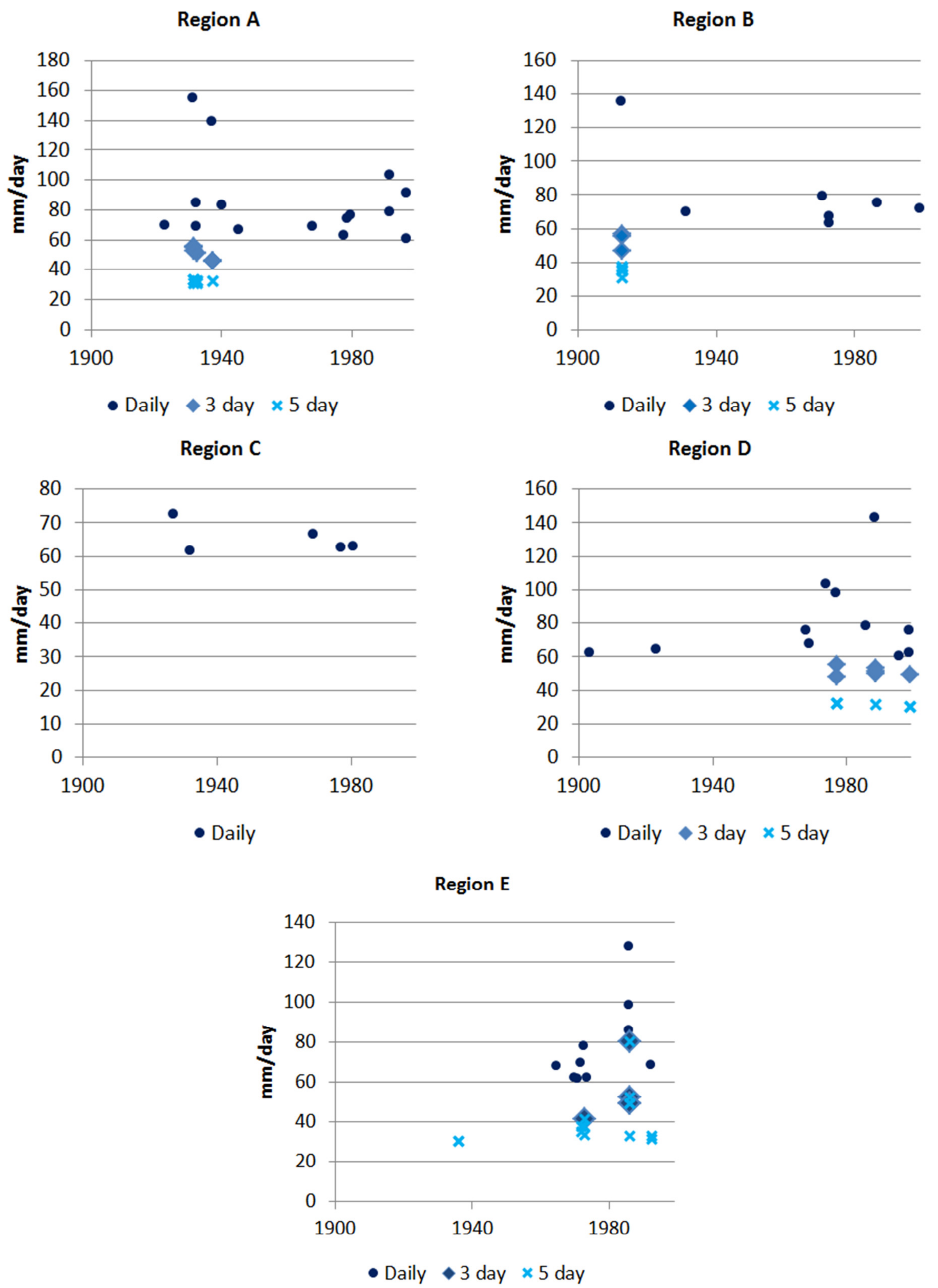

Figure 4.5: *Extreme rainfall events from 1900 – 2013. Plots show daily events > 60mm/day, 3 day events > 40 mm/day and 5 day events > 30 mm/day for all five regions. 3 and 5 day events are calculated by using a running average*

Region B in the Norfolk area has only one event, the famous storm of 1912, which is picked up by the 3 and 5 day thresholds. However, this area which is in a relatively flat, dry part of the country still receives a large number of extreme daily rainfall events which are likely to be due to convective events which could be triggered by instability in the atmosphere due either insolation or synoptic instability. Region A exhibits similar characteristics to Region B, with many daily extreme events and fewer events which are longer in duration.

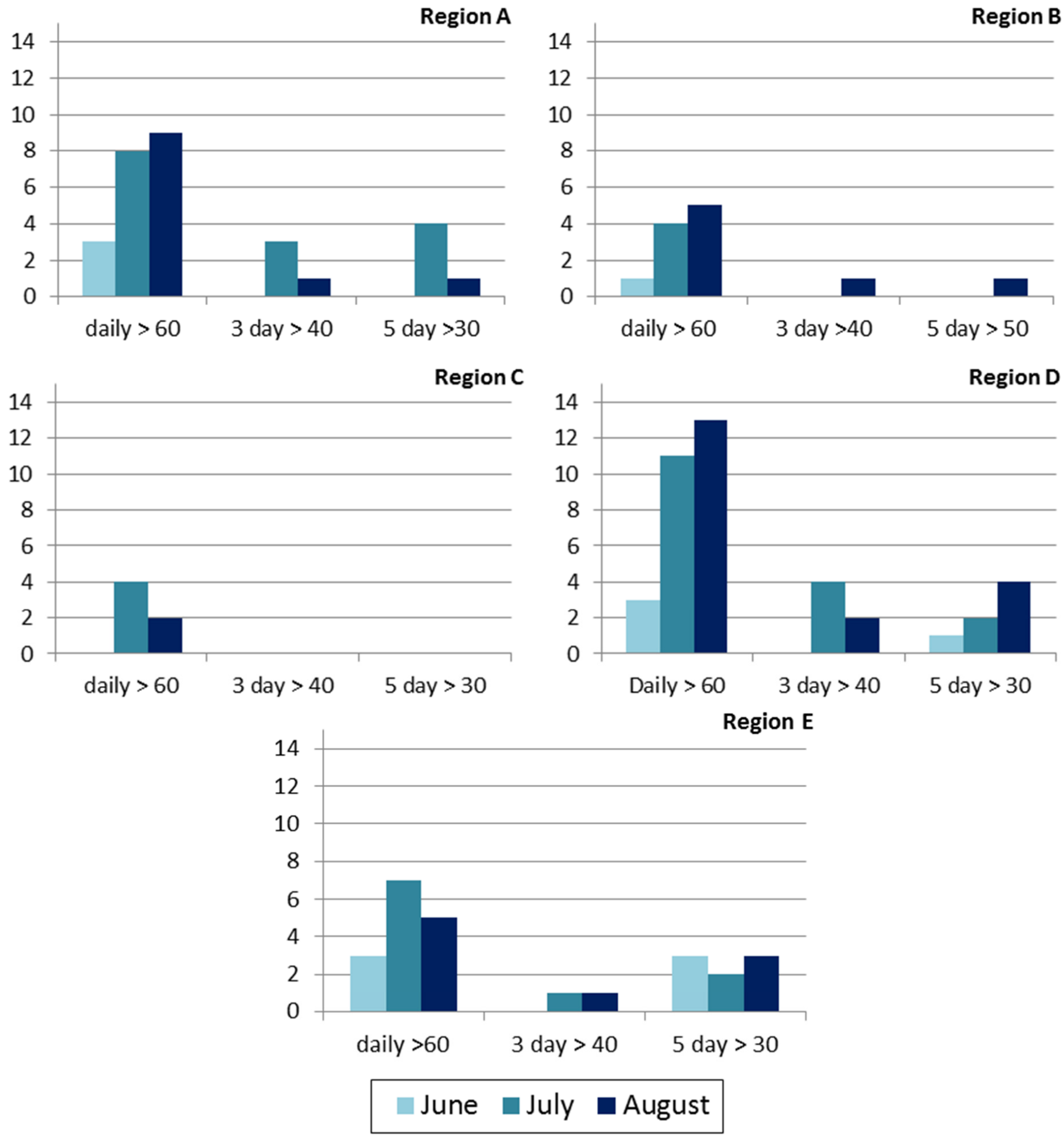

Figure 4.6: *Monthly distribution of events identified using the thresholds of 60, 40 and 30 mm/day for daily, 3 day and 5 day rainfall events respectively.*

Figure 4.6 shows the monthly distribution of all events which lie above the chosen thresholds showing that in all areas the maximum number of extreme rainfall events fell during July and August and with the exception of region E in North Wales, there are virtually no 3 or 5 day rainfall events in June. In fact, the number of events in June is generally very low, with a maximum of three events falling in any region. In contrast, the number of events falling in August is relatively high, with a maximum of thirteen events recorded in Region D.

4.4 Comparison of Raingauge Data with Historical Flood Records

Using the methods outlined, a comprehensive list all daily rainfall events which were recorded to be greater that 60mm was compiled (Tables 4.1 – 4.5). Some of these events have been previously identified in flood records and in these cases, the source of information is provided. Any events which have been found in the historical flood data, but have not been identified by raingauges data are also included in the list.

Although every effort has been made to determine the conditions and flood records for the events which lie above the 60mm/day threshold, there will be many localised flash flooding events which lie below this threshold which have not been identified in the flood records. Some of these events have been identified, but the list is unlikely to be comprehensive and a full study of all historic flood records would have to be carried out. It would be useful in future work to lower the threshold and investigate a larger sample of events, as it can be seen that in regions B and C in particular there are several flooding events which fall below the 60mm/day threshold.

Key for Tables 4.1 – 4.5:

No records of flooding found
Flood identified from historic flood data, but daily rainfall below 60mm threshold

Region A

Date	Rainfall (mm)	Notes	Source
07/08/1922	69.8	Heavy rainfall associated with a deep depression, but no flood record found	British Rainfall
09/08/1931	154.9	Boston flood. Frontal System causing widespread flooding	British Rainfall
14/07/1932	83.6	Cranwell flood	British Rainfall
16/07/1937	138.7	Boston flood. Frontal weather system	British Rainfall
11/07/1940	83.1	Frontal system. Heavy rainfall and flooding	Met office monthly weather report
30/08/1945	66.3	No flood record found	
11/07/1968	68.6	A Spanish plume weather pattern saw a low over the northwest of Spain track across the Bay of Biscay, hot and humid air advected to the eastern side of the low leading to severe storms and floods	British Rainfall
30/06/1978	62.4	No flood record found	
30/07/1979	74.3	Thunderstorms. Localised flooding reported.	Met office monthly weather report
15/08/1980	76.3	Flooding reported. A series of small depressions passing over the country	Met office monthly weather report
17/08/1992	78.5	No flood record found	
27/08/1992	103	Frontal system and reports of thundery showers	Met office monthly weather report
13/08/1997	61	No flood record found	
18/07/2001	66.5	Weybourne flood	Met Office Records
20/07/2001	90	Thunderstorms and flooding reported	Local press
31/07/2002	69.2	Reports of flooding across region	Met Office climate summary
16/08/2004	64.8	Date of Boscastle flood, but no reports of flooding in area	
04/06/2007	81.4	Widespread flooding. Frontal system	National press
25/06/2007	63.2	Widespread flooding. Frontal system	National press
20/07/2007	61.2	Widespread flooding. Frontal system	National press

Table 4.1: *Rainfall events above 60mm/day in Region A*

Region B

Date	Rainfall (mm)	Notes	Source
27/08/1912	135.4	Norfolk. Heavy flooding. Frontal event	Brooks (2012)
09/08/1931	69.8	Pulham Market	Hydrochronolog y database
08/07/1946		Bungay	Hydrochronolog y database
29/07/1971	79.2	Great Yarmouth severe floods reported from thunderstorms	Met office monthly weather summary
06/06/1963		Norfolk, Southery	Hand (2004)
01/08/1972		Heavy flooding in Norwich. Thunderstorms and outbreaks for thundery rain. 137.7mm rainfall recorded in Norwich.	Met office monthly weather summary
20/06/1973	66.5	No flood record found	
01/08/1973		Norwich	British Rainfall –
07/07/1973	62.6	Thunderstorms high temps	Met office monthly weather summary
26/08/1987	75	Heavy rains, possible flooding	Hydrochronolog y database
10/08/1999	71.6	Radio Norfolk reported that during a late morning storm 43 mm of rain had fallen in one hour at Lowestoft and there was severe flooding in the town	Roger Brugge weather diary
18/07/2001		There was also severe flooding in the Cromer - Sheringham area; every track and road had been turned into a river, the water was flowing across the fields from the hills behind Cromer and through the main car park and into Cromer High Street where it entered several shops	Roger Brugge weather diary
31/07/2002	88.3	Marham flood	Met Office climate summary
29/07/2008	79.8	Heavy thunderstorms. On the evening of the 26th, isolated thunderstorms broke out across East Anglia and the east Midlands. Later on the 28th, more-widespread heavy rain and thunderstorms developed in the south-west, and spread north-eastwards during the evening and night.	Met office climate summary
17/08/2008	84	Heavy thunderstorms Low pressure returned, with very unsettled and at times windy conditions. There were rain or showers, and many of the showers were heavy with thunder, especially for northern and eastern England.	Met office climate summary

Table 4.2: *Rainfall events above 60mm/day in Region B*

Region C

Date	Rainfall (mm)	Notes	Source
08/08/1913		Folkstone	Hydrochronology database
07/07/1927	72.4	Deal, Kent. Flooding reported. The thunderstorm rain caused by this instability was succeeded by continuous heavy rain, associated with the passage of the "warm front " of a depression	British Rainfall
26/07/1932	61.5	Reports an irregular distribution of thunderstorms	British rainfall
20/06/1958		Margate	Hydrochronology database
29/07/1969	66.3	Frontal system bringing heavy rain	Met office monthly weather report
27/06/1974		Thundery rain and flooding in Hastings	Met office monthly weather report
26/08/1977	62.5	Flooding reported Dartford. Depression moving up the English channel	Met office monthly weather report
01/07/1981	63	No flood record found	
29/08/2001	62.6	No flood record found	Met office climate summary
19/06/2007		Flash flooding throughout Kent	Local press

***Table 4.3:** Rainfall events above 60mm/day in Region C*

Region D

Date	Rainfall (mm)	Notes	Source
30/08/1903	62.2	No flood record found	
22/07/1907		South Wales flooding	British Rainfall
26/08/1923	64.8	No flood record found	
11/07/1968	75	Cardiff. Flooding	Hydrochronology database
29/07/1969	67.3	Frontal system bringing heavy rain and flooding	Met office monthly weather report
07/07/1974	102.6	Heavy rain, thunderstorms triggered by small depressions. Localised flooding	Hydrochronology database
23/08/1977	98.6	Frontal system bringing heavy rain. No flood records found, but may be unreported	Met office monthly weather report
26/08/1986	77.9	South Wales (Hurricane Charley)	British Rainfall (monthly rainfall)
02/07/1989	143.2	Frontal system bringing heavy rains. . No flood records found, but may be unreported	
12/08/1996	60.1	No flood record found	
10/08/1999	62	No flood record found, but fronts associated with a depression off SW England brought more heavy, thundery rain to England and Wales,	Roger Brugge weather dairy
27/08/1999	75.5	Reports of rain, but not flooding	
02/06/2000	75.8	No flooding reported, but weather reported to be rainy and drizzly	
27/07/2000	64.1	Thunderstorms and localised flooding reported	
28/06/2005	62.8	Heavy and thundery showers moved north across England and Wales. Torrential downpours and frequent flooding.	Met office climate summery
30/07/2005	70	No flood reported, but day of Birmingham tornado	
21/08/2006	60	No flood record found	
25/07/2007	103	Widespread flooding	National Press
06/07/2008	77.2	Thundery and warm	met office climate summary
08/07/2008	65	Thundery and warm. No flood records found	met office climate summary
16/07/2008	75	Thundery and warm, persistent rain. No flood records found	Met office climate summary
12/08/2008	71	Heavy rain reported. No flood records found	Met office climate summary
19/08/2008	74.2	No flood record found	Met office climate summary
07/06/2009	60.8	Thundery showers persistant rain, No flood record found	Met office climate summary
20/08/2010	75.4	Persistent rain, No flood record found	Met office climate summary
26/08/2010	65.2	Persistent rain, No flood record found	Met office climate summary
05/08/2013	68.2	Flash flooding in various regions	National press

Table 4.4: *Rainfall events above 60mm/day in Region D*

Region E

Date	Rainfall (mm)	Notes	Source
11/07/1914		Flooding in Mostyn	Hydrochronology database
08/08/1914		Flooding in Conwy	Hydrochronology database
24/07/1965	67.8	No flood reported	
21/08/1970	62.6	Thunderstorms and heavy rain. Flooding reported around the country, but not specifically in this region	
04/07/1971	61.5	Flood damage in many places. River Gele overflowed at Abergele	Met office monthly report
01/08/1972	69.6	Thundery rain. Localised flooding reported	Met office monthly report
16/07/1973	78	Flooding reported	British Rainfall
17/06/1974	62	Flood recorded	Met office monthly report
26/08/1986	98.5	North Wales (Hurricane Charley)	British Rainfall (monthly rainfall)
27/08/1986	86.1	North Wales (Hurricane Charley)	British Rainfall (monthly rainfall)
28/08/1986	128	North Wales (Hurricane Charley)	British Rainfall (monthly rainfall)
11/06/1993	69	Thundery showers. No flood records found	
17/07/2000	74.5	No flood records found	
04/07/2001	67.2	Thunderstorms. No flood records found	Met office climate summary
05/07/2001	105.2	Thunderstorms. No flood records found	Met office climate summary
18/07/2003	76.2	Low pressure moving across country. No flood records found	Met office climate summary
09/08/2004	66.2	Hot sultry weather. Thundery outbreaks. No flood records found	Met office climate summary
26/06/2007	86.9	Widespread flooding	National press

Table 4.5: *Rainfall events above 60mm/day in Region E*

The more widespread frontal summer floods were identified by using this threshold method, however, it can be seen that several of the more localised flash flooding events were missed. Not all raingauges were used for this study, so a small scale local event may not have coincided with any of the selected raingauges. Also, flash floods can be produced by relatively small rainfall amounts if the conditions are favourable. A short intense downpour in an already saturated location which has a fast response time will not be picked up in this study.

The daily rainfall records have identified several days when the rainfall was classed as "heavy" by records such as British Rainfall however there is no indication of flooding in the records. It is very difficult to ascertain whether or not this is actually the case, smaller flash flooding events often go unreported. It is realistic to assume that there was a possibility of flooding on these occasions.

4.5 Use of a percentile threshold

From these results it is apparent that applying different thresholds for each region is appropriate. However the difficulty once again lies in the choice of threshold. It order to circumvent this problem an alternative method of selecting extreme events is proposed. By selecting only events above a certain percentile, it is not necessary to opt for an absolute threshold value, but allows the threshold to vary according to the rainfall levels in each region.

Due to the very large number of days with low or no rainfall occurring, it was necessary to choose a high percentile threshold to prevent an excessive number of events being selected. It was decided to extract all events above the 99.5th percentile of the rainfall amount (i.e. all events which lie within the top 0.5 of the maximum rainfall amount), which led to an extreme event count which fell between 50 and 100 events for all five regions. This method of extracting events leads to thresholds which are dependent on maximum rainfall values within each region and also leads to a variation in the number of events selected in each region.

The thresholds, shown in table 4.1, are considerably lower than the fixed 60mm/day threshold used in the earlier part of this chapter and a detailed analysis of each of these events would be unrealistic, however it interesting to note if any of the events which were not identified by the 60mm/day threshold have now been extracted from the dataset.

Region	Threshold (mm/day)	Number of Events
A	36	86
B	32	99
C	40	50
D	47	54
E	43	55

Table 4.6: *By using the 99.5th percentile as a threshold level, the actual threshold value and the number of events are identified in each region.*

By applying the thresholds in table 4.6, all but four of the floods identified in the tables 4.1 – 4.5 were extracted from the data. Out of the four remaining floods it was found that there was no data available for three of them, leaving only one flood which was not picked up by these thresholds.

4.6 Distribution of Frontal and Convective Events

Summer flooding events can be divided into the two broad categories of frontal and convective events. In the summer, very few of the extreme events are due to purely frontal rainfall, but often have convection and orographic processes embedded within the frontal system, with the low pressure being a trigger. These events have been classified as frontal events for the purpose of this analysis and Figure 4.7 shows a breakdown of the two types of extreme rainfall events. In this case, an extreme event is classified as an event which lies above the 60mm/day threshold and the classification of event type has been determined from historic flood records, by using the length of the event, the description of the type of rainfall, spatial coverage and any other indicators which can be ascertained from the often highly descriptive accounts of floods. Historical data often mentions large hail when describing a thunderstorm. This is often a good proxy for CAPE and an indication that the event has is strong convective element.

Since the data used to compile Figure 4.7 is not complete it is likely that there are events which have been missed. Therefore although the absolute numbers of events may not be meaningful, the distribution of events in each region is very marked.

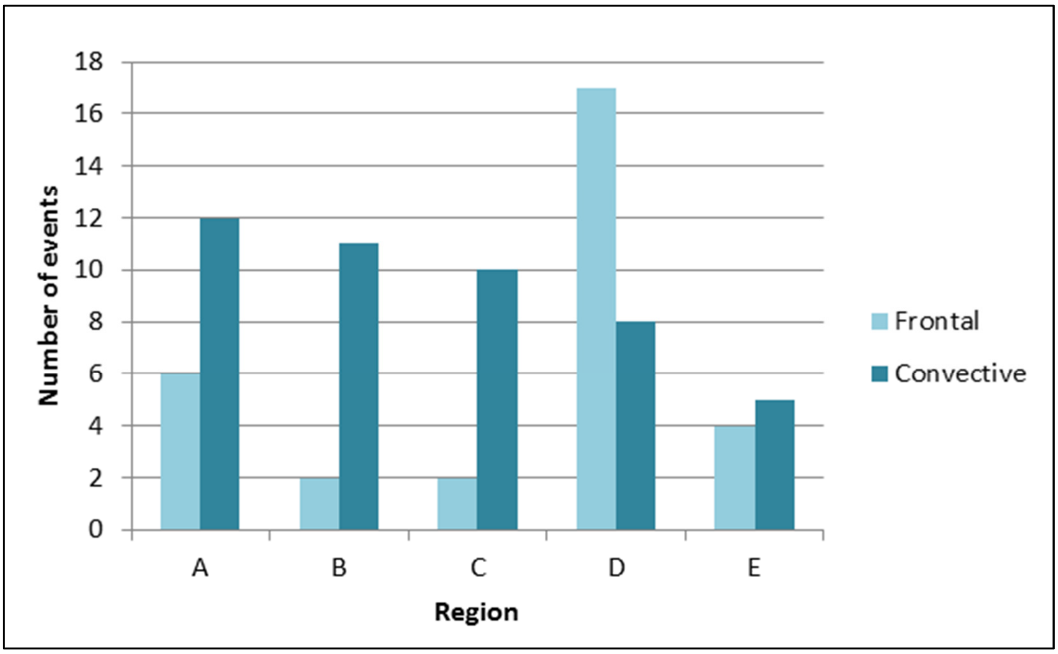

Figure 4.7: *Types of extreme event in each region. Frontal events include those with embedded convection or embedded events due to orography.*

On the West side of the UK, the South Wales region D exhibits a large number of frontal events in comparison to convective events, and the region E in North Wales receives fewer events overall with a fairly equal distribution between the frontal and the convective events.

The Eastern regions A, B and C receive a relatively large number of convective rainfall events and much fewer frontal events, with the greatest numbers of events being in the more northerly Lincolnshire region A and the number of events reducing towards the south of the country in Region C in East Sussex and Kent.

4.7 Summary

The choice of threshold for the identification of an extreme event has been shown to be significant and it appears to be necessary to use variable thresholds determined by the rainfall values in each region, therefore the use of a percentile method to determine threshold may be more appropriate.

Based on a range of fixed thresholds, it was shown that 3-5 day events are more common in the Welsh regions D and E, with South Wales also receiving the greatest number of daily extreme events. By using variable thresholds more events would be identified in the other 3 regions, but further collection of historic flood data would be necessary to categorise many of the lower value rainfall events as flooding events, or purely heavy rainfall events.

A broad classification of frontal and convective events has been carried out by using historic data to categorise each event. Chapter 6 will investigate the atmospheric processes behind some of these events to aid classification.

This chapter highlights the need for quality control of the raw data prior to analysis. The most challenging problem is the presence of occasional spikes in the data on the first of the month. Further investigation into the statistical significance of these readings would be useful, through a comparison of the observational time series taken from the first day of every month, with the time series of, for example, the second day of every month. The result of this investigation could lead to a decision on whether or not to remove all the readings from the first of every month, or simply those which lie above a threshold.

5. Statistical Analysis of Rainfall Data

The previous chapter detailed the analysis of rainfall observations by a comparison of extreme events, which were identified using a cut off threshold, with historic rainfall data in order to investigate the flood threshold level for any particular region or individual location.

This chapter takes a statistical approach to the analysis by using the in2extRemes Extreme Value Analysis software to calculate probability distributions of the extreme events from each raingauge. Whereas in the previous chapter a range of fixed thresholds were used, the statistical method employed implements thresholds specific to each individual dataset in order to calculate the probability distribution of events which lie above the threshold and hence determine return values for each location.

5.1 Estimation of Thresholds for Extreme Value Analysis

The threshold used for the calculation of the GPD for each raingauge was estimated by fitting probability distributions to a range of thresholds as described in section 2.3.4. This method was chosen in preference to the mean residual plot method, also described in section 2.3.4, which proved to be more difficult to interpret.

Figure 5.1 shows a plot of the scale and shape parameters from a family of GPDs for a range of thresholds for daily rainfall data obtained from a single raingauge. At high thresholds, large perturbations in the parameters can be observed as the threshold is changed. However, these perturbations in the parameters are small when compared to the sampling errors, shown by the vertical lines. Therefore for this particular raingauge a threshold value of 40mm/day appears to be a reasonable choice when selecting data to calculate the probability distribution, as at thresholds above this value the shape and scale parameters remain constant within the bounds of the sampling errors.

This method of threshold estimation was repeated for each the observational time series for each individual raingauge. This leads to each probability distribution being calculated using a different threshold.

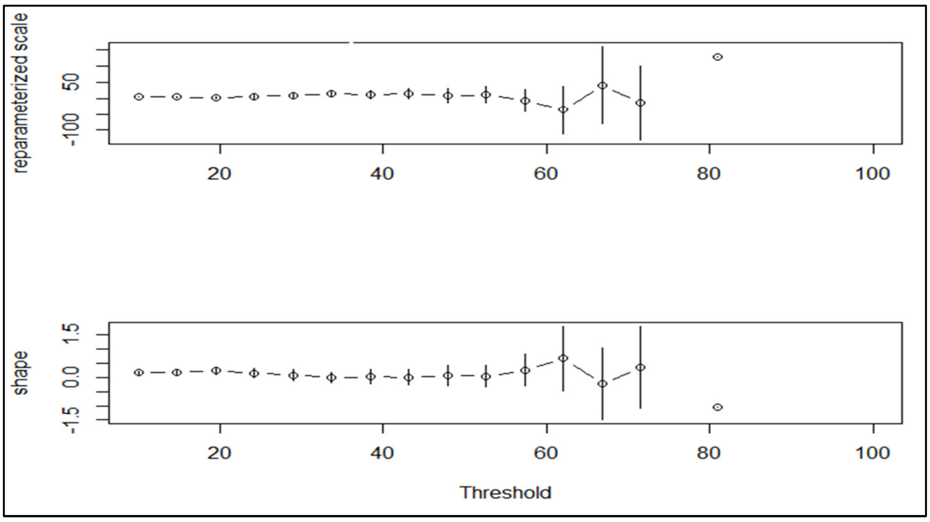

Figure 5.1: *Estimates of parameters for a GPD for a range of thresholds for daily rainfall data from a single raingauge. The upper plot shows the scale parameter at a range of thresholds. The lower plot shows the shape parameter, ξ, at a range of thresholds. The vertical line shows the sampling error which is very large at high thresholds due to the low number of observations at these levels.*

It could be argued that the same threshold should be used for all raingauges in order to compare the results, however it would be very difficult, if not impossible, to find a threshold which would produce an accurate probability distribution for all locations. The number of extreme events and also the amount of rainfall which is observed across the country varies widely, so a threshold which optimises the number of data points with which to calculate a probability distribution for each location is a better solution for statistical analysis than a fixed threshold value which produces a poor fit in many cases.

5.2 Probability Distributions

Applying thresholds calculated using the above method, probability distributions were calculated using the in2extRemes software. The goodness of fit of the model distribution can be assessed though both a quantile plot which plots the quantiles of the model against those of the empirical data, and a density plot. A good fit would result in a quantile plot which lies along the line y=x, and a density plot in which the model and the empirical distribution form a close match. Figure 5.2 shows an example of such a plot for raingauge 3 in region C. In this case, the diagnostic plots seem to be convincing, supporting the fit of the model.

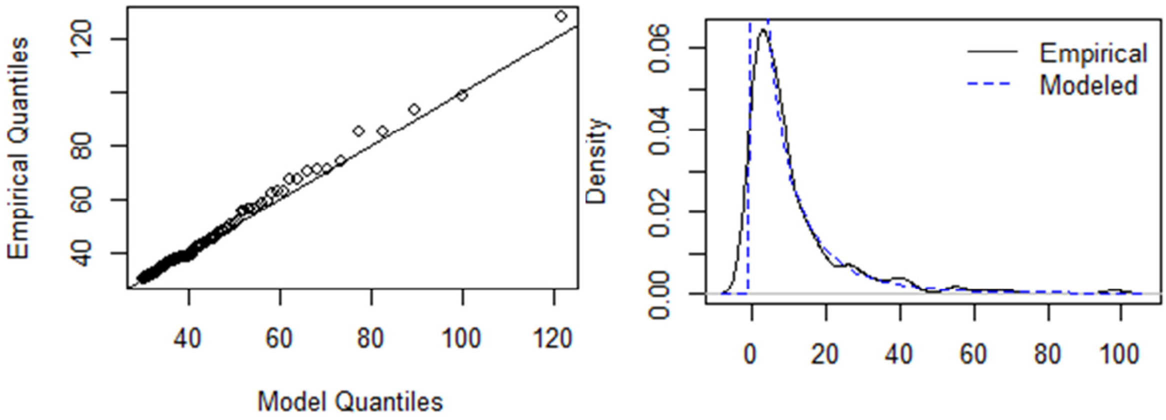

Figure 5.2: *Diagnostic plots for GDP for raingauge 3, region C. The quantile plot and density plot show good agreement between the model and the empirical data, confirming the goodness of fit.*

5.3 Return Values for Selected Raingauges

The return period for a particular event is defined to be the amount of time which passes between recurrences of the event. The return level for a particular return period is, in the case of rainfall, the quantity of rainfall associated with a particular return period. This is of course a theoretical definition which can be quite misleading – especially when being used to communicate information to the general public. A more useful way of communicating this idea would be as a probability or percentage chance of an event occurring in any one year, i.e. a 100 year flood (a flood with a return period of 100 years) has a 1% chance of occurring in any given year.

Figure 5.3 shows an example of a typical return value plot calculated from the daily rainfall data from a single rain gauge and the return levels for a range of return periods. The model extrapolates the data to estimate return levels for return periods which exceed the length of the observational dataset, but as can be seen the 95% confidence bands, shown as dotted lines in the plot, are very large at the higher levels indicating that some caution must be used before drawing conclusions regarding longer return periods.

The continuous series of observations of approximately 48 years which was obtained for the majority of the raingauges is relatively short, and for some of the raingauges there may be only one or two summer flooding events recorded during this time. From this data alone it is not possible to determine return periods of 100 years or more with any certainty. However, using the GPD it is possible to extrapolate beyond the limits of the observed events to calculate return periods of greater length than the span of the observed data. As mentioned earlier, it is important to realise that these long return periods have a high degree of uncertainty.

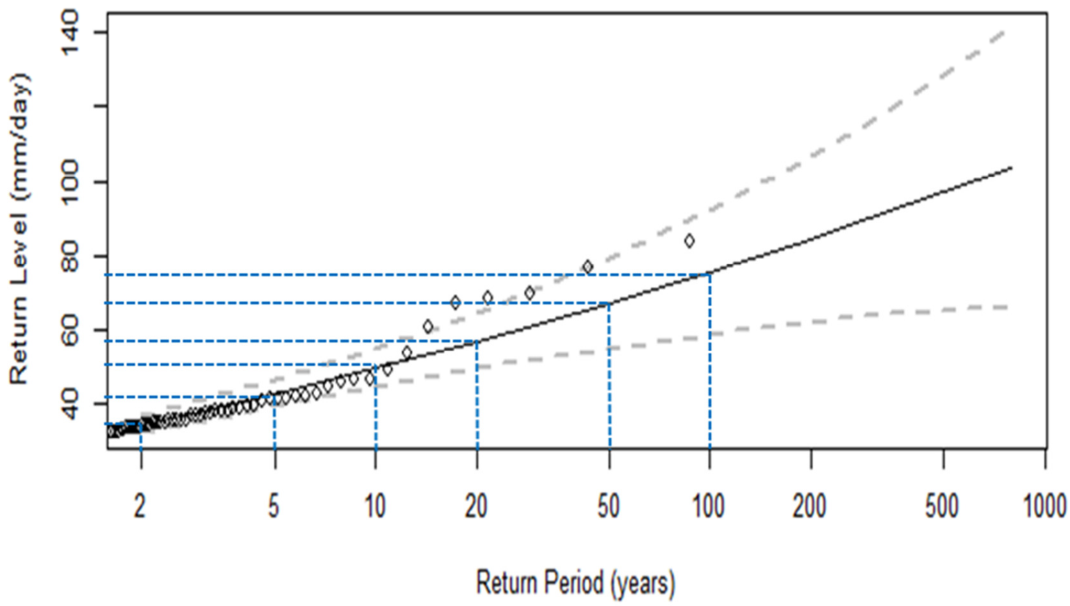

Figure 5.3: *Return value plot showing return levels for a range of return periods using data from raingauge 4 in Region A. 2 year (20mm/day), 5 year (41mm/day), 10 year (50mm/day), 20 year (58mm/day), 50 year (68mm/day), 100 year (76mm/day). Dotted lines show 95% confidence bands which indicate the high uncertainty for return periods of over ~50 years.*

Bearing this in mind, return period plots have been produced for each of the selected raingauges and return values extracted for 2, 5, 10, 20, 50 and 100 year rainfall events using data from June, July and August only. This result are of relevance to flooding-related insurance, as it gives an indication of the regularity of extreme precipitation events in specific locations within the areas in which they have expressed an interest.

Return value plots for all the selected raingauges are shown in Appendix B and return values were extracted from these plots. The results for each individual location are given for only the 2, 5, 10, 20 and 50 year events, as in the majority of cases the uncertainty in the 100 year event return levels was too high to be useful for analysis. It is hoped that the regional return periods may be a useful aid to Catlin.

Region A

Figures 5.4 and 5.6 show that eight out of the ten raingauges in this region exhibit similar return period profiles, as would be expected for an area which is predominantly flat, with return values of between 55 and 100 mm/day for a 50 years rainfall event and values of between 50 and 70 mm/day for a 20 year rainfall event. However, raingauges 1 and 9 produce anomalously high return values for this region, with 50 year rainfall events being estimated at 190 and 150 mm/day respectively. Upon closer examination of the data it can be seem that these large return values are caused by the presence of two extreme events in each of the observational datasets.

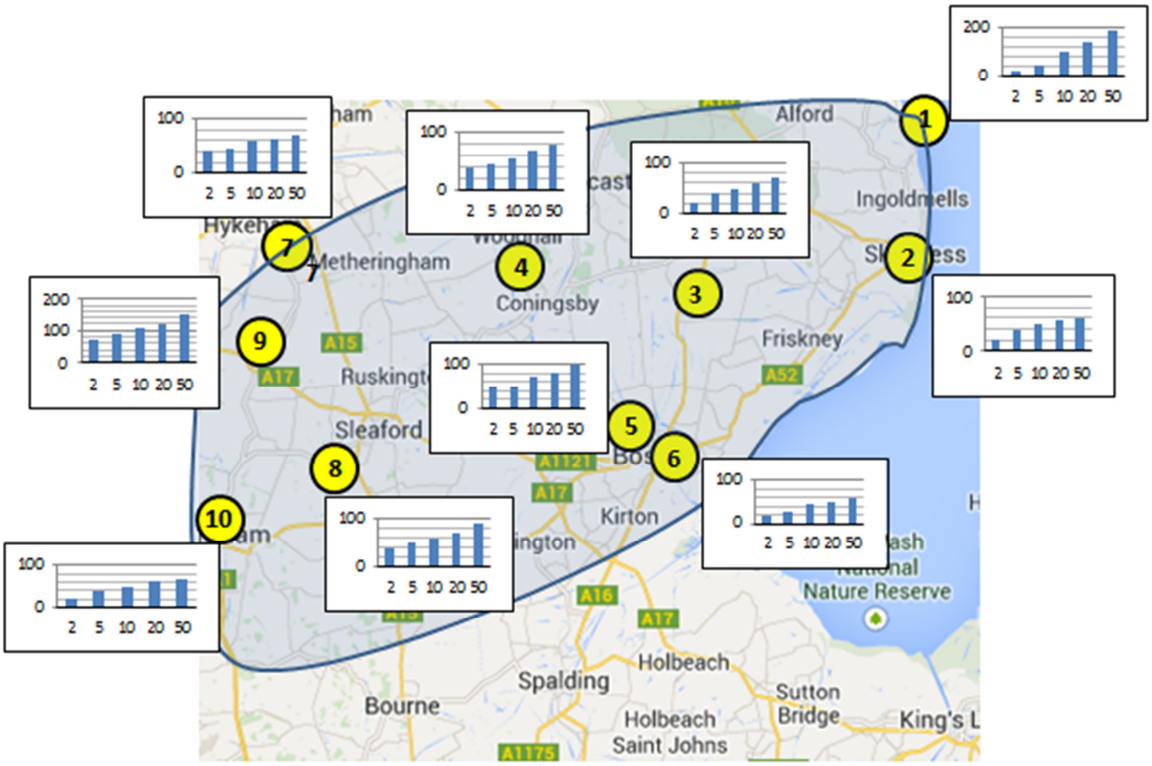

Figure 5.4: *Return values for selected raingauges in Region A. The bar charts show return values up to a 50 year return period. The 100 year return period has been excluded due to the large variation associated with this value.*

Figure 5.5 shows the daily rainfall time series for June, July and August for the raingauge 1, located on the coast, north of Skegness. As can be seen, there are two major events, July 2007 and August 1992 which not only resulted in significant amounts of daily rainfall, but also lasted for several days. Most of the raingauges in the region registered these events, but very few recorded the exceptionally high values which were observed at the location of raingauge 1, which resulted in the higher return values.

Raingauge 9 is located approximately 20km inland of Skegness and has also captured the intense summer flooding event of 2007 with a maximum daily rainfall of 220mm. The maximum recorded observation from the surrounding gauges for July of this year is 110 mm.

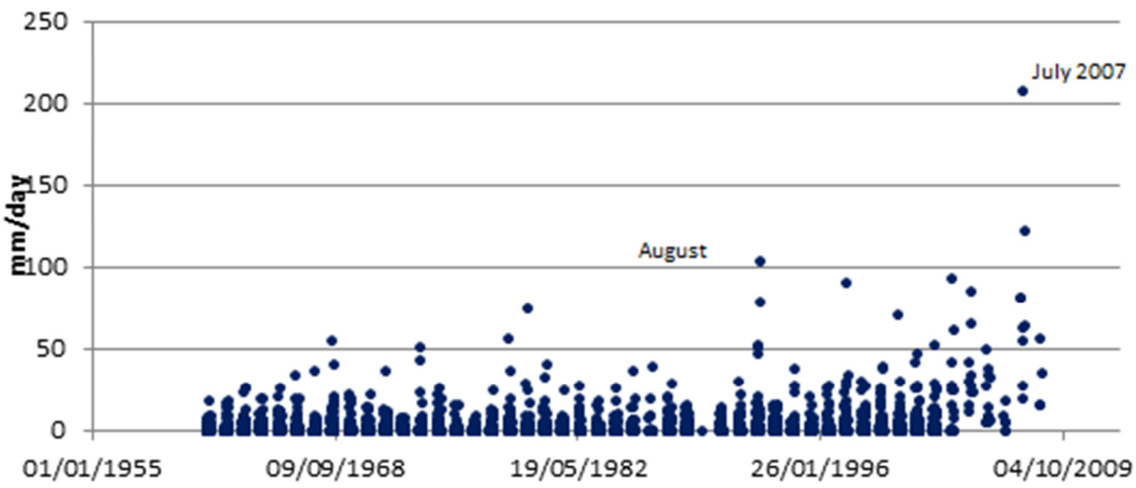

Figure 5.5: *Rainfall observations for JJA for raingauge 1, region A showing the extreme events of July 2007 and August 1992, which led to higher return values.*

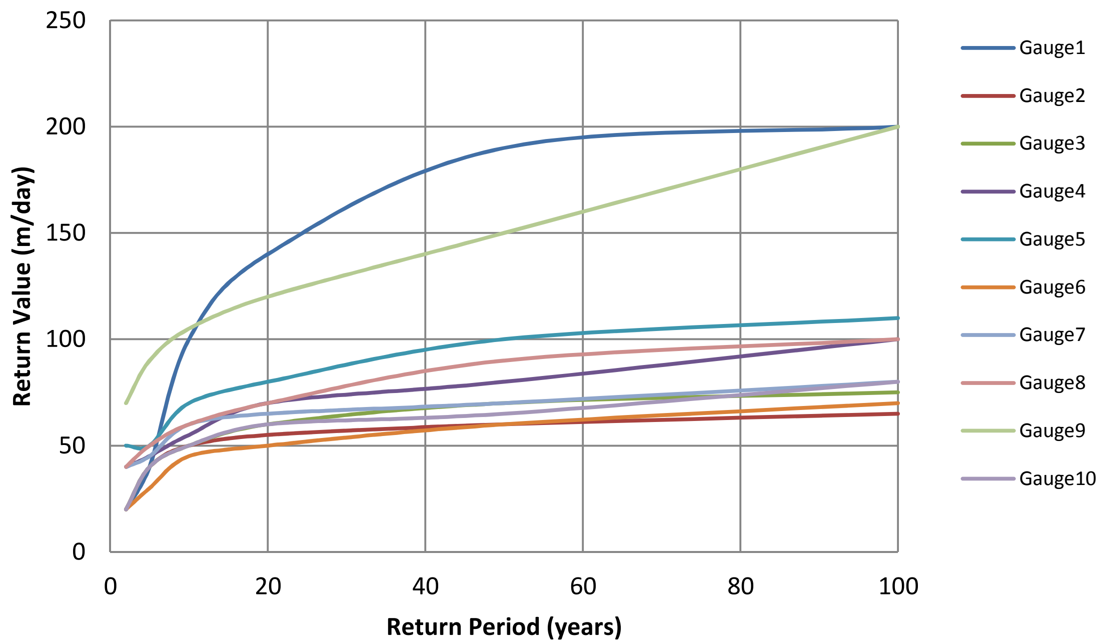

***Figure 5.6**: Return levels for 2, 5, 10, 20 and 50 year events for Region A. See appendix B for individual plots for each raingauge which show uncertainty bands for each location.*

Figure 5.7 shows return periods averaged for the entire region. Note the increase in error as the return period increases showing the large spatial variation in the more extreme events compared to the smaller variation associated with the shorter return period and lower return value events.

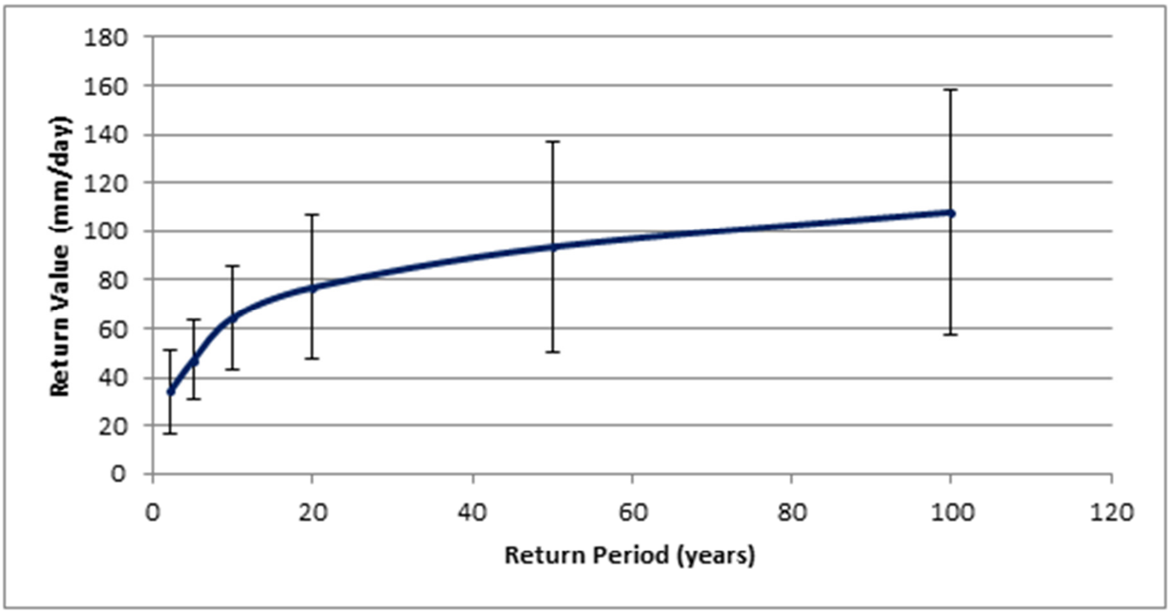

Figure 5.7: *Return Period plot for Region A showing average return periods for the entire region. The errors shown here are given by the standard deviation of the 10 raingauge readings. It is important to note that this does not include the large errors associated with the initial return value calculation*

Return period graphs for regions B, C, D and E can be found in Appendix B.

Region B

The ten raingauges in the Norfolk region exhibit a spread of return periods with the return values for 50 years events ranging from 55 to 110 mm/day. As can be seen from Figure B1 (Appendix B) the variation in return periods across the region is lower than that in the Lincolnshire area in Region A, with the return values also being typically 20mm/day lower. The two areas are topographically similar, but the plots show Region B to be drier and with fewer extreme events.

Region C

Observations from Raingauge 8 have produced a return value plot for this raingauge which deviates from the pattern followed by all other raingauges in this location. On closer inspection of the data it is found that the anomaly is caused by 2 events in excess of 100 mm/day which occurred in June of 2003 and July of 2004. Both these events fall on the first of the month, but were not high enough to have been eliminated by the quality control process described in chapter 3 therefore there is a possibility that the events are errors in the data.

Region D

Out of the five areas investigated, this region shows the most variation amongst the selected raingauges. The data falls into two distinct groups with larger return values being predicted for the inland raingauges which border the mountainous region of the Brecon Beacons and lower values being predicted for the coastal areas, where holiday homes and caravan sites are located. This leads to the average return values for the region having the largest variation of the five regions, due to the discrepancy between the north and the south of the region.

Region E

This area shows a fairly uniform spatial distribution with the highest return values being towards the West of the region, closest to Snowdonia National Park, and the lowest values being found towards the East, indicating that the discrepancies in rainfall within the region are closely related to orography. Overall, the return values calculated for this region are markedly lower than those obtained for region D, the only other West coast region investigated in this study. These lower values can be attributed to the fact that the region is sheltered from frontal systems by the mountains of Snowdonia to the West, whereas region D in the South of Wales is much more exposed.

5.4 Summary

These results indicate that a degree of caution must be maintained when interpreting the return values. Most of the raingauges only have a 50 year dataset, therefore it may only be realistic to look at return values for return periods up to around 50 years at the most. Some of the datasets are simply not long enough to have captured sufficient extreme events to produce a meaningful result, and where unusually high return values are calculated, it is always beneficial to return to the raw data in order to analyse why these values have been produced. As was seen in several cases, a high return value can sometimes be attributed to a single extreme rainfall event.

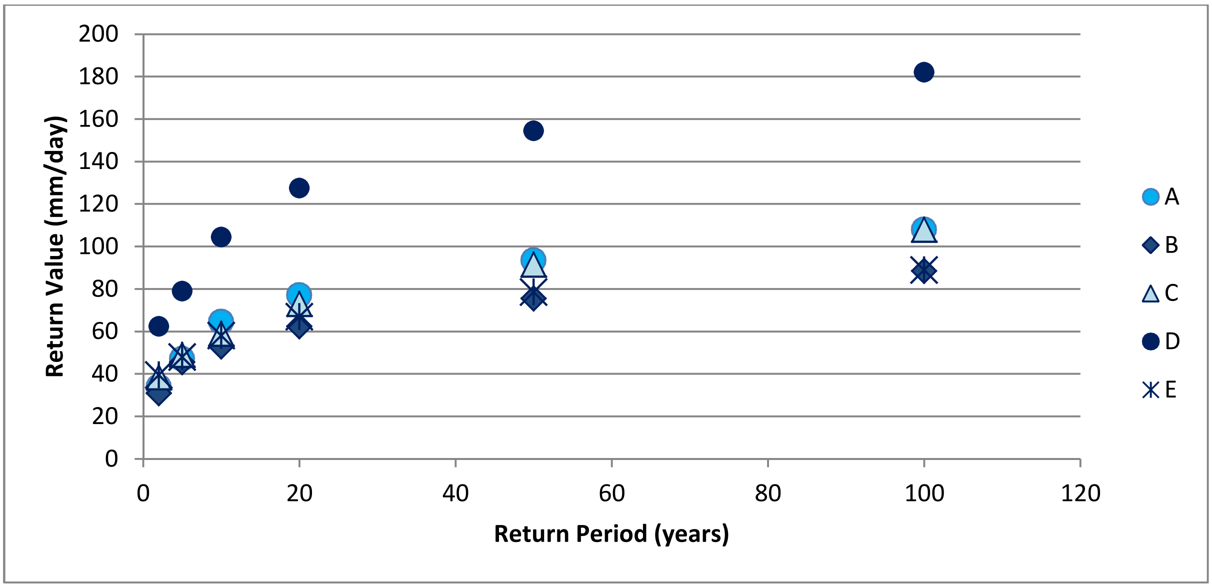

Figure 5.8: *Average return values for all five regions. Error bars not shown to aid clarity, but can be seen on graphs for individual regions.*

Figure 5.8 summarises the results from the five regions and could be of use to Catlin in the calculation of risk analysis for each area under investigation. Region D, South Wales shows considerable higher return values than all other regions, which exhibit very similar return periods. However, it was found that the higher return values in region D were produced by those raingauges which border the mountainous region, which lays several kilometres inland, whereas those raingauges in the coastal regions exhibit lower values, more in line with the other four regions under investigation.

6. Case Studies of Atmospheric Conditions Prior to Historical Flooding Events

In this chapter atmospheric reanalysis data is used to conduct a further investigation into individual events in order to understand the atmospheric conditions during and prior to an extreme rainfall event. The work presented here is not an in-depth analysis of each event, rather an overview of the main climatic features in order to identify patterns in the atmospheric conditions which might lead to these events and which it is intended to guide future research. The reanalysis data plots show daily composite mean values and are all produced using NOAA's 20th century reanalysis product (see section 3.3 for more details).

By examining vector wind and atmospheric water vapour plots, the transport of moisture can be estimated in order to find any connections between the large scale atmospheric conditions of events under examination. It was found by Lavers and Villarini (2014) that much of the variability in precipitation across Europe can be explained using the three parameters of 850mb zonal and meridional winds and integrated water vapour. This is more applicable to the widespread frontal events than the small scale convective events and Lavers and Villarini (2014) showed that the relationships were stronger in the winter than in the summer.

It was shown in figure 4.7 that convective events are more common than frontal events in most regions during the summer months by using a very broad definition of a frontal event. However, as will be observed in this chapter, many of the flooding events contain frontal, convective and orographic processes.

An event is classed as being frontal if it leads to continuous rainfall over a wide area and can be associated with a clearly identifiable synoptic scale frontal weather system. By examining the mean sea level pressure (mslp) plots, the depressions associated with these events were identified. Precipitable water and wind vector plots give an indication of the moisture transport during the event and it is interesting to compare the summer frontal events to those which occur during winter months in order to investigate the presence of atmospheric rivers (Lavers, 2011) which are a feature during the winter.

As discussed in section 2.1.4, one of the most useful parameters with which to identify convective events is Convective Available Potential Energy (CAPE) which quantifies of the amount of energy available for convection and hence the severity of the event. For a detailed analysis of the build-up and release of CAPE during the course of an event, data from soundings at the location of the event would provide valuable information. However, this type of data is rarely available therefore reanalysis data was used to find the approximate location of areas with raised CAPE. This is not an ideal data source for this quantity, as CAPE often builds over the course of a few hours and the reanalysis data set used provides a daily mean. Also, with a resolution of 2x2 degrees, the data is useful to give a general picture of the atmosphere for any 24 hours, but cannot resolve the detail which would be useful for further investigation.

6.1. The Norfolk Floods of 26th /27th August, 1912 – frontal event

This synoptic event was characterised by heavy rains falling for several days over many parts of the UK. However Norfolk was the only area to suffer from flooding, with parts of the county being devastated by both the duration and the intensity of the rainfall. This is the only event which was identified by the 3 and 5 day thresholds in this region (Figure 4.3, Region B), and historical records appear to confirm that no other flooding events of this magnitude have affected Norfolk during the summer months. The storm which produced this flood tracked northwards from an area East of Kent towards the North Sea as shown in Figure 6.1a. The position of the depression is confirmed accurately by reanalysis data as shown in Figure 6.1b, bearing in mind that this plot is a composite daily mean.

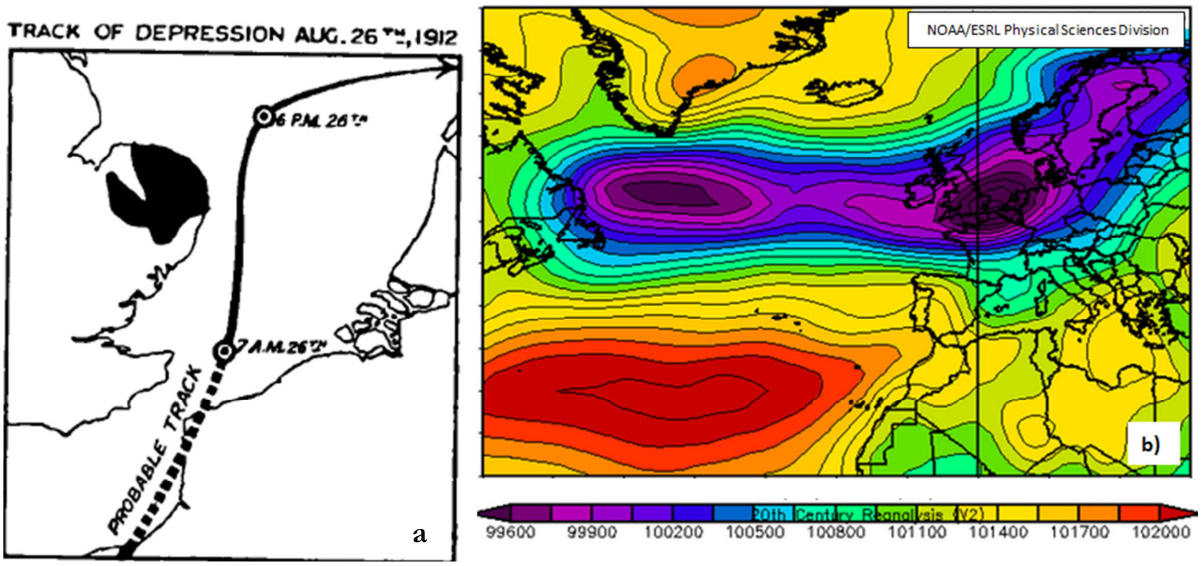

Figure 6.1: *a) track of storm with the area of most intense rainfall shown by the dark shading (British Rainfall, 2012). b) Composite mean of sea level pressure (Pa) for August 26th 2012.*

Figure 6.2 shows the total atmospheric precipitable water two days before the flooding event. A band of high precipitable water with moisture levels of 40-50 kgm^{-2} coincides with the path of the jet stream which is identified by the 250 mb vector winds in Figure 6.3. The jet stream is at an unusually low latitude for this time of year and this could be a factor which led to the convergence of moisture towards the south of the UK. This ribbon of raised precipitable water levels shows a similarity to the atmospheric river events common during winter flooding. The jet stream turns northwards off the East coast of the UK, possibly producing the cut off region of moisture, with maximum precipitable water levels of 30 kgm^{-2}, off the coast of East Anglia (Figure 6.4).

Lavers (2011) used Integrated Vapour Transport (IVT) levels to calculate thresholds required for the occurrence of a flood event when applied to atmospheric rivers which persisted for 18 hours or more. The study showed that IVT levels were required to be over 500$kgm^{-1}s^{-1}$ (the precise figure was dependent on the reanalysis data being used) for a flooding event to occur. IVT is a parameter that was not investigated directly in this project, however, the maximum precipitable water content of 30 kgm^{-2} observed in this event, combined with wind speeds of 12-14 ms^{-1} (Figure 6.5), would lead to an estimated maximum level of IVT of around 400$kgm^{-1}s^{-1}$, which is lower than the thresholds estimated by Lavers for winter flooding events caused by atmospheric rivers.

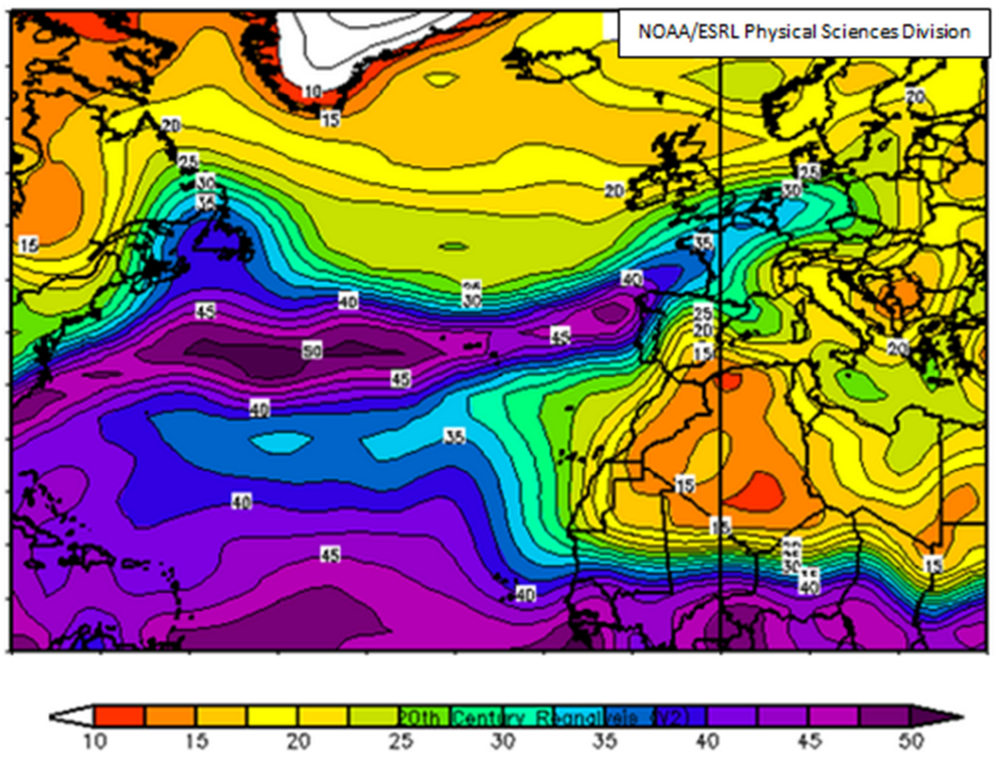

Figure 6.2: *Composite daily mean of precipitable water for entire atmosphere (kgm^{-2}) for August 26th 1912*

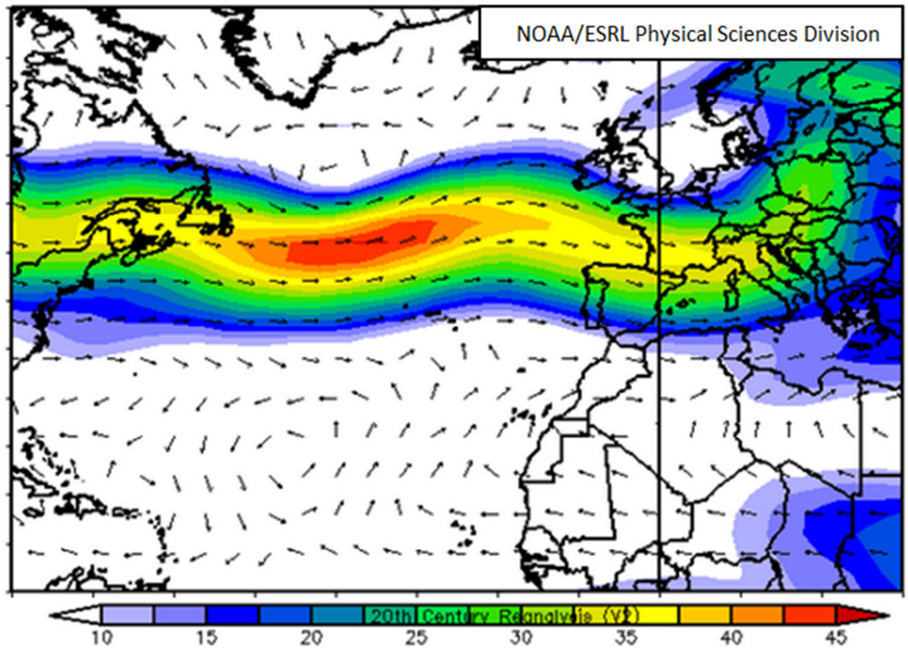

Figure 6.3: *Composite daily mean for 250 mb vector winds (ms^{-1}) for 26th August 1912.*

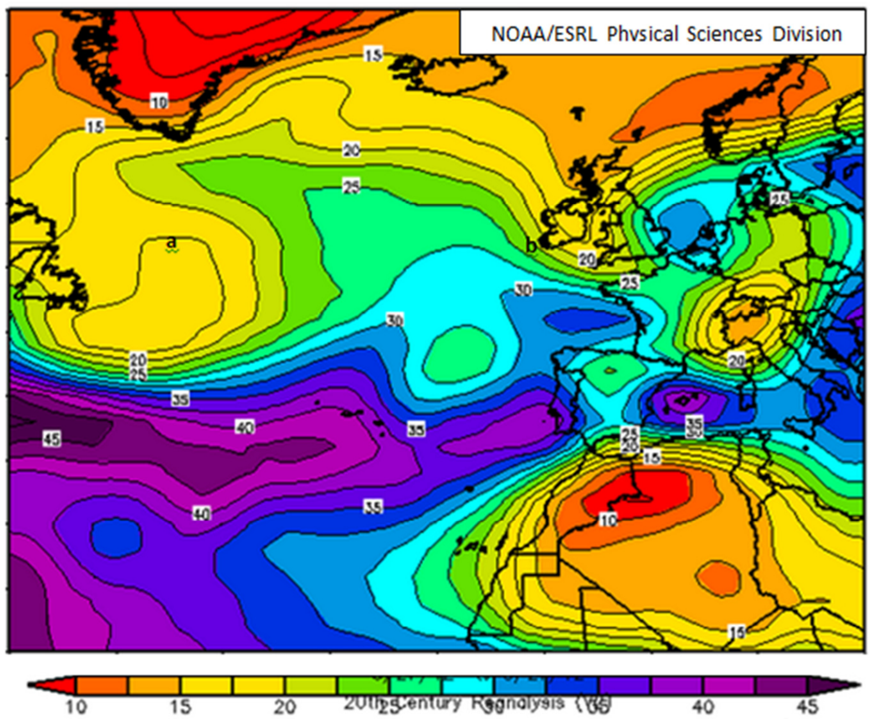

Figure 6.4*: Composite daily mean of precipitable water for entire atmosphere (kgm^{-2}) for August 26th 1912*

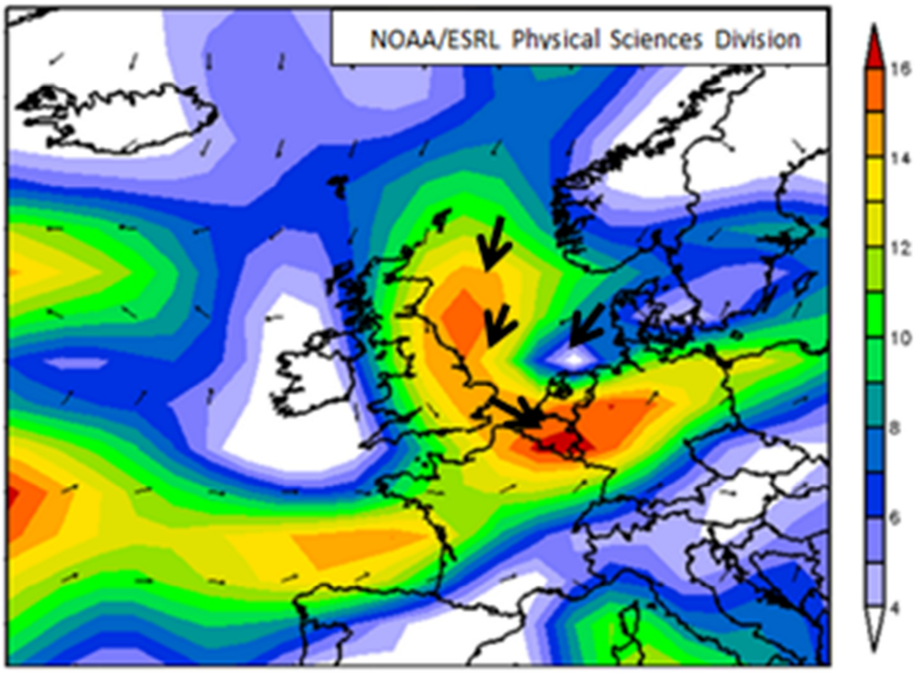

Figure 6.5: *950 mb vector winds (ms^{-1}) for 27th August 1912. (Note: larger arrows overlaid for clarity to indicate wind direction)*

The 950mb vector wind plot, Figure 6.5 shows that the winds in the area of most intense flooding are strong northerly onshore winds of around 15ms^{-1} bringing moisture to the region. There does not appear to be a convective element to this event as reports indicate that the temperatures were very low for the time of year (Met Office monthly weather, 1912) and there are no reports of severe thunderstorms which would be an indication of convective activity.

6.2 Cranwell Floods, Lincolnshire - 12/07/1932 – convective event

This convective event was characterised by highly localised rainfall with heavy rain falling within areas which are a few tens of kilometres across, leaving nearby areas completely dry. Figure 6.6, taken from the 1932 issue of British Rainfall, shows the rainfall distribution on the date of this event, indicating a pattern which is typical of a thundery convection. This flood was identified by the raingauge data from region A in section 4.4, but as only two of the selected ten raingauges were in operation on this date, the distribution of the rainfall could not be studied.

The sea level pressure plots (not shown) indicate that there were no significant synoptic features affecting the UK during or prior to this event. Figure 6.7 shows that CAPE on the day of this event was highest in the South West of the UK, several hundred kilometres east of the flooding event, reaching values of over 500 Jkg^{-1}. Levels in Lincolnshire in the region of the flood were slightly lower, at around 400Jkg^{-1}. However, temperature records (Met office monthly weather report) indicate that East Anglia was the hottest part of the country with highs of over 30°C.

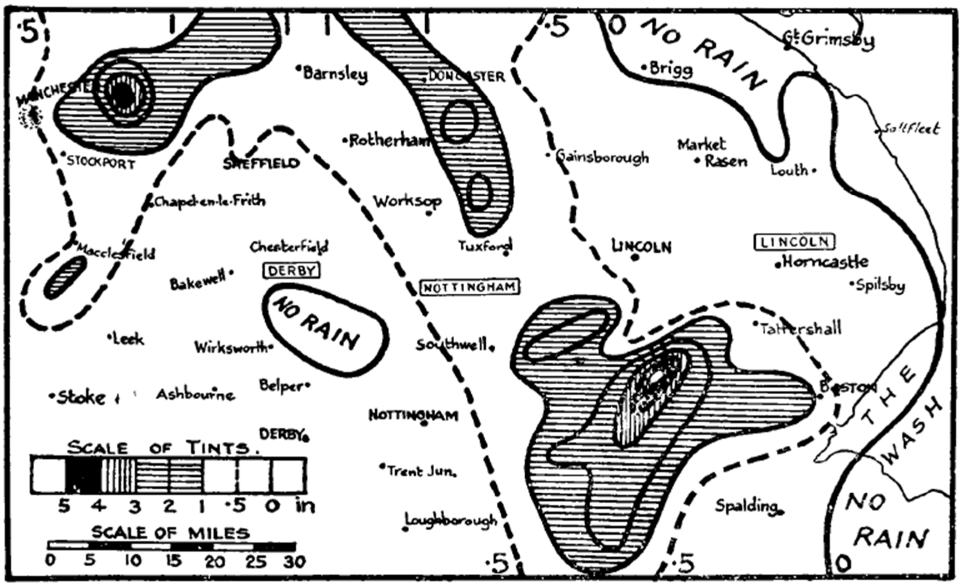

Figure 6.6: *Rainfall distribution in Lincolnshire on July 12th, 1932 (British Rainfall, 1932)*

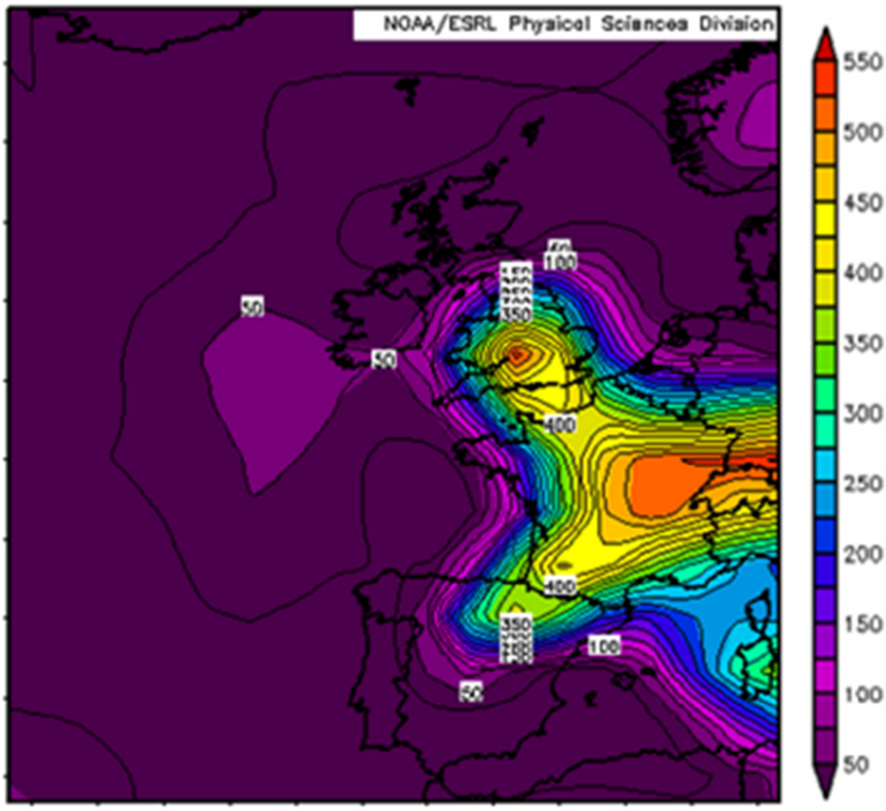

Figure 6.7: *Composite daily mean CAPE (Jkg^{-1}) on 12th July 1932*

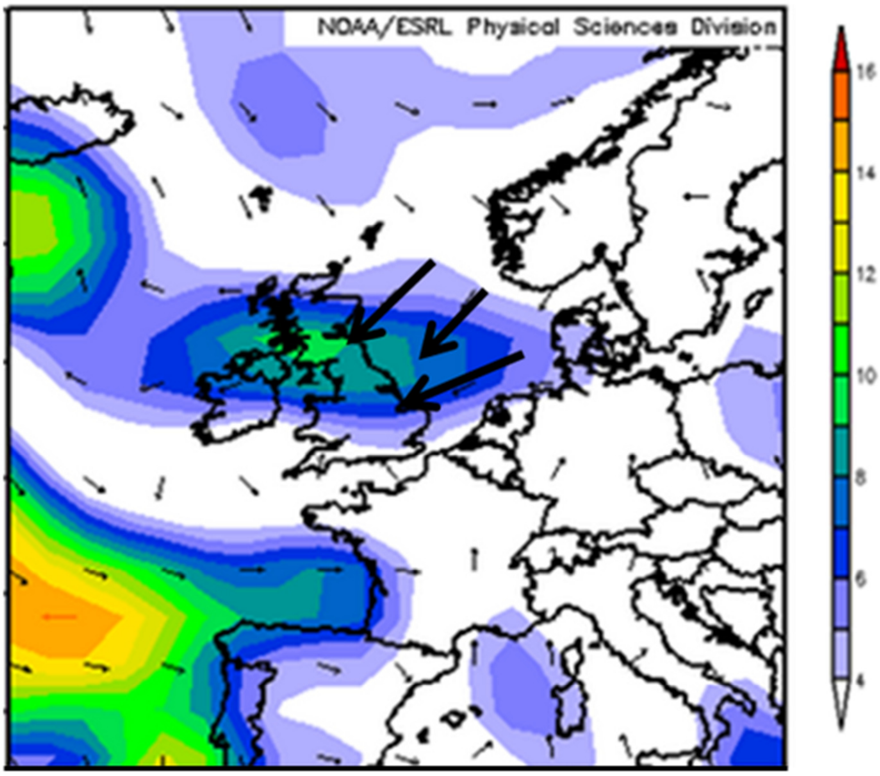

Figure 6.8: *950mb vector winds (ms^{-1}) on 12th July 1932 (Note: larger arrows overlaid for clarity to indicate wind direction)*

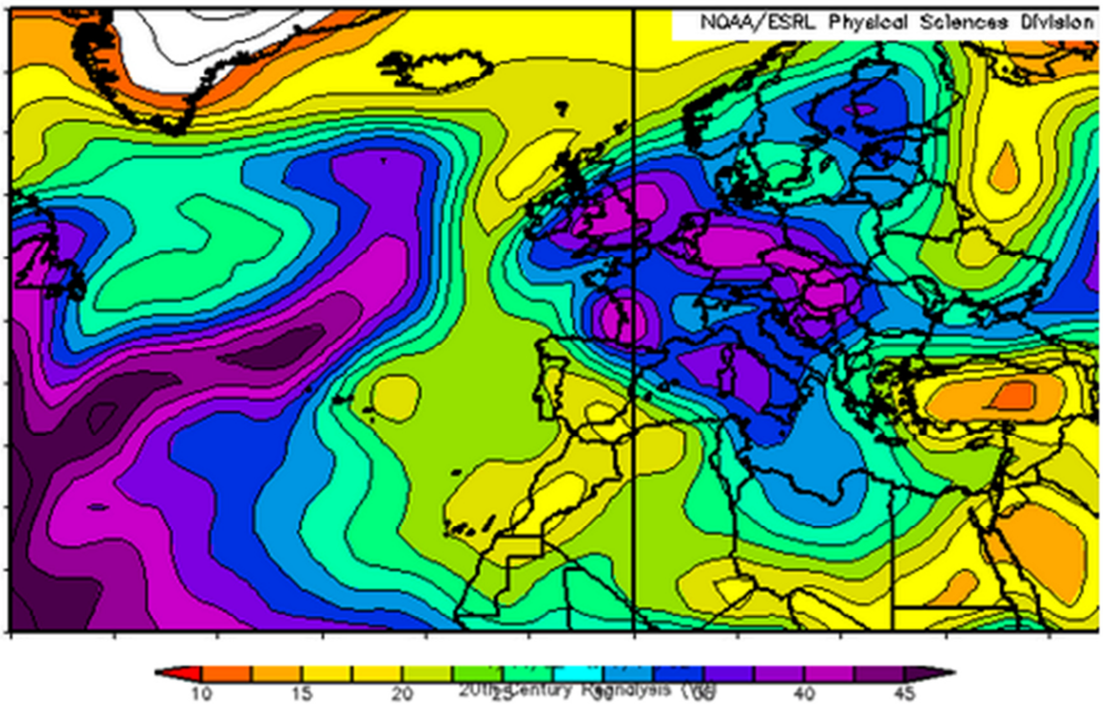

Figure 6.9: *Composite daily mean precipitable water for entire atmosphere (kgm^{-2}) for 12th July 1932*

North Easterly winds of 8-10ms^{-1} blowing along the line of raised precipitable water levels of around 35kgm^{-2} (Figure 6.9) advected cool moist air over the hot land mass. This combination of high levels of moisture being transported inland and the high temperatures would have led to instability and the build-up of CAPE which led to the intense thunderstorms which were reported on this date. Flood reports were found only for the Lincolnshire area, however, an extreme rainfall event of 61.5mm was also identified in Kent on this date (Table 4.3), where according to the reanalysis data, wind speeds and moisture levels were slightly lower than in Lincolnshire.

6.3 10/07/1959 – Norfolk – convective event

This convective event caused heavy flooding in Norfolk which was reported by British Rainfall, but the maximum daily rainfall in the area using the raingauges selected in the region was 53mm, so the event was not identified by the 60mm threshold. The implication behind the low daily rainfall observation is that this was likely to have been a short, intense event which produced a flash flooding.

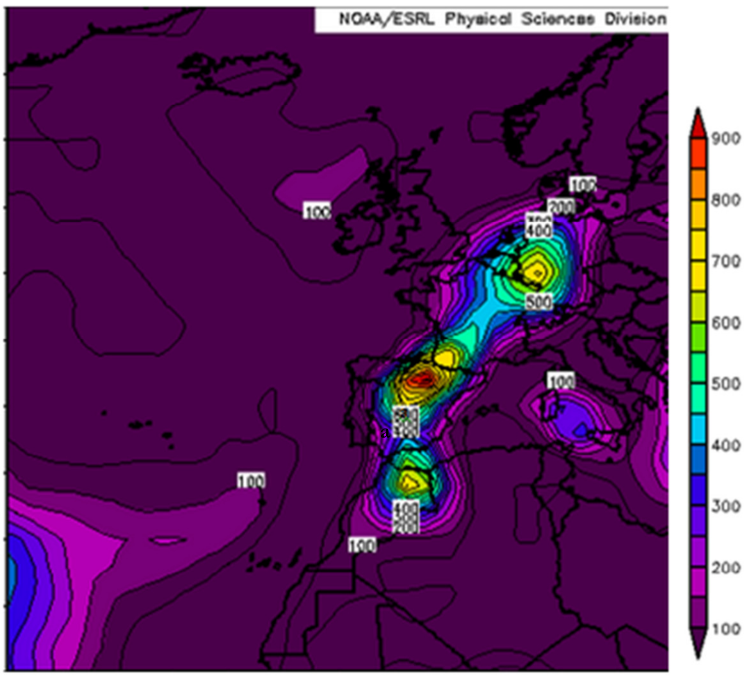

Figure 6.10: *Composite daily mean CAPE (Jkg^{-1}) on 10th July 1957*

Figure 6.10 shows that CAPE on the day of this event was low (<100Jkg^{-1}) in the UK, however very high CAPE of 900Jkg^{-1} was observed in Spain. Figure 6.12 shows that Southerly winds were responsible for the advection of warm air from Spain, which transported moisture from the area of high precipitable water located to the South of the UK, Figure 6.11.

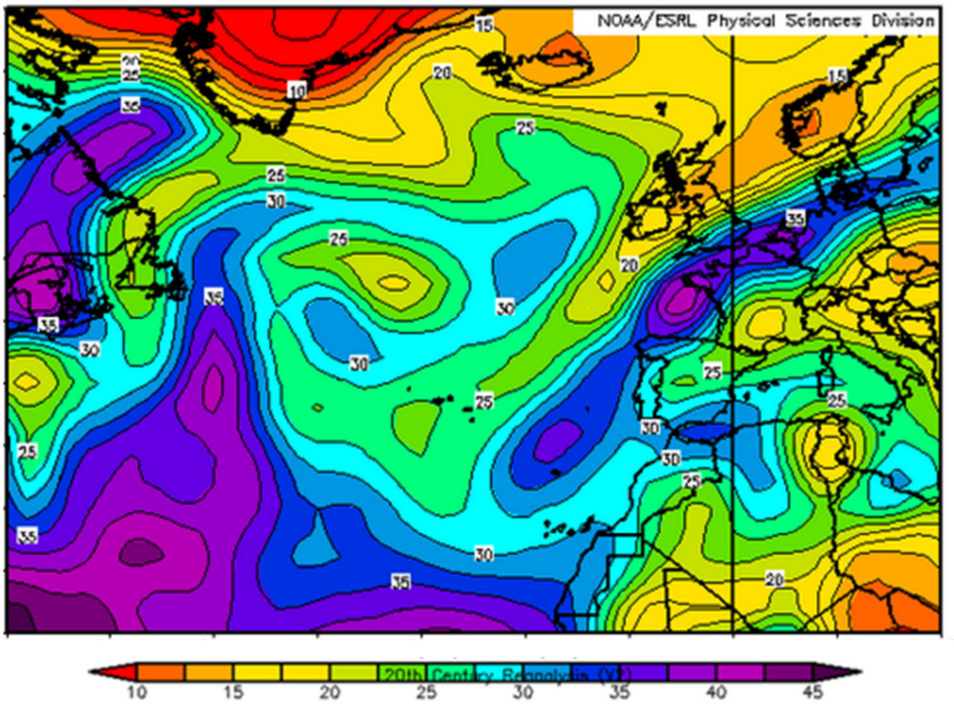

Figure 6.11: *Composite daily mean precipitable water for entire atmosphere (kgm^{-2}) for 10th July 1959*

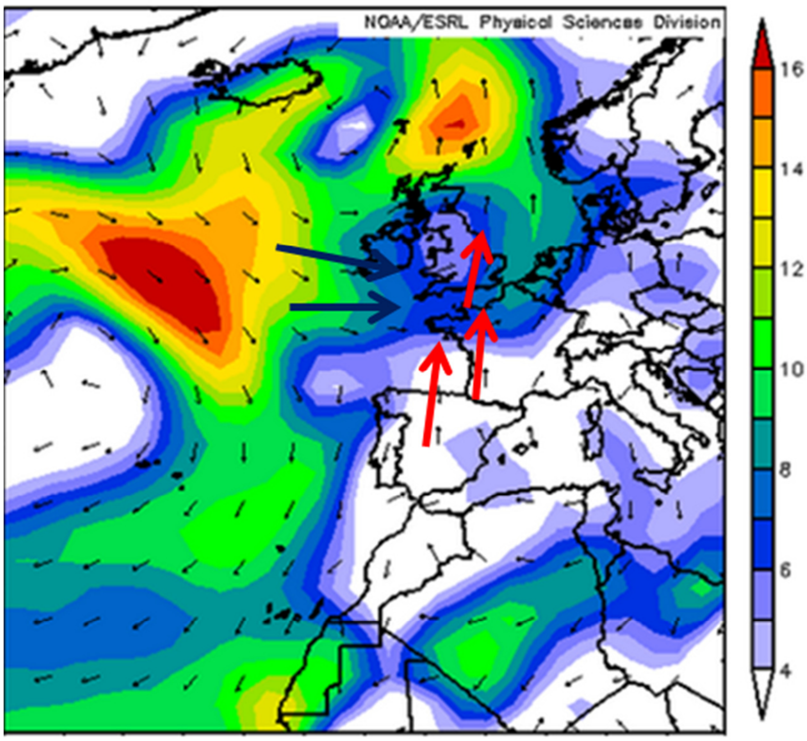

Figure 6.12: *950mb vector winds (ms^{-1}) on 10th July 1959 (Note: larger arrows overlaid for clarity to indicate wind direction – warm air shown in red, cold air shown in blue)*

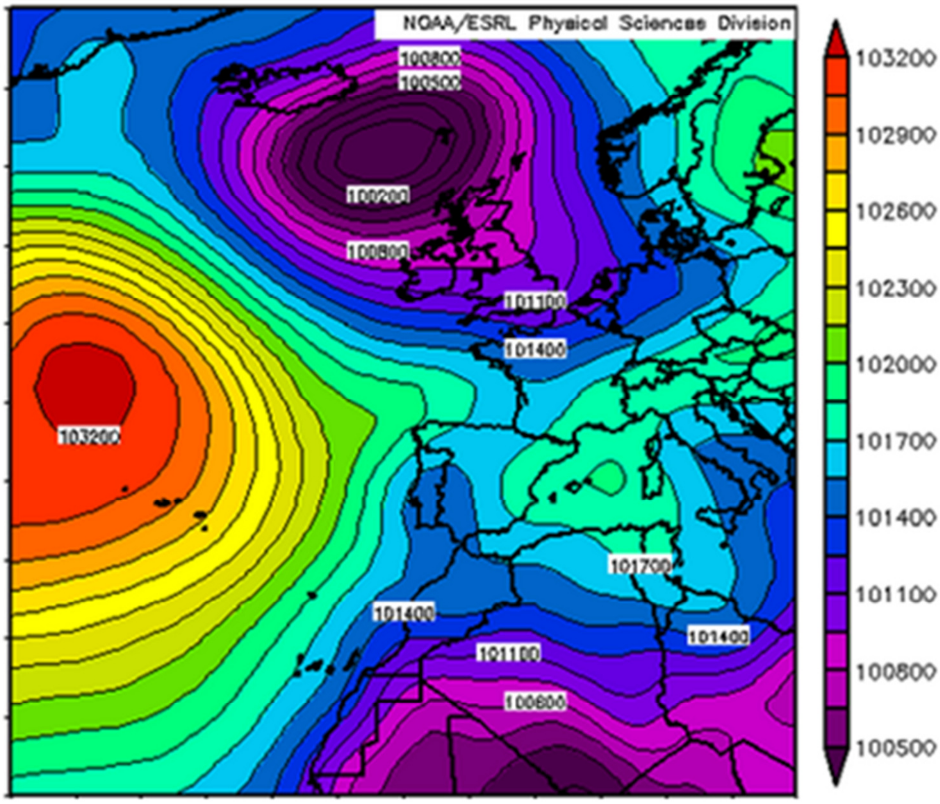

Figure 6.13: *Composite mean of sea level pressure (Pa) for 10th July 1959.*

An area of low pressure to the North West of the UK, Figure 6.13, brought cold air into the UK from the South West as can be seen from the 950 mb wind vector plot. This cold air would have increased the instability which was building due to the warm air from the South, leading to the intense thunderstorms which were reported.

Figure 6.14 shows that the rainfall follows a narrow band travelling north across the UK, following the path of the warm southerly wind from the Isle of Wight towards East Anglia, with the heaviest rainfall being in the Norfolk where the surface temperatures were highest and therefore the location of maximum instability.

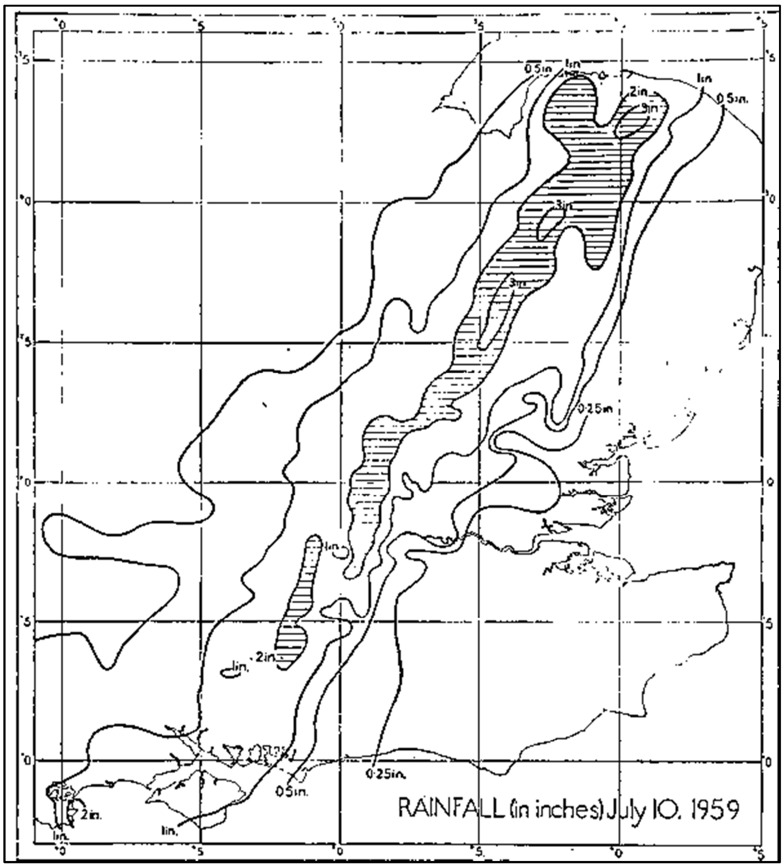

Figure 6.14: *Rainfall distribution on July 10th, 1959. Shows band of rain with highest rainfall in East Anglia*

6.4 27/06/1974 – Hastings – convective event

This event which was reported in British Rainfall was not identified by the rain-gauge data, as it was highly localised and did not fall within the range of one of the selected gauges, the nearest of which was a little over 10 kilometres away, confirming the need for a dense network of raingauges to analyse summer flooding.

Figure 6.17 shows that affected region in East Sussex lay between two depressions, one of which was located to the North East over Scandinavia, and the other to the West of the UK. The depression over Scandinavia brought cool dry air from the North, whereas to the West of the UK tropical maritime winds travelled across northern France bring. The convergence of the cold, very dry air from the North with the warm moist air from the South West led to a region of instability, which triggered the thunderstorms causing the Hastings flood.

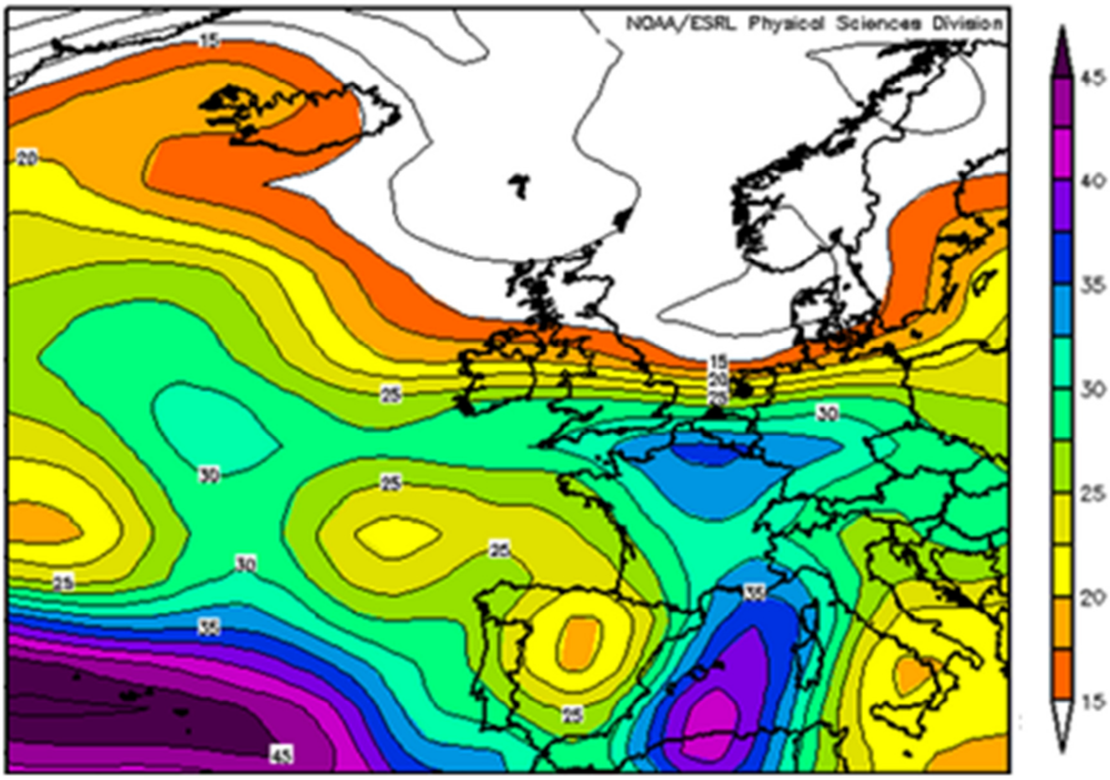

Figure 6.15: *Composite daily mean precipitable water for entire atmosphere (kgm^{-2}) for 26^{th} June 1974*

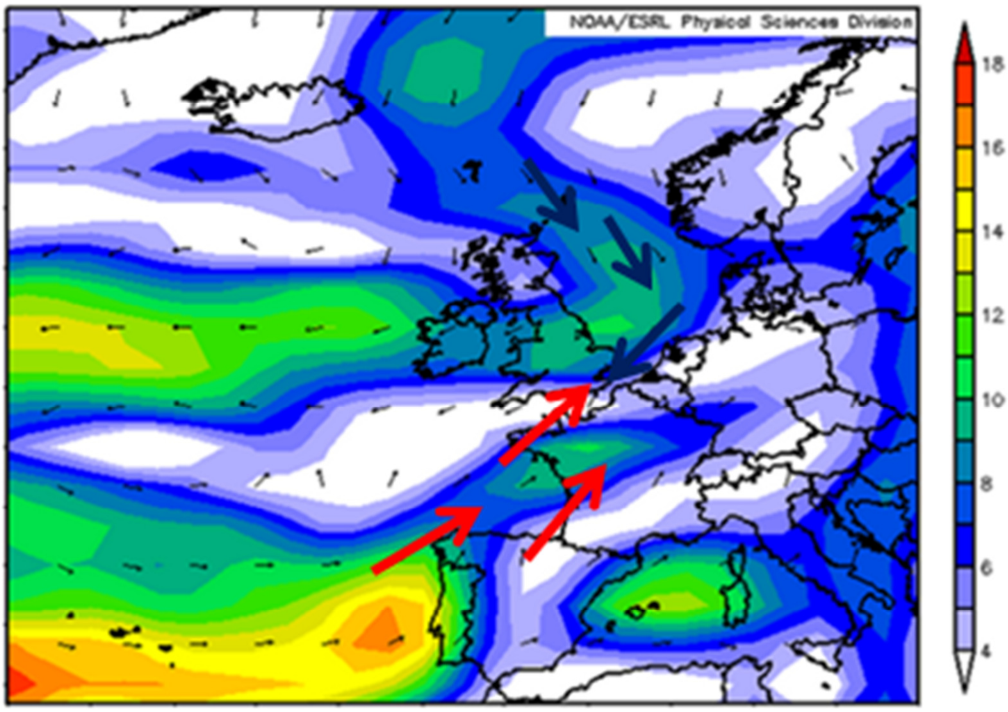

Figure 6.16: *950mb vector winds (ms^{-1}) on 26^{th} June 1974 (Note: larger arrows overlaid for clarity to indicate wind direction – warm air shown in red, cold air shown in blue)*

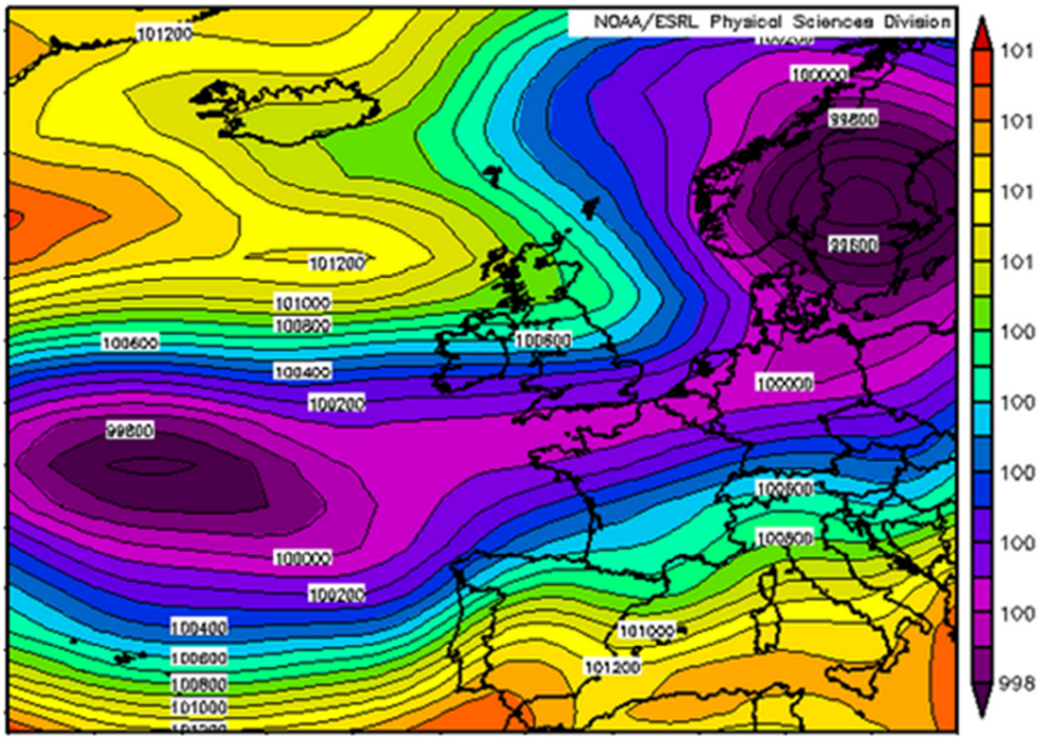

Figure 6.17: *Composite mean of sea level pressure (Pa) for 26th June 1974.*

6.5 01/08/1972 – North Wales and Norfolk – frontal event with embedded convection

This event which was triggered by a frontal weather system affected many parts of Norwich and on the same day local flooding was widely reported in North Wales and several other parts of England.Reports indicate that parts of Norfolk received some of the heaviest rainfall with Costessey near Norwich receiving 137.7mm in three quarters of an hour (Met Office Monthly Weather Report) causing heavy flooding.

Unfortunately, because this event fell on the first of the month, this event was removed from the raingauge data during the quality control process. By returning to the original raw data it was found that there was a spike in the data on this month of over 300mm/day, which fell above the threshold used for valid data, so the true reading for this date was not recorded in the area under investigation. High rainfall levels were recorded in other parts of Norfolk on this date, but none reached the 60mm/day level required to be identified.

Figure 6.18 shows the UK lying under an area of low pressure. Levels of CAPE were low during this period (plot not shown) and temperature records from the Met office monthly weather report show that it was unseasonably cool for the time of year, around 12°C (from reanalysis data, plot not shown) due to the polar maritime cyclonic winds which can be seen sweeping across the UK from the North in Figure 6.19.

This event was partly caused by frontal rainfall, however there are indications that embedded convection caused some of the very intense thundery downpours which led to the flooding in Norfolk. In North Wales the Northerly wind flow, combined with the orography of Snowdonia National Park may have led to orographic uplift and the seeder-feeder mechanism being the cause of the localised flooding. However, the lack of orography in East Anglia suggests that another mechanism for producing instability was present for the intense thunderstorms and lightning witnessed in this region. It is possible that there was some localised heating or an onshore wind which may have led to convection.

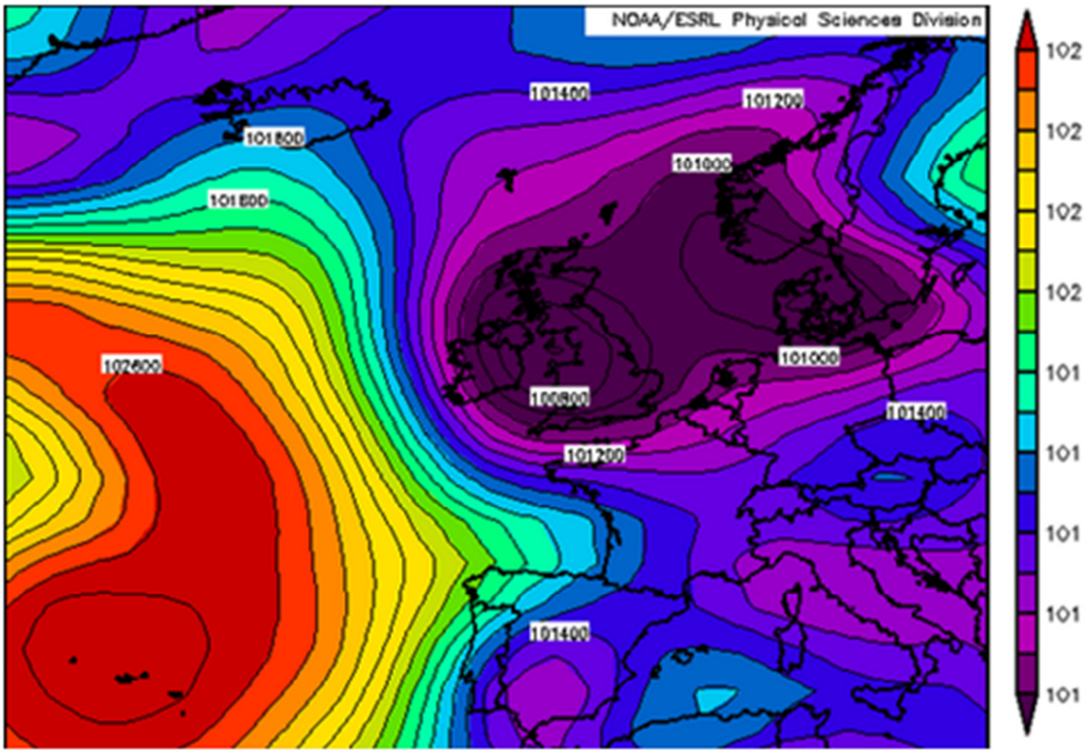

Figure 6.18: *Composite mean of sea level pressure (Pa) for 1st August 1972.*

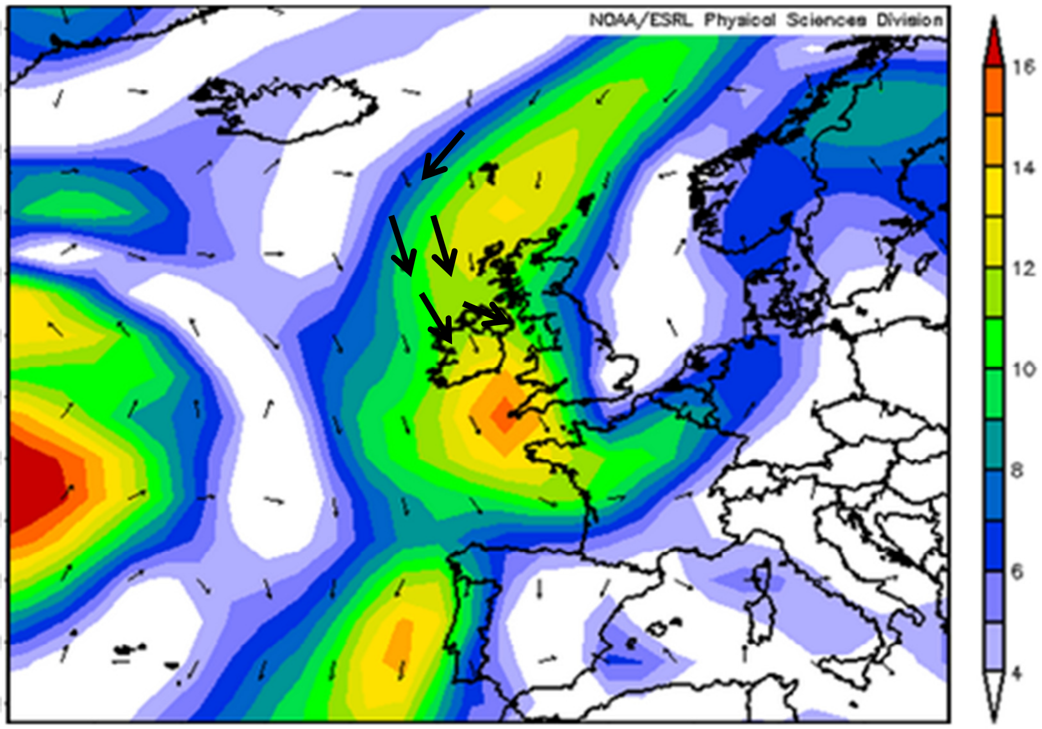

Figure 6.19: *950 mb vector winds (ms^{-1}) on 1st August 1972 (Note: larger arrows overlaid for clarity to indicate wind direction)*

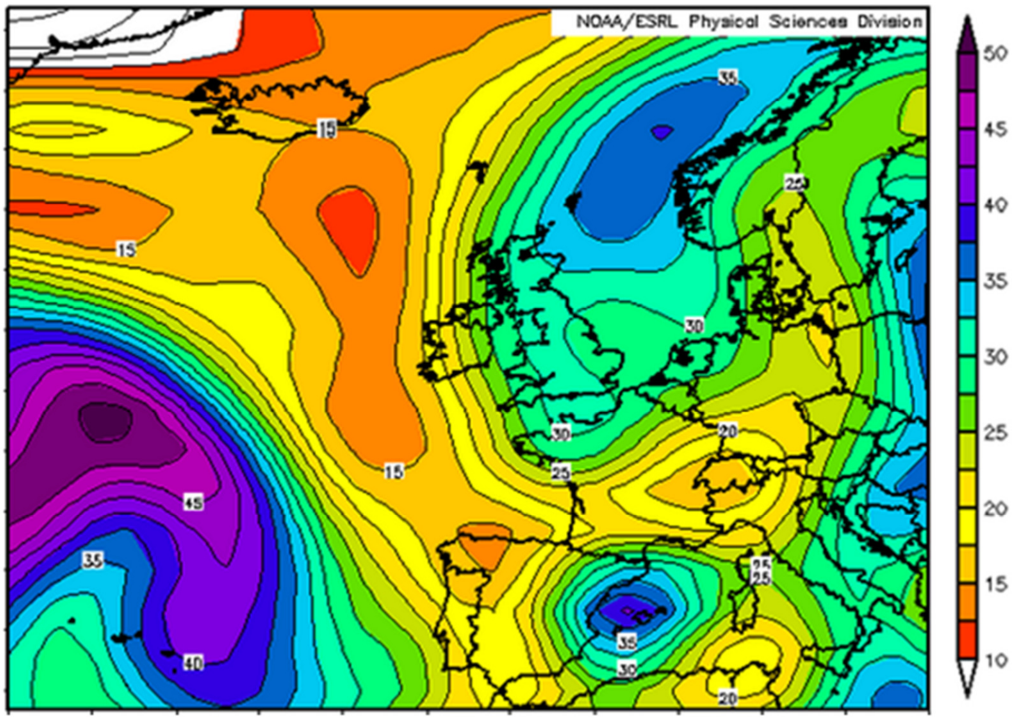

Figure 6.20: *Composite daily mean precipitable water for entire atmosphere (kgm^{-2}) for 1st August 1972*

6.6 07/07/1974 – South Wales - convective event

This event was unusual in that the UK was under an area of high pressure (Figure 6.23) at the time of the flooding. The maximum rainfall observation for this day in this region was 102.6mm (Table 4.4), which is high, even for this region of Wales which receives some very heavy rainfall events and although it is not apparent from the daily composite mean plots, the Met Office monthly weather report measured wind gust speeds of over 82knots (42ms^{-1}) in coastal districts in the south of the UK (Met Office Monthly Weather Report, July 1974). By returning to the observational raingauge data for the region on this data it was found that data was available from 5 out of the 10 raingauges, but only one, raingauge 9, which is inlandand close to the border of the mountainous Brecon Beacons National Park, recorded high rainfall levels. This was a daily event, with no rainfall observation above 16mm/day on the two days before and after this event.

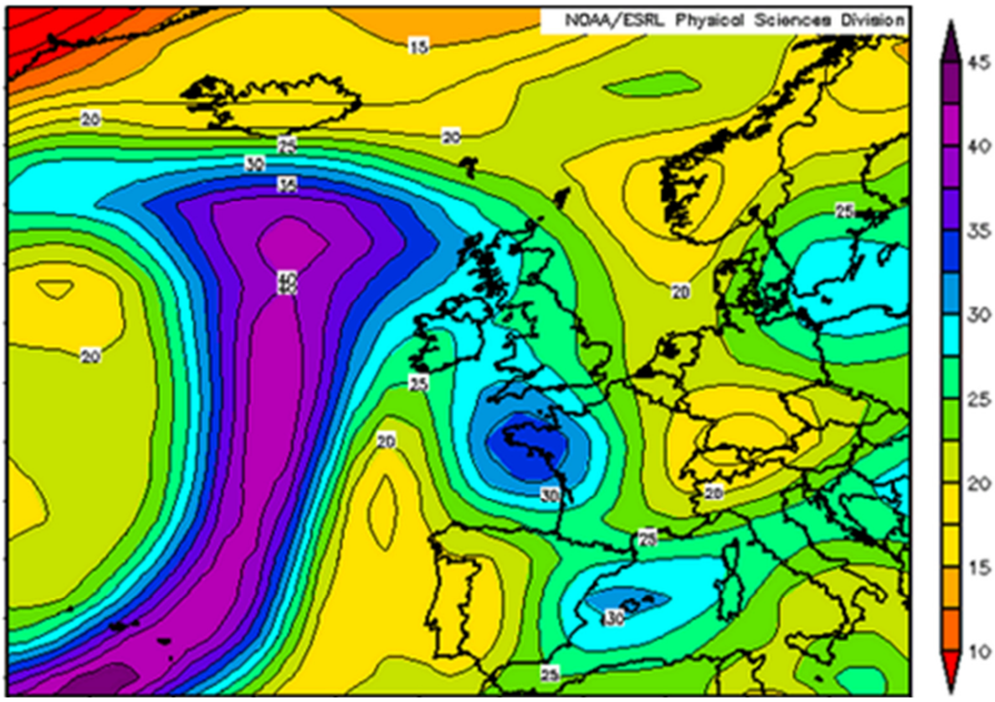

Figure 6.21: *Composite daily mean precipitable water for entire atmosphere (kgm^{-2}) for 7th July 1974.*

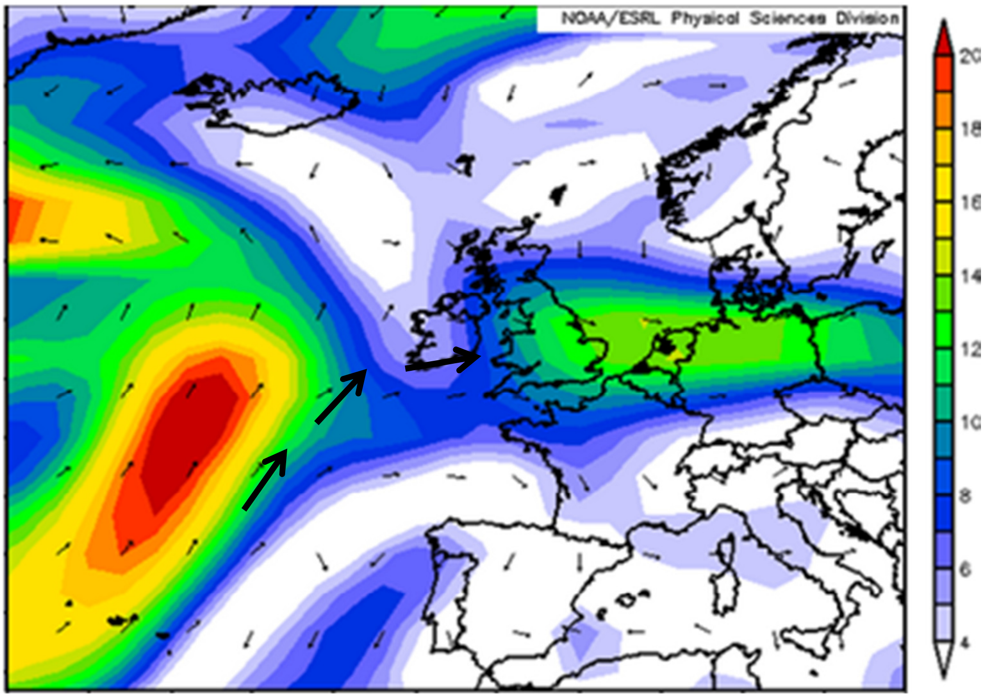

Figure 6.22: *950mb vector winds (ms^{-1}) on 7th July 1972 (Note: larger arrows overlaid for clarity to indicate wind direction)*

The South Wales flooding events were reported to be caused by a series of thundery storms (Hydrochronology Database) which caused highly localised flooding. The high winds (up to 20ms^{-1}), which were produced by the depression to the West of the UK (Figure 6.23) led to a convergence of moisture which can be seen to the West of the UK (Figure 6.21). The anti-cyclonic wind pattern of the high pressure system over the UK drew this moisture towards the West coast and into Wales as shown by the arrows in Figure 6.22.

It is likely that the thundery rain which caused the floods was a result of orographic lifting when the warm, moisture-laden Westerly winds were forced upwards by the mountainous area in the region around raingauge 9.

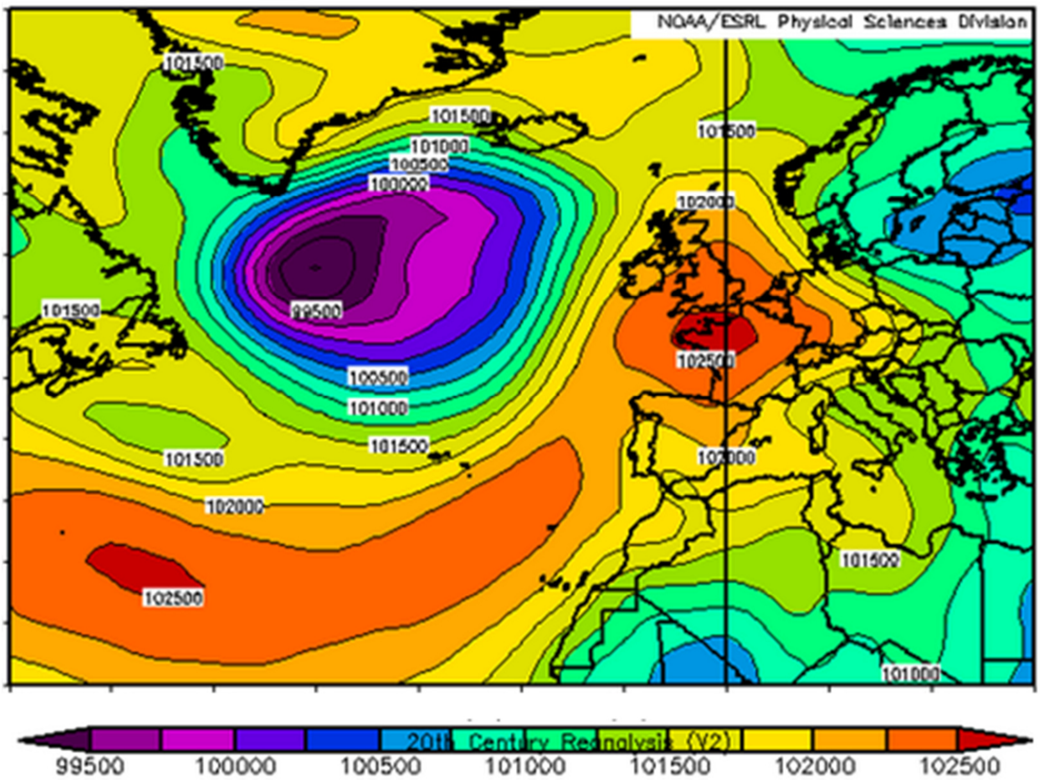

Figure 6.23: *Composite mean of sea level pressure (Pa) for 7th July 1974.*

6.7 Summary

The findings of this chapter suggest that there are a wide variety of conditions that can lead to a summer flood. This preliminary analysis is purely descriptive in its approach, but further investigation with a dynamical approach to the analysis of a larger sample of events is essential in order to define a range of patterns which lead to summer extreme rainfall.

The flooding event of 26th August 1912 was an example of an event which was purely synoptic in its nature. It was particularly devastating due to the duration of the rainfall, which fell over several days. The position of the jet stream could be significant in this event and further analysis of the upper atmosphere, particularly for events which involve low pressure systems would be very beneficial.

The event of July 1974 which affected South Wales was identified as being orographic in nature, although the source of moisture was a depression to the West of the UK. Once again, the need for a dense raingauge network is highlighted, as this event was only identified by one raingauge in the area.

The importance of data quality control was emphasised by the event of 1st August 1972, as this event was removed from the raingauge data after being wrongly identified as erroneous. In this case, rainfall was produced by a combination of synoptic and convective processes which affected a wide area, but was nevertheless not identified by the raingauge data.

Another case which highlighted an issue with the raingauge data analysis was that of August 26th 1974 which affected the East Sussex town of Hastings. This event was not identified due to its highly localised nature, with the nearest selected raingauge being over 10 kilometres away from the centre of the flood. This result reaffirms the need to include a larger number of raingauges in the study.

7. Conclusions

Summer flooding has serious impacts on the UK and, whilst individual events are often well understood, the forecasting and prediction of summer flooding events is still very difficult. This investigation combined daily raingauge data and historical flood data in order to assess the frequency and distribution of these events, along with a preliminary investigation into the atmospheric conditions surrounding the floods.

Whilst the UK is covered by a dense network of raingauges the observations of daily rainfall data are often not continuous and it was found that there are several issues with quality control. However, by using the available data and by combining observations from multiple raingauges using a nearest neighbour method, time series' of daily rainfall observations which were long enough for statistical analysis were produced.

This study found that by using raingauge data it was possible to successfully identified those summer flooding events which were produced by frontal systems, as these events tended to be more widespread and longer in duration therefore the density of the raingauge network is of less importance and daily rainfall levels were high enough to be identified by the 60mm/day threshold which was applied. However it was often not possible to identify flash flooding and events which were purely convective in nature by using daily rainfall data alone. Some of the convective events were intense enough to exceed the threshold of 60 mm/day which was used to identify floods, but the threshold was often too high to pick up events which may have occurred over very short periods of time. By lowering the threshold, many events which were purely heavy rainfall rather than flooding events would also be included in the sample. A percentile method of threshold selection was tested and it was found that this would be a better method of data selection, but for the scope of this project was not practicable due to the large number of events identified.

One of the events, the 1st of August, 1972 floods, was not identified by the raingauge data collected from the selected raingauges identified in Chapter 3, as the quality control method which was implemented according to the methods described in Section 4.1 led to the removal of the data for this particular day. This result highlights the importance of data quality control and the significance of historical flood data to confirm the presence of floods.

In four out of the five regions investigated it was found that during the summer months, flooding events were caused mainly by convective events. The exception was the area in South

Wales which experienced a higher number of frontal rainfall events, however the heaviest rainfall in this region was found inland, close to the mountainous region of the Brecon Beacons, which is means that this result becomes less significant for the insurance of caravans and holiday homes which are located closer to the coast. Based on a range of fixed thresholds, it was shown that 3-5 day events are more common in the Welsh regions D and E, with South Wales also receiving the greatest number of daily extreme events.

By using extreme value theory to fit probability distributions and to calculate return periods for each raingauge selected for this study it was possible to estimate return values for a range of return periods. However, due to the relatively short observational time series which were available, it was found that the uncertainty in the result was very high for return periods of above 50 years. Whilst the average return values calculated for each region are a useful result, it is apparent that it is necessary to look at the analysis of individual raingauges at specific locations, as spatial variation within each region is significant.

7.1 Future Work

- This project utilised raingauge data from five regions of the UK using a total of 50 raingauges. This method was partially successful in the identification of extreme rainfall events and provided useful information on the probability distribution of extreme events at specific locations. However, in order to form a more complete picture of each region studied, it would be beneficial to create a gridded dataset using observations from all available raingauges in each region. The data could be combined using the 'nearest neighbour' method used in this project, or a more sophisticated data interpolation method could be used. This would provide the density of observations required to identify some of the highly localised events which are typical of summer extreme rainfall.

- All the work was carried out using only daily rainfall records. It is apparent that it is essential to include hourly and even sub hourly data in order to identify flash flooding events. A flood which is caused by less than 60 mm of rain falling within the space of a few hours will not have been picked up by the thresholds applied in this study. It is unrealistic to lower the threshold further whilst still using daily rainfall data, as this leads to very large numbers of events being included in the study, many of which will not lead to flooding.

- Although efforts were made to identify as many floods as possible using historic flood records, this is a very time consuming process and it is apparent that many events have been overlooked. Further work needs to be carried out to put together a complete historic flood record for the UK using all available data sources.

- A preliminary study of the atmosphere showed that there are a range of conditions and processes which can lead to a flooding event. Further investigation into the dynamical processes involved in these flooding events would be of value, along with the inclusion of a larger sample of events in order to identify atmospheric patterns in the precursors to summer flooding events.

Appendix A

Start date and end date for each raingauge before modification using nearest neighbour method to fill in missing data and extend observational period.

Region A

src_id	Name	Station start date	Station end date	Latitude	Longitude
3803	CHAPEL ST LEONARDS P STA	01/01/1954	Current	53.2299	0.33688
393	CONINGSBY	01/01/1961	Current	53.0935	-0.17119
386	CRANWELL	01/01/1917	Current	53.0309	-0.50194
3957	EASTVILLE	01/01/1933	01/05/2002	53.1211	0.09828
390	GIBRALTAR POINT	01/01/1975	Current	53.0952	0.32304
3965	HOBHOLE P STA	01/01/1958	Current	52.939	0.0318
3959	LADE BANK BRIDGE	01-01-1883	Current	53.0698	0.05757
3888	NAVENBY: CROP FACTORY	01/01/1948	Current	53.1075	-0.46104
3825	SALTERSFORD P STA	01-01-1890	31/12/1990	52.8898	-0.62352
3932	SKIRBECK: BLACK SLUICE	01-01-1895	Current	52.9669	-0.02495
3919	WALCOT	01/01/1976	Current	52.9031	-0.42486

Region B

src_id	Name	Station start date	Station end date	Latitude	Longitude
4758	BROWICK HALL	01-01-1890	Current	52.5696	1.14379
4785	COLKIRK HALL	01/01/1951	01/10/2010	52.8029	0.85478
432	GORLESTON	30/07/1915	Current	52.5716	1.74002
4580	KILVERSTONE HALL	01/01/1906	31/12/1991	52.4218	0.78129
409	MARHAM	01/01/1951	Current	52.651	0.56772
4732	MELTON CONSTABLE	01/01/1969	Current	52.8554	1.0449
4745	NORTHREPPS HALL	01-01-1884	31/12/1966	52.9098	1.31829
4938	ORMESBY ST MICHAEL W WKS	01/01/1901	Current	52.6799	1.65041
4870	PULHAM ST MARY	01/01/1903	Current	52.4197	1.24779
4901	WOODGATE HOUSE	01-01-1884	Current	52.7868	1.23503

Region C

src_id	Name	Station start date	Station end date	Latitude	Longitude
6980	ASHFORD	01/01/1921	31/08/1995	51.1511	0.88009
7003	BARHAM P STA	01/01/1928	Current	51.2149	1.14864
6966	BROADSTAIRS: PIERREMONT PARK	01/01/1910	31/12/1952	51.3573	1.43899
7031	DOVER W WKS	01-01-1892	Current	51.1303	1.31964

6889	GREAT TONG	01/01/1944	Current	51.1881	0.62168
7034	HYTHE: OAKLANDS	01/01/1911	31/12/1974	51.0685	1.08626
7096	ICKLESHAM: NEWBANK	01/01/1916	01/03/2004	50.9305	0.58174
7084	PLAYDEN: SCOTS FLOAT	01/01/1943	Current	50.9689	0.7524
6866	SCOTNEY CASTLE	01-01-1873	01/10/2012	51.093	0.40749
7027	WALMER W WKS	01-01-1896	31/12/1990	51.2078	1.38344

Region D

src_id	Name	Station start date	Station end date	Latitude	Longitude
10910	CAE R-LLWYN ISAF FARM	01/01/1941	01/01/2007	51.6329	-3.17517
1263	CYMMER	01/01/1958	31/12/2001	51.6519	-3.62925
11010	LLANTRISANT S WKS	01/01/1956	Current	51.5544	-3.40197
10998	MAERDY W WKS	01/01/1972	Current	51.6786	-3.48697
11047	MERTHYR MAWR: SCHWYLL P STA	01/01/1944	Current	51.4812	-3.60271
1255	MUMBLES HEAD	01/01/1958	Current	51.5651	-3.98056
10878	NEWPORT: FROBISHER ROAD	01/01/1960	01/05/1999	51.582	-2.95842
1267	RHOOSE	01/01/1954	Current	51.4001	-3.3428
10912	ROGERSTONE GOLF CLUB	01/01/1931	31/12/1983	51.5973	-3.05693
11080	WERNFADOG	01/01/1920	31/12/1976	51.6835	-3.92118

Region E

src_id	Name	Area	Station end date	Latitude	Longitude
11636	ALWEN DAM	CLWYD	31/12/1973	53.0619	-3.55957
11686	CAE LLWYD RESR	CLWYD	Current	53.0243	-3.08787
11704	CILCAIN RESR NO 2	CLWYD	30/06/1996	53.1716	-3.25232
11558	DENBIGH HOSPITAL	CLWYD	31/12/1991	53.176	-3.42005
11589	GLASCOED FILTERS	CLWYD	Current	53.2495	-3.5058
11710	LEESWOOD FARM	CLWYD	31/12/1992	53.1362	-3.11374
11534	PEN-Y-FRON: TROFARTH	CLWYD	31/01/2001	53.2293	-3.74096
11659	VIVOD	CLWYD	01/05/2005	52.9728	-3.20535
11494	VOELAS HALL	CLWYD	Current	53.0487	-3.71425
11690	WREXHAM: CAMBERLEY DRIVE	CLWYD	01/07/2004	53.0537	-2.9818

Appendix B

Return Value Plots for regions B, C, D and E

Region B

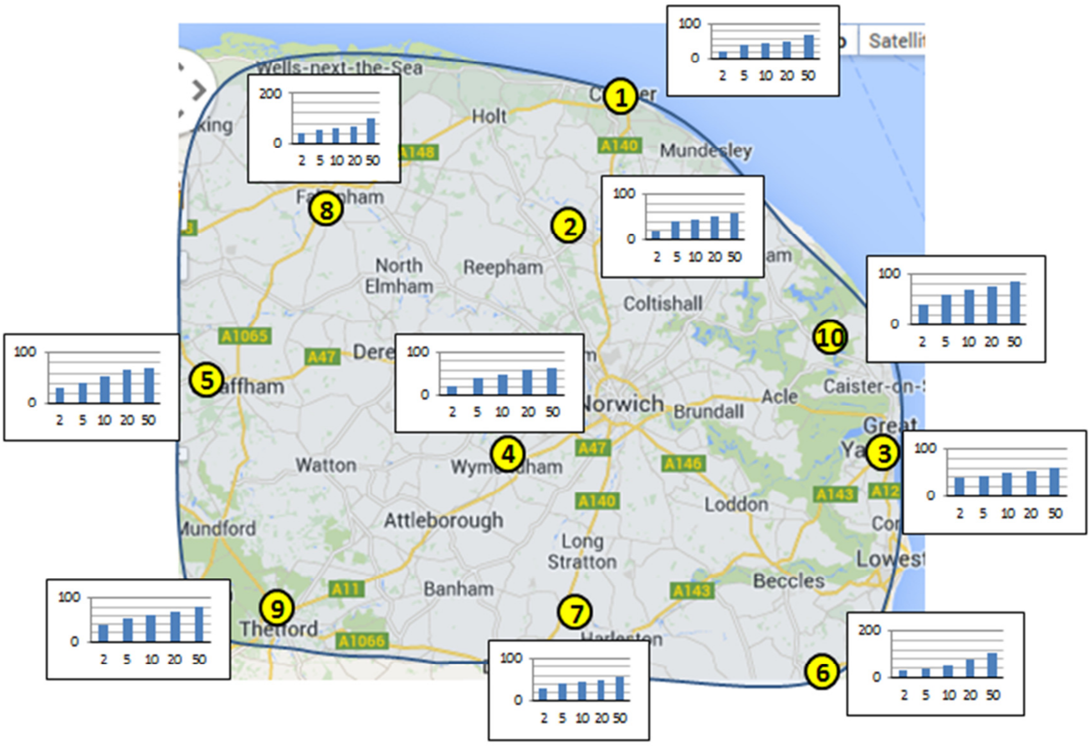

Figure B1: *Return values for selected raingauges in Region B. The bar charts show return values up to a 50 year return period. The 100 year return period has been excluded due to the large variation associated with this value.*

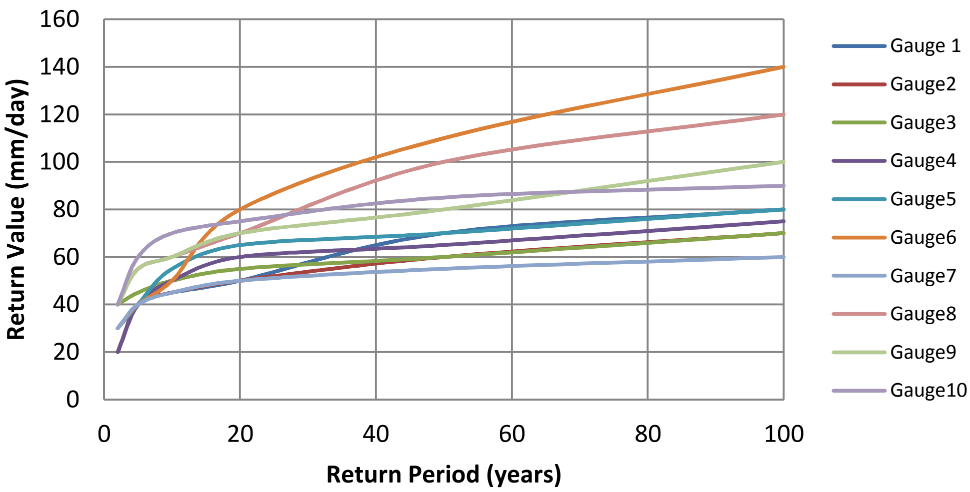

Figure B2: *Return levels for 2, 5, 10, 20 and 50 year events for Region B*

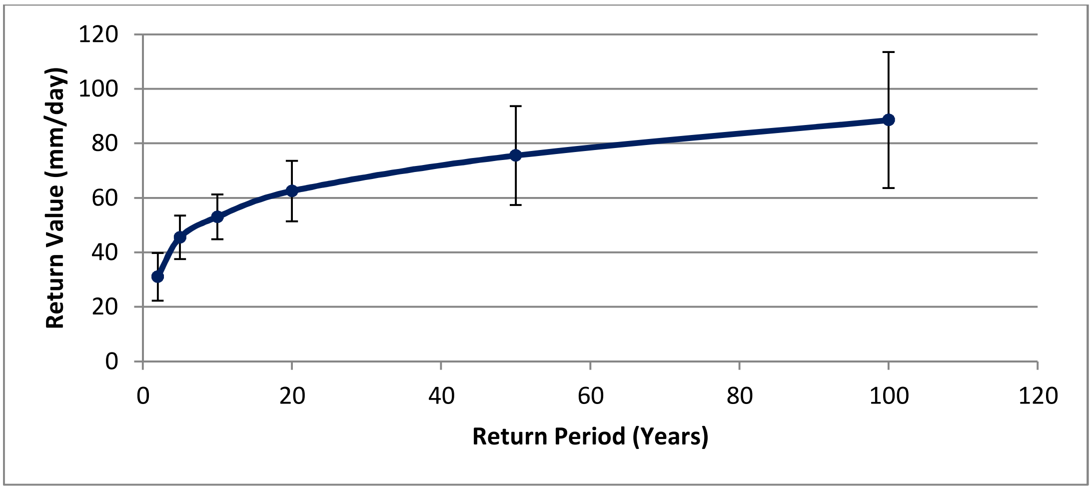

Figure B3: *Return Period plot for Region B showing average return periods for the entire region. The errors shown here are given by the standard deviation of the 10 raingauge readings. It is important to note that this does not include the large errors associated with the initial return value calculation*

Region C

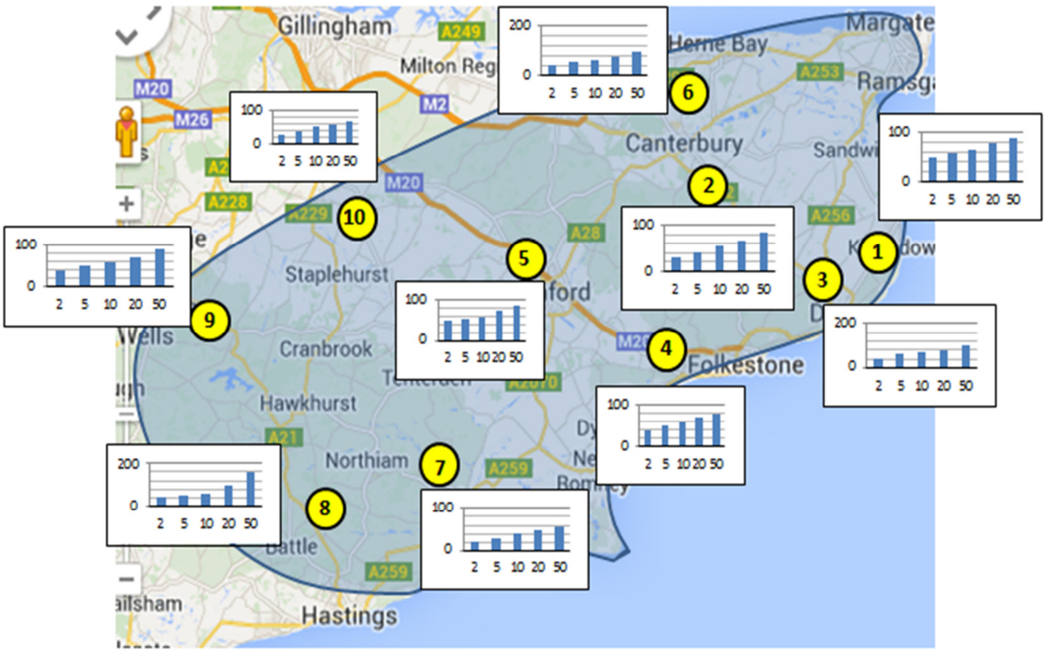

Figure B4: *Return values for selected raingauges in Region C. The bar charts show return values up to a 50 year return period. The 100 year return period has been excluded due to the large variation associated with this value.*

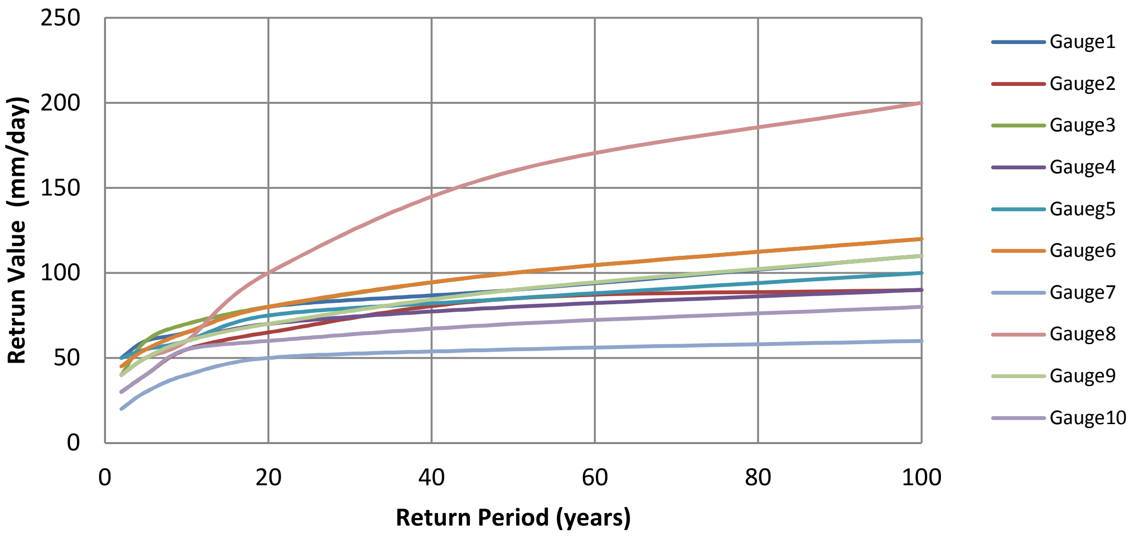

Figure B5: *Return levels for 2, 5, 10, 20 and 50 year events for Region C.*

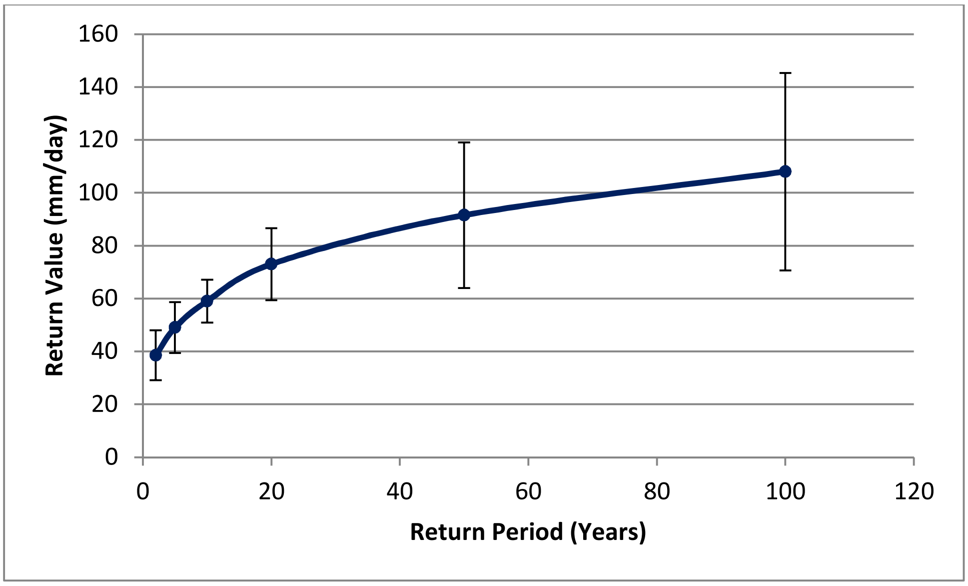

Figure B6: *Return Period plot for Region C showing average return periods for the entire region. The errors shown here are given by the standard deviation of the 10 raingauge readings. It is important to note that this does not include the large errors associated with the initial return value calculation*

Region D

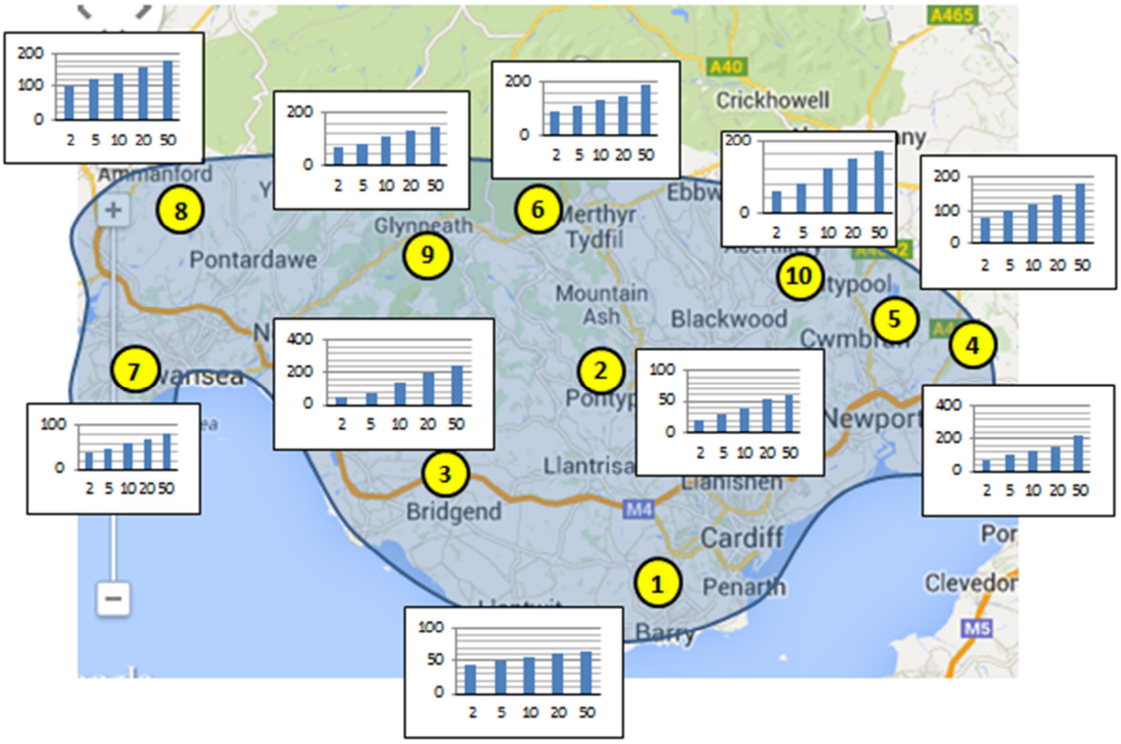

Figure B7: *Return values for selected raingauges in Region D. The bar charts show return values up to a 50 year return period. The 100 year return period has been excluded due to the large variation associated with this value.*

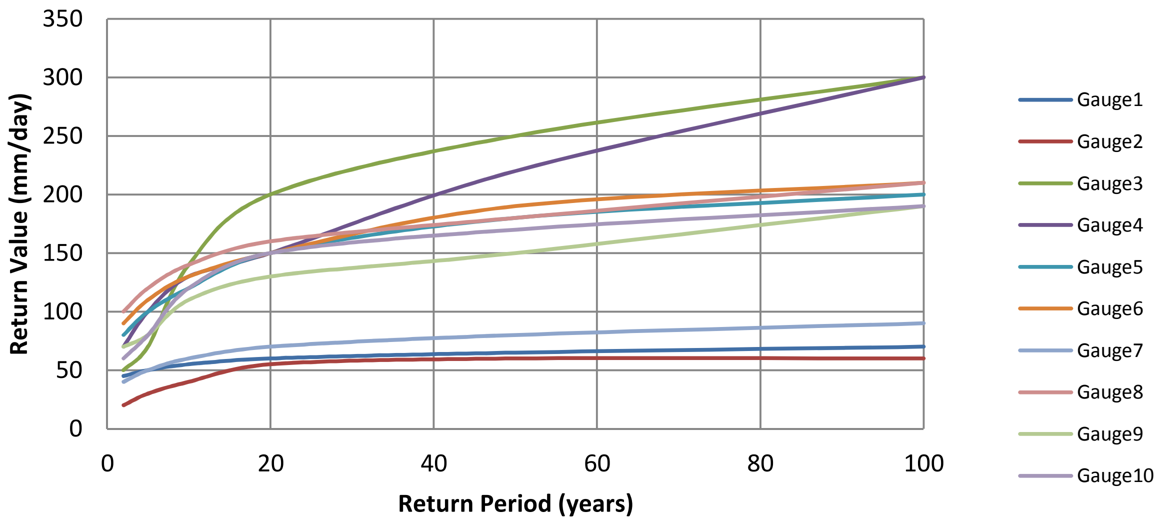

Figure B8: *Return levels for 2, 5, 10, 20 and 50 year events for Region D.*

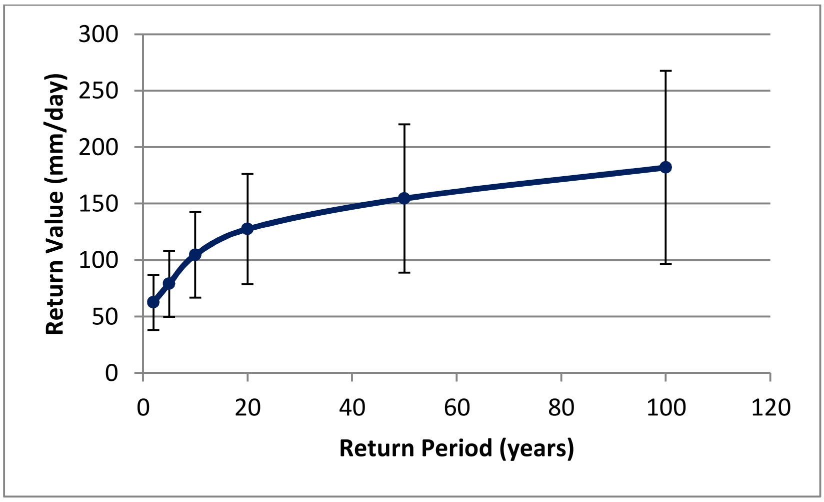

Figure B9: *Return Period plot for Region D showing average return periods for the entire region. The errors shown here are given by the standard deviation of the 10 raingauge readings. It is important to note that this does not include the large errors associated with the initial return value calculation*

Region E

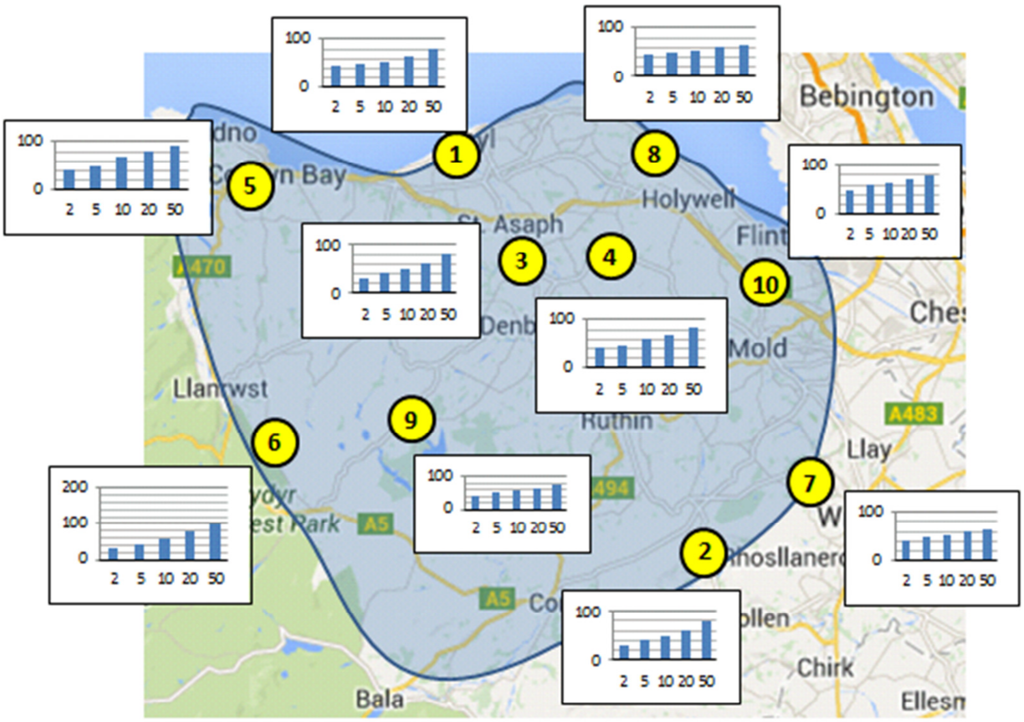

Figure B10: *Return values for selected raingauges in Region E. The bar charts show return values up to a 50 year return period. The 100 year return period has been excluded due to the large variation associated with this value.*

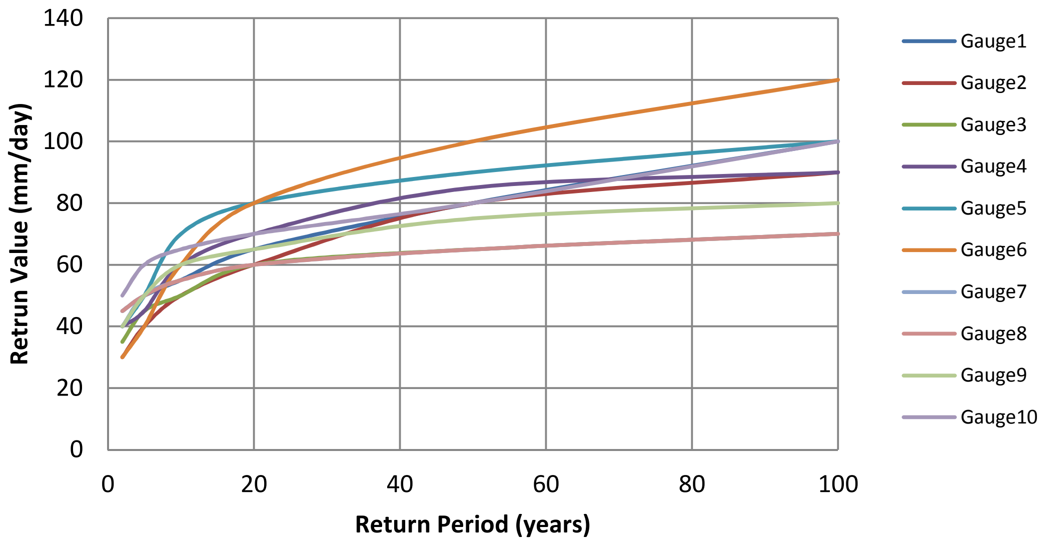

Figure B11: *Return levels for 2, 5, 10, 20 and 50 year events for Region E.*

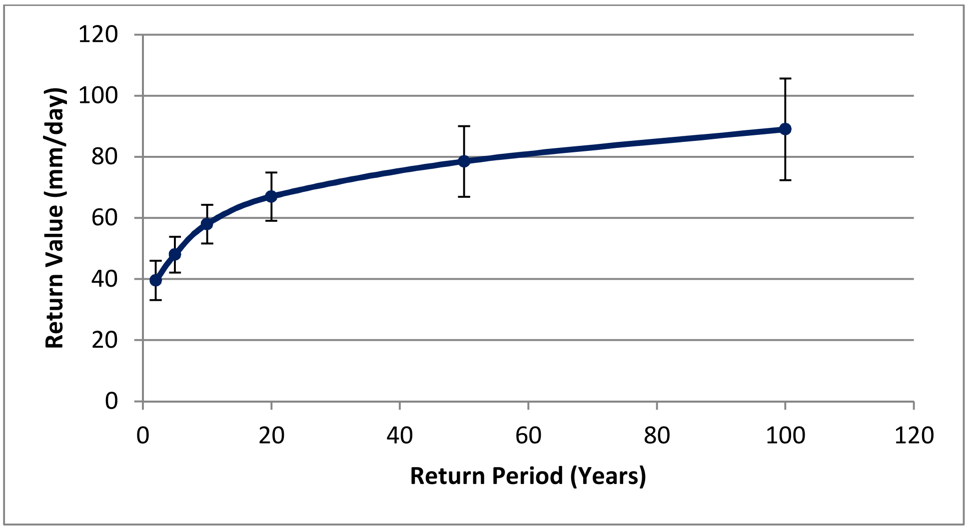

Figure B12: *Return Period plot for Region E showing average return periods for the entire region. The errors shown here are given by the standard deviation of the 10 raingauge readings. It is important to note that this does not include the large errors associated with the initial return value calculation*

References

Acreman, M (1998). Extreme historical UK floods and maximum flood estimation. Journal of the Institute of Water and Environmental Management. 3 p.404-?-412.

Almond, C. (2013). Heavy rain and flooding in southwest England on 6-7 July 2012. *Weather*, *68*(7), 171–175. doi:10.1002/wea.2084

Bayliss, A. C., & Reed, D. W. (n.d.). The use of historical data in flood frequency estimation, (March 2001).

Blackburn, M., Methven, J., & Roberts, N. (2008). Large-scale context for the UK floods in summer 2007. *Weather*, *63*(9), 280–288. doi:10.1002/wea.322

British Rainfall (1912): The great rain storm of August 25th−26th. London: HMSO, 28−47

British Rainfall (1930) July 23rd. London: HMSO, 63−66.

British Rainfall (1931a) August 8th. London: HMSO, 61−62.

British Rainfall (1931b) November 3rd. London: HMSO, 70−73.

British Rainfall (1937) July 15th. London: HMSO, 62−63.

British Rainfall (1959) Heavy falls in short periods. London:HMSO

Brooks, N. (2012). The August 1912 floods in Norfolk. *Weather*, *67*(8), 204–205. doi:10.1002/wea.1926

Burton, C. (2011). How weather patterns have contributed to extreme precipitation in the United Kingdom , and links to past flood events.

Chatterton, J., Viavattene, C., Morris, J., Penning-rowsell, E., & Tapsell, S. (2007). *The costs of the summer 2007 floods in protecting and improving the environment in England*

Chronology of British Hydrological Events: Available at http://www.trp.dundee.ac.uk/cbhe/

Stuart Coles, 2001: An Introduction to Statistical Modeling of Extreme Values. *Springer*

Compo, G. P., Whitaker, J. S., & Sardeshmukh, P. D. (2006). Feasibility of a 100-Year Reanalysis Using Only Surface Pressure Data. *Bulletin of the American Meteorological Society*, *87*(2), 175–190. doi:10.1175/BAMS-87-2-175

Compo, G. P., Whitaker, J. S., Sardeshmukh, P. D., Matsui, N., & Allan, R. J. (2011). Review Article The Twentieth Century Reanalysis Project.

Dales, M. Y., & Reed, D. W. (n.d.). Report No . 102 Regional flood and storm hazard assessment.

Date, O., & Sanderson, M. (2010). Changes in the frequency of extreme rainfall events for selected towns and cities For : Ofwat Date : July 2010 Author : Michael Sanderson, (July).

Flood Studies Report (1975) Volume II: Meteorological Studies. Swindon: Natural Environment Research Council.

Fowler, H. J., & Wilby, R. L. (2010). Detecting changes in seasonal precipitation extremes using regional climate model projections: Implications for managing fluvial flood risk. *Water Resources Research*, *46*(3), n/a–n/a. doi:10.1029/2008WR007636

Golding, B., Clark, P., & May, B. (2005). The Boscastle flood: Meteorological analysis of the conditions leading to flooding on 16 August 2004. *Weather*, *60*(8), 230–235. doi:10.1256/wea.71.05

Hand, W. H., Fox, N. I., & Collier, C. G. (2004). A study of twentieth-century extreme rainfall events in the United Kingdom with implications for forecasting. *Meteorological Applications*, *11*(1), 15–31. doi:10.1017/S1350482703001117

Hasan, M. M. (2013). Filling gaps in daily rainfall data : a statistical approach, (December), 1–6.

Jones, M. R., Blenkinsop, S., Fowler, H. J., & Kilsby, C. G. (2014). Objective classification of extreme rainfall regions for the UK and updated estimates of trends in regional extreme rainfall. *International Journal of Climatology*, *34*(3), 751–765. doi:10.1002/joc.3720

Lavers, D. a, Allan, R. P., Villarini, G., Lloyd-Hughes, B., Brayshaw, D. J., & Wade, A. J. (2013). Future changes in atmospheric rivers and their implications for winter flooding in Britain. *Environmental Research Letters*, *8*(3), 034010. doi:10.1088/1748-9326/8/3/034010

Lavers, D. a., Allan, R. P., Wood, E. F., Villarini, G., Brayshaw, D. J., & Wade, A. J. (2011). Winter floods in Britain are connected to atmospheric rivers. *Geophysical Research Letters*, *38*(23), n/a–n/a. doi:10.1029/2011GL049783

Lavers, D. a., & Villarini, G. (2014). The relationship between daily European precipitation and measures of atmospheric water vapour transport. *International Journal of Climatology*, n/a–n/a. doi:10.1002/joc.4119

Lavers, D. a., Villarini, G., Allan, R. P., Wood, E. F., & Wade, A. J. (2012). The detection of atmospheric rivers in atmospheric reanalyses and their links to British winter floods and the large-scale climatic circulation. *Journal of Geophysical Research: Atmospheres*, *117*(D20), n/a–n/a. doi:10.1029/2012JD018027

Maraun, D. (2014). Extreme Value Theory in a Nutshell. (February).

Mayes, J., & Winterton, J. (2007). The west Surrey thunderstorm of 13 August 2006, (August 2006), 50–55.

Met Office Monthly Weather Report: http://www.metoffice.gov.uk/archive/monthly-weather-report

Mortimer, S. (2004). Cloudburst upon Hendraburnick Down : The Boscastle storm of 16 August 2004, (August), 219–227.

NOAA (2011). 20th Century Reanalysis. Available at: http://www.esrl.noaa.gov/psd/cgi-bin/data/composites/plot20thc.day.v2.pl

Parry, S., & Kendon, M. (2013). 2012 : from drought to floods in England and Wales, (2001).

Riemann-Campe, K., Fraedrich, K., & Lunkeit, F. (2009). Global climatology of Convective Available Potential Energy (CAPE) and Convective Inhibition (CIN) in ERA-40 reanalysis. *Atmospheric Research*, *93*(1-3), 534–545. doi:10.1016/j.atmosres.2008.09.037

Rodda, H. J. E., Little, M. A., Wood, R. G., Macdougall, N., & Mcsharry, P. E. (2007). A digital archive of extreme rainfalls in the British Isles from 1866 to 1968 based on British Rainfall, *1907*(July 1907), 71–75.

Sibley, A. (2012). Thunderstorms from a Spanish Plume event on 28 June 2011. *Weather*, *67*(6), 143–146. doi:10.1002/wea.1928

Tardivo, G., & Berti, A. (2013). ISSN : 2276-7495 COMPARISON OF FOUR METHODS TO FILL THE GAPS IN DAILY PRECIPITATION DATA COLLECTED BY A DENSE WEATHER NETWORK. doi:10.7237/sjeer/265

Van den Brink, H. W., Können, G. P., Opsteegh, J. D., van Oldenborgh, G. J., & Burgers, G. (2005). Estimating return periods of extreme events from ECMWF seasonal forecast ensembles. *International Journal of Climatology*, *25*(10), 1345–1354. doi:10.1002/joc.1155

Young, M. V. (2013). Thunderstorms over northern England on 6 August 2011. *Weather*, *68*(8), 212–217. doi:10.1002/wea.1996