University of Reading

Department of Meteorology

How weather patterns have contributed to extreme precipitation in the United Kingdom, and links to past flood events

Christopher Burton

A dissertation submitted in partial fulfilment of the requirement for the degree of

MSc Applied Meteorology

15th August 2011

Abstract

Extreme precipitation events were compiled on one day, five day and monthly timescales between 1931-2008 for the coherent precipitation regions of Northern Scotland and South East England in the UK, using the MetOffice HADUKP precipitation series. The weather patterns over the UK for each of these events was analysed, using the 20th Century Reanalysis data, to determine whether certain weather patterns are repeated during the timescales of these events. Eight categories of weather types associated with extreme rainfall were compiled, and each event was assigned to a category. It was found that events in Northern Scotland were dominated by a strong Icelandic Low to the north and west of Scotland. In comparison events in South East England showed a wide range causal weather types. Extreme events were also compared to recorded flood events during the period, and it was found that shorter extreme events were more likely to cause flooding in Northern Scotland, with more monthly extreme events associated with flooding in South East England. Many flood events were not associated with extreme rainfall, and this was argued to be down to several factors. These included the fact that extreme events can be highly localised, and be missed in a regional dataset, or the fact that much longer periods of extreme rainfall (greater than one month) can lead to flooding.

Acknowledgements

I would like to thank my project supervisors, Richard Allan and Andrew Wade as well as David Lavers for their initial advice and ideas at the start of the project. Throughout the development of the project they have also provided significant feedback and assistance which has been greatly appreciated.

Contents Page

List of Tables and Figures

1. Introduction

1.1 Flooding in the United Kingdom

Flooding is one of the major natural hazards which impacts the United Kingdom, and can lead to significant damage to infrastructure and property, with an estimated 0.1% of the country's GDP (or around £2 billion) being lost to flood damage annually (European Environment Agency, 2003). It is estimated that over 5 million people in England and Wales alone live and work in properties at risk of flooding (Environment Agency, 2011). The Department for Food, the Environment and Rural affairs plans to spend at least £2.1 billion on flood (and coastal erosion) defences over the next few years (DEFRA, online, 2011), providing further evidence that flooding in the UK is a serious and costly problem. There have been concerns that with future climate change, rainfall events will become more intense and frequent, and therefore increase the risk of flooding (Fowler et al, 2005). For example the 2000 floods have been considered to have been intensified by anthropogenic greenhouse gas emissions (Pall et al, 2011). There is also a perceived idea that flooding is increasing, with the widespread flooding in spring 1998, autumn 2000, winter 2003 and summer 2007; however there is little trend in the frequency of flooding in the UK over the past 60-120 years (Robson, 2002).

Flooding, defined as when peak discharge of a river exceeds its channel capacity (Mayhew, 2004), has many different causes and sources, and can be broken down into events that are caused by the weather, or events that are created in different ways. These events may include ice-dam failure, human-dam failure due to landslides, or sub glacial volcanic melt water discharge (USGS, 2004). However many of these flooding causes are irrelevant to the UK, as the country does not have glaciers, or occur very infrequently. Meteorological induced flooding can be further split into four main categories (Idea.gov.uk, 2011). (1) River or fluvial flooding occurs when a watercourse overtops its banks and floods the surrounding low lying areas. (2) Surface or pluvial flooding, which occurs when rainfall is too intense to infiltrate into the ground. (3) Groundwater flooding arises when the water table rises to the surface, with the surface becoming saturated with water, and (4) flooding arising from coastal processes, such as storm surges and exceptionally high tides. However this study is primarily focused on fluvial flooding. This category of flooding generally arises from excessive amounts of rainfall during a period of time. High rainfall events that also lead to flooding are determined by four main factors. These are the intensity of the rainfall, the duration of the rainfall, antecedent soil moisture, and the response of the catchment (Hand et al, 2004).

1.2 Precipitation in the United Kingdom

There are large spatial differences in precipitation across the United Kingdom, with a north-west to south-east gradient in annual rainfall totals. This is generally due to the fact that much of the high ground in the country is in the north and west, and thus orographic processes can causes significant accumulation of rainfall in these areas. These mountainous areas are exposed to moist westerly airflow, and this shelters the south and east of the country (Lavers et al, 2010). In the Ewe river catchment in north west Scotland, the 1961-1990 average for the area was 2,273mm of rainfall annually (Centre for Ecology and Hydrology, 2011a). In the Great Stour in South East England the average rainfall over the same period is just 747mm(Centre for Ecology and Hydrology, 2011b), and shows the significant contrast in precipitation between the opposite ends of the United Kingdom, as shown in figure 1.1.

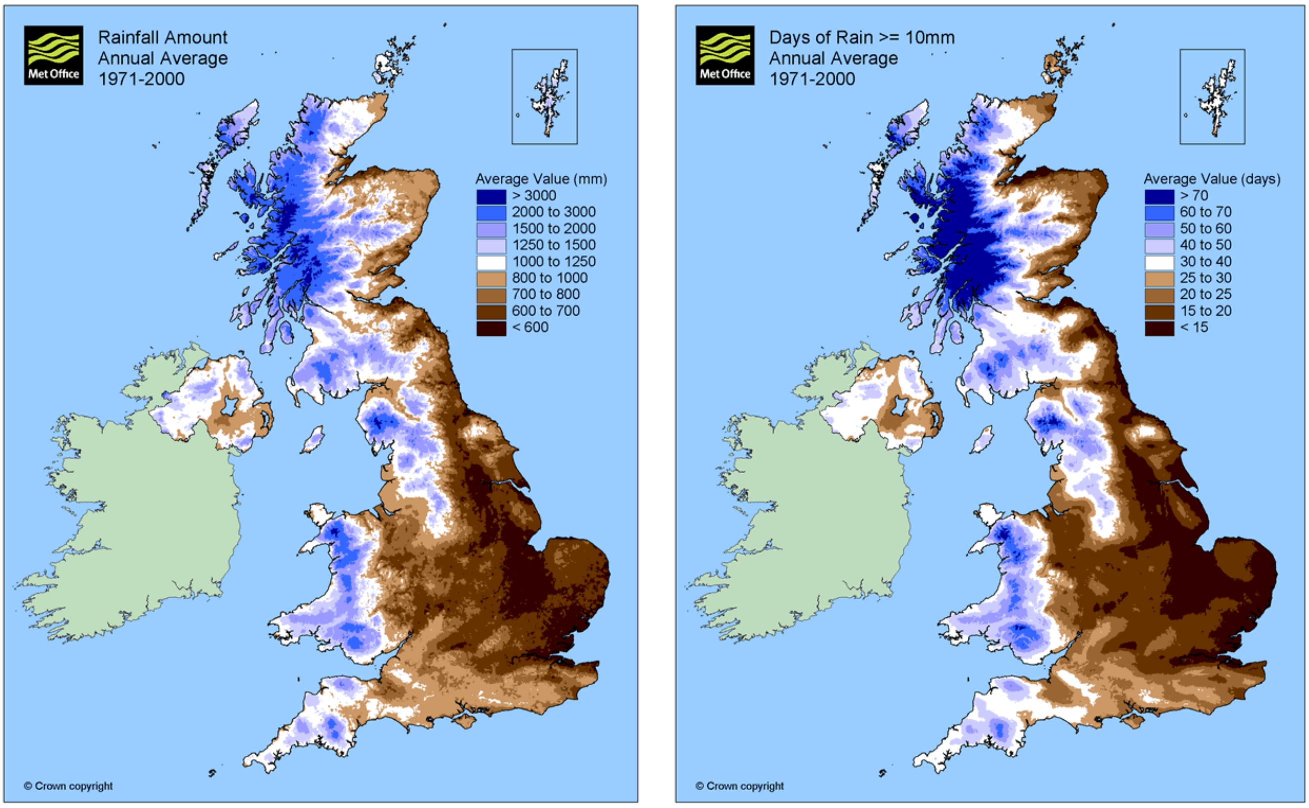

Figure 1.1. (a) Annual average rainfall across the United Kingdom (1971-2000). (b) Annual average days with rainfall exceeding 10mm. (Source: MetOffice, 2011b)

In terms of heavy rainfall events (greater than 10mm in a day), there is a similar pattern, with more heavy rainfall events occurring in the mountainous regions in the north and west of the country (figure 1.2). Therefore extreme rainfall events are likely to be larger in magnitude in the north west as opposed to the south east.

Although the total amount of rainfall over a year has not shown any significant trends over the past 100 years, both the intensity of rainfall, and the number of very wet 5 day events has shown some increases over the period, especially during winter (Osborn and Maraun, 2008). With future climate change, these trends are also expected to continue and potentially increase (Fowler et al, 2005). It is the intensity, or prolonged nature of rainfall which can lead to significant runoff, and therefore increase the risk of flooding. If this trend therefore increases into the future, it potentially could also lead to increases in flooding.

1.3 Aims and Objectives

The aim of this investigation was to determine whether the weather patterns which act to create extreme rainfall over various timescales between 1931 and 2008, can be categorised into specific groups, depending on the characteristics of the synoptic scale circulation patterns during the period of the extreme rainfall. The weather regimes which act to create extreme rainfall have been compared between Northern Scotland and South East England and linked to flooding and high flow events which have occurred during the period.

This will be carried out by three objectives. Firstly extreme rainfall events have been extracted from the precipitation time series for both Northern Scotland and South East England, on timescales of one day, five days and a month. Secondly the synoptic scale weather patterns during these rainfall events were compiled using reanalysis data, and placed in categories depending on similar characteristics in specific atmospheric variables. Thirdly, these rainfall events have been related to past flooding and high river flow events in both Northern Scotland and South East England, using both historical records of flooding, and using two case study catchments, one in each region.

If the risks of flooding are likely to increase, it will become ever more important to understand the causes of heavy and prolonged rainfall which lead to flooding. Therefore it is important to be able to understand whether there are certain weather regimes which lead to heavy rainfall over the UK, so that better forecasting of these events may be possible. This will provide the first step in being able to determine the weather regimes which need to be focused on within global climate models (GCMs) in order to forecast extreme rainfall events more accurately at present, and into the future with the threat of global climate change.

2. Literature Review/Background

Previous research into past flooding events was critically analysed, with an emphasis on the meteorological causes of these events. It is argued that although substantial research has been undertaken into individual events, little work has gone into whether the weather patterns associated with extreme rainfall and flooding show similar characteristics between events. The trends in UK precipitation will be looked at first, with research into future scenarios under climate change being discussed. Studies into the exceptional flooding during the autumn of 2000 will be used as a case study. Finally research categorising weather events, and links between large scale atmospheric circulation to precipitation and river flows will then be analysed.

2.1 Trends in UK rainfall and future climate change

Rainfall records in parts of the UK are some of the longest continual datasets on precipitation in the world. The England and Wales precipitation series began in 1766, which is the longest instrumental record of its kind, and therefore allows the analysis of trends in precipitation over this region over a relatively long period of time (MetOffice, 2011a). Monthly and daily series of rainfall however extend to 1931 for all regions of the UK. Research using such data has indicated that precipitation between 1961-2000 has increased in terms of total winter and autumn precipitation as well as an increased frequency and intensity of heavy rainfall events, with the greatest increases occurring in Scotland (Osborn and Hulme, 2002). The opposite has been found during the summer months, with the greatest decreases found in the south east of England (Osborn and Hulme, 2002). It is argued that these changes are not only due to natural variability alone, but are also partly due to climate change over the period, as temperatures have increased between 0.4-0.6^{0}C since the start of the last century, and as the changes in the North Atlantic Oscillation (NAO) cannot be used to explain the trends shown entirely (Osborn and Hulme, 2002).

Despite the long records available in this country, they still have serious limitations when trying to identify whether the data shows a long term trend or just naturally variability, where the oscillation in the data may have a period which is far longer than that of the data set. The last half of the twentieth century has experienced significant climatic variability, and it has been considered that it will be difficult to assess the likely trend in future flood risk associated with extreme events (Macklin and Rumsby, 2007).

The intensity of the rainfall has also shown an increase in winter. For example the total contribution of heavy rainfall (greater than 15mm per day) to winter totals has increased from 7% to 12% between 1910 and 2005 (Osborn and Maraun, 2008). This could have impacts on increasing the risk of localised flooding events, especially in urban areas, as well as increasing the risks of surface erosion. Increases in 5-day spells of very wet weather (more than 15mm on each day) also indicate that the risks of flooding could have increased over the period (Osborn and Maraun, 2008). Despite the increase in winter rainfall over the period, there is no significant increasing trend in flood frequency in the UK (Robson, 2002). Potentially this could partially be due to the fact that increasing atmospheric temperatures may lead to an increase in evaporation.

If these observed trends in precipitation have been seen during the last century, before the major impacts of climate change have been felt, it is important that we are able to understand whether such trends will continue and increase into the future. However caution should be taken not to over state the significance of trends which may be present in what is a fairly short time series of precipitation data, especially when looking at only 40 years of data as was the case in the Osborn and Hulme (2002) investigation. Without a longer period of data, it is impossible to confidently determine whether the trends in the data are down to a possible regime change in rainfall over the UK, which may be partly attributed to anthropogenic greenhouse gas emissions. It may well in fact just be down to natural variability in rainfall patterns over the UK, and therefore may well return back to levels seen at the beginning of the century within the next few decades, a matter which was argued by Robson (2002). Therefore we need to continue to analyse precipitation datasets into the future to see whether the trends shown in the last few decades further develop. In fact certain studies such as Thompson (1999) have argued that there is no long-term trend in precipitation over the British Isles.

However, generally, with these observed trends, and the potential risks of present and future climate change, many studies have looked into whether precipitation amount, rate and distribution will change into the future over the United Kingdom (Fowler and Kilsby, 2003; Zolina et al 2010; Durman et al, 2001; Haylock et al, 2006). IPCC projections of precipitation by 2080-2099 indicate that the trends seen in precipitation over the last 50 years will continue to increase in magnitude. It is expected that winter precipitation will increase across the whole of the UK by 10-15% from 1980-1990 levels, with summer precipitation decreasing by 10-20% in South East England but staying fairly similar in Northern Scotland (see figure 2.1) (IPCC, 2007). Increases in winter precipitation are most pronounced in model runs which also simulate an increase in the north-south pressure gradient over the region, and therefore an increase in moisture laden westerly winds across the UK. It is also expected that over northern and central Europe (including the UK), that extremes in winter precipitation will increase in magnitude and frequency. Whether or not extreme summer rainfall will change by the end of the decade is uncertain however (IPCC, 2007). With a change in intensity and distribution of precipitation towards more extreme events, it is therefore likely that flood events will increase in magnitude and frequency over the next century (Durman et al, 2001), especially as the changes are may occur too quickly for the hydrological system to adapt to increases in winter rainfall.

However it must be noted that there is significant spread in the results for precipitation trends into the future. This comes from the use of different models, scenarios of future greenhouse gas emissions and using different initial conditions. For example in the study by Haylock et al (2006), there was a large spread in results between different models, with large uncertainties on each individual result also. For example the observed trend for wetter winters in South East England was not evident in all of the results from the 6 models used. This is also evident in the bottom three plots shown in figure 2.1, which indicates the number of models that show an increase in precipitation. Except for Northern Scotland in winter, there is never a 100% certainty in whether precipitation will increase or decrease into the future (IPCC, 2007).

(a) (b) (c)

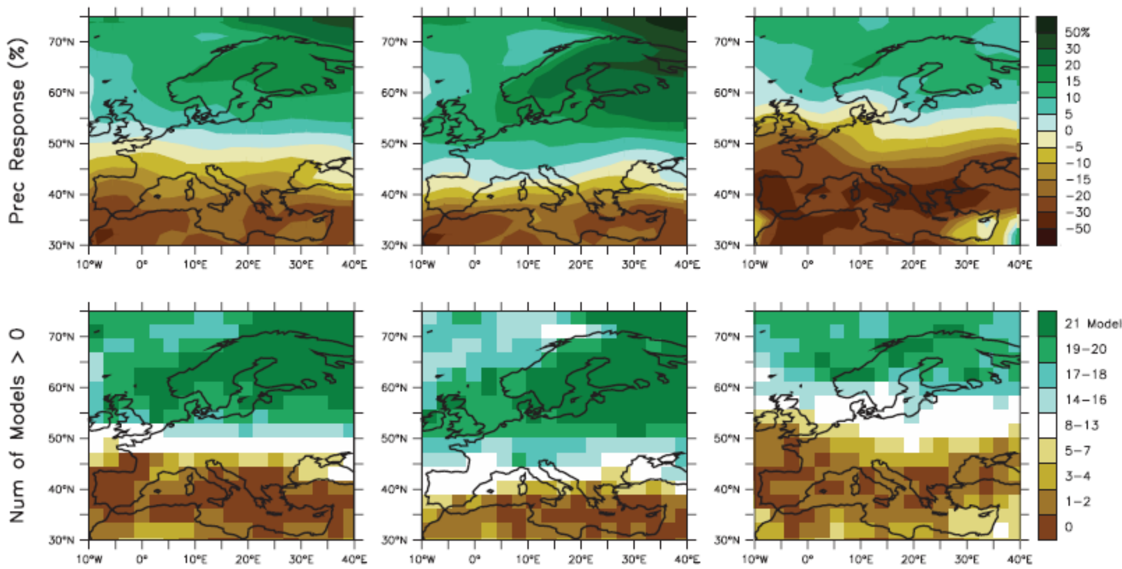

Figure 2.1 IPPC projections of precipitation over Europe by 2080-2099. (a) Annual, (b) winter DJF, (c) summer JJA. The bottom row of plots indicates the number of model runs which showed an increase in precipitation (Source: IPCC, 2007)

There is also evidence from general circulation model experiments that the Northern Europe storm track is increasing with intensity, and will continue to strengthen into the future due to anthropogenic greenhouse gas forcing (Ulbrich and Christoph, 1999). With this it would be expected that an increase in storm track intensity would lead to an increase in the frequency of extreme rainfall from such storms and potentially increase the risks of flooding from such events. With the potential of extreme rainfall events increasing in magnitude and frequency over the UK, and therefore the increased likelihood of flooding and the costs that this will likely cause for the people and economy of the country, it will become ever more important to further understand the weather patterns that are associated with these extreme events in the UK.

The increases in precipitation intensity can easily be explained with increasing atmospheric temperature and atmospheric physics. By using the Clausius-Clapeyron equation, with a 1°C increase in temperature, the atmosphere near the Earth's surface can hold 6-7% more moisture (Allan, 2011). Intense rainfall is local phenomenon, and it is argued that an intense rainfall event is caused by the transport of moisture from further afield to the event location. Therefore it is likely that already fairly wet regions will experience an increase in precipitation, and drier regions will see a reduction (Allan, 2011). This suggests that the risks of both flooding and drought will increase into the future. Therefore being able to understand both the atmospheric circulation and thermodynamic mechanisms that lead to precipitation are paramount if it is going to be possible to mitigate against future changes at regional and local scales.

2.2 The Autumn 2000 floods

The flooding during the autumn of 2000 was arguably the most widespread and severe event in recent times, with much of the UK and Western Europe being affected. It was the wettest Autumn on record (since 1766) in England and Wales, with several other locations between France and Norway seeing at least double their average autumn rainfall (Blackburn and Hoskins, 2001). In the UK alone, over 10,000 properties alone were damaged by flood waters causing £1.3 billion in estimated insured losses, as well as significant disruption and damage to the infrastructure and the economy (Pall et al, 2011). The flooding was the most widespread and damaging since the snow-melt induced floods of 1947 (Marsh and Dale, 2002). Therefore it is understandable that a lot of research has been undertaken into the causes of this record breaking event, and whether its intensity can be attributed to climate change.

The conditions which led to the extreme rainfall during the Autumn of 2000, and into the winter, were characterised by sustained westerly airflow and the passage of deep low pressure systems towards the UK, with some being the remnants of Atlantic hurricanes (Marsh and Dale, 2002). This was due to the fact that the jet stream during the period was displaced eastwards and southwards towards the UK, and such allowed intense low pressure systems to be driven right across the UK and into Western Europe (Blackburn and Hoskins, 2001). This was also associated in a line of geopotential anomalies from the central Atlantic, across Europe and into Russia, with a strong cyclone over the UK and a strong anticyclone over Scandinavia (Blackburn and Hoskins, 2001). Such a pattern is termed the Scandinavian pattern, with a blocking anticyclone over the area. Research into this has found that there is a link between such a pattern and autumnal rainfall over the UK, as well as links to weather over the tropical Pacific and South America (Blackburn and Hoskins, 2001). This therefore offers a basis of attempting to improve seasonal forecasting especially for autumn rainfall in the UK, and potentially predicting the risks of a particular autumn being exceptionally wet. Whether such a pattern is observed in other extreme monthly events was also investigated within this report, to determine whether the events leading up to the Autumn 2000 floods have occurred before in the recent past.

The extreme rainfall and flooding during the Autumn of 2000, and the fact that there have been several other significant flood events in the country over the last decade (such as the winter 2003, Boscastle 2004, summer 2007, and Cumbria 2009 events), has prompted the media to speculate whether such events can be attributed to global warming due to anthropogenic greenhouse gas emissions (Pall et al, 2011; Marsh and Dale, 2002; Robson, 2002; Fowler and Kilsby, 2003; Burt and Horton, 2007). This has allowed the public to understand, even if rather simplistically, the idea that climate change and greenhouse gas emissions may be starting to impact on our weather (Burt and Horton, 2007). In fact the autumn 2000 floods were seen as a wakeup call by the government to the future likelihood of an increased risk of such events into the future (Blackburn and Hoskins, 2001). Therefore it is important to understand whether global warming has had an impact on such events, and whether they will become more prevalent in the future, so that the government and local authorities are able to prepare and better deal with flooding disasters. Pall et al (2011) used an ensemble of seasonal forecast climate model simulations, using sea surface temperature (SST) patterns from a coupled climate model simulation with and without the greenhouse gas forcing signal. Using a precipitation-runoff model they were able to simulate severe events in England and Wales, and they found that in 90% of model runs, manmade greenhouse gas emissions increased the risk of floods occurring in the region at that time by 20% (Pall et al, 2011). The risk increased to 90% in two thirds of cases, and shows that it is likely that the severity of the flooding in Autumn 2000 was likely to have been increased by global warming (Pall et al, 2011). Although the study has shown that global warming can be partly attributed to the severity of the flooding in Autumn 2000, it does not provide clear evidence of whether flooding will increase into the future, only that flooding may become more severe. However it still provides the most robust evidence to date, that climate change driven by anthropogenic greenhouse gas emissions has an impact on flooding in the United Kingdom.

2.3 Research into categorising weather events, and linking rainfall to large scale dynamics

Categorising the weather of the British Isles or in fact any region of the world, can be an important tool in being able to determine links between precipitation and the synoptic pattern over that region (Sweeney and O'Hare, 1992). A subjective classification of the synoptic flow over the British Isles into seven types was devised by Lamb (1950), and then updated to include up to 26 different weather types over the area in 1972 (Lamb, 1972) . This system is based on the direction from which the wind flow is from at noon on that day, and is also based on whether the flow is anticyclonic or cyclonic. This was further developed by Jenkinson, in which a more objective approach was used, by using daily grid-point mean sea level pressure (Jenkinson and Collison, 1977). However Sweeney and O'Hare (1992) argue that there are several limitations to using such a catalogue of daily weather types, which may be appropriate to this study. Firstly the category for each day is dependent on the weather at noon on that day. Therefore if the weather situation is particularly dynamic and quickly changing during the day, more than one type of category may be relevant for a specific day. This may be the case where a fast moving low pressure system is moving across the British Isles. The predominant weather for the day may not be classified as cyclonic however, because the low pressure system may have quickly passed over the country before noon. Therefore the classification for that day may be different, potentially North Easterly. Another issue is that the British Isles can be affected by more than one different air mass at any one time. For example the North of Scotland may be experiencing an arctic northerly flow, but further south a warm front may be moving northwards introducing warmer south westerly flow. This is an important factor to note, as this investigation will be looking into Northern Scotland and South East England regions, which are at opposite ends of the country. An air mass may be influencing one of these regions which may be different to the rest of the area, and therefore will not be picked up in the lamb classification for that day. Therefore this was considered when using this classification system in this investigations own classification of extreme rainfall events.

The Sweeney and O'Hare (1992) study looked into how precipitation varied across the British Isles with different weather types. In terms of Northern Scotland and South East England, large differences in lamb weather types produced significant differences in precipitation across Northern Scotland compared to South East England. Generally westerly flow or anticyclonic westerly flow produced the highest mean rainfall for Northern Scotland (with Stornoway having a mean of 10.06mm on westerly days), whereas Cyclonic days produced the highest mean rainfall totals in South East England (with Dover recording a mean of 4.24mm on such days)(Sweeney and O'Hare, 1992). This relates to the fact that cyclonic flow over the region would indicate a more southerly track of lows across the UK, and therefore would produce more rainfall further south across South East England. Table 2.1 indicates the 5 lamb types which produce the highest precipitation over the two selected regions.

Northern Scotland	**South East England**
1. Cyclonic South Westerly	1. Cyclonic North Easterly
2. Westerly	2. Cyclonic Easterly
3. Cyclonic Westerly	3. Cyclonic South Easterly
4. Anticyclonic South Westerly	4. Cyclonic
5. Anticyclonic Westerly	5. Cyclonic South Westerly

Table 2.1. Lamb types which produce the most rainfall over Northern Scotland and South East England. (Data source: Sweeney and O'Hare, 1992)

If these are the Lamb weather types which produce the highest mean precipitation over these regions, it may be expected that the periods of extreme rainfall may also fall within the categories shown in Table 2.1. Therefore this was investigated as part of the project.

Other studies have tried to classify extreme precipitation events by grouping them depending on how they were caused. Hand et al (2004) identified 50 extreme point rainfall events during the twentieth century under 60 hours in duration, and classified them depending on whether the rain was caused by frontal, convective or orographic processes or a combination of any of the three. All orographic events occurred during the winter months, and were associated with a strong south westerly or westerly airflow (Hand et al, 2004). Therefore it may be hypothesised that extreme rainfall events in Northern Scotland, where orographic processes will be significant in producing high rainfall totals, are more likely in the winter and as suggested by Sweeney and O'Hare (1992) under south-westerly airflow. They also found that extreme rainfall under 60 hours in length did not occur during February to April, and therefore it would be expected that short extreme events such as one day events would be unlikely to occur during these months within this investigation. In comparison convective events, which may be more likely to cause short term extreme rainfall in South East England were more likely to occur in the summer months (Hand et al, 2004).

Generally very little research has focused in on multiday to monthly extreme precipitation over the UK in the recent past, even though arguably the more widespread flooding and devastating flooding to have affected the UK in recent years has been caused by a period of several weeks of heavy rainfall. Obviously there are exceptions to this, most notably the devastating floods that affected Boscastle in August 2004. However it has been argued that generally one day totals in the UK have been unremarkable, with the more extreme events occurring over several days

(Fowler et al, 2005). Therefore this states the importance of investigating both 5 day rainfall events and monthly totals.

Being able to identify links between climate, precipitation and river flows can be quite difficult, due to the fact that many factors and processes lead to the generation of river flows. Lavers et al (2010) looked into the relationships between large-scale circulation patterns with precipitation and river flows in ten near natural river basins across Great Britain. It was found that large scale atmospheric circulation showed greater correlation with precipitation in the west of Britain and during the winter months, with a strong correlation between precipitation and the NAO in northwest Scotland during the winter (Lavers et al, 2010). Therefore as it can be hypothesised that extreme rainfall events in Northern Scotland may well be associated with a strong Icelandic Low and Azores high. This is also significant for this region as the NAO is projected to increase in the future, with an increase in intensity of the North Atlantic storm track, which may lead to increased rainfall in Northern Scotland (Ulbrich and Christoph, 1999). The disadvantage of the NAO is the fact that it does not take into account the shift in low or high pressure systems towards or away from the UK, as it uses fixed locations to calculate the index. Even the NAOI, which uses principal components analysis, does not produce strong statistical relationships, as found with gridded data sets (Lavers et al, 2010). This investigation used 20th century reanalysis data (NOAA, 2011), and therefore was able to identify the location, and not just the intensity of low pressure systems. It also argued that the links between atmospheric patterns and river flows were much weaker than those between atmospheric patterns and precipitation (Lavers et al, 2010). This is due to the fact that basin properties (such as bedrock permeability and topography) have huge impacts on the production of channel runoff. Therefore it will be important to understand this when comparing the identified extreme rainfall events and historically recorded flooding and high river flows.

In relation to the impacts of the hydrological system into the future, a study on the River Kennet in Berkshire was undertaken to assess the impacts climate change scenarios would have (Limbrick et al, 2000). In this part of the country it is expected that summer and autumn soil moisture deficits would increase, and therefore this may reduce the impacts of flooding arising from prolonged extreme rainfall events (Limbrick et al, 2000). Reduced summer rainfall would mean that it would take longer for soil moisture levels to recover into the winter, and therefore would reduce the risks of saturation occurring (Limbrick et al, 2000). However hard-baked ground would mean that short but intense rainfall events would potentially be more likely to cause flooding as infiltration would be impeded.

The chapter has looked into the past research undertaken into flooding, the categorisation of weather events, and the analysis of past and future trends in UK rainfall. It can be argued that very little knowledge of the identification of extreme rainfall events, over longer periods of time (greater than 60 hours), and the classification of such events is known. There is also very little evidence of research into the links between extreme events and flooding. Therefore this investigation will combine previous research in the field, to fill the gap in knowledge of the classification and identification of extreme rainfall events that have affected the UK from 1931-2008 and determine the links to associated floods in Northern Scotland and South East England.

3. Methodology

The process and methods for identifying extreme rainfall events will now be explained, along with the way in which large scale weather patterns were also identified for each of these events. The data that has been used in this process will be discussed, how this data was manipulated for the purpose of this project, as well as any limitations of the data and methods used.

3.1 Identification of extreme rainfall events

To look at rainfall extremes across a range of temporal scales, it was decided that extreme rainfall totals would be looked at for three differing time scales. This is so as to allow comparison between weather regimes which cause extreme rainfall events on short (1 day), medium (5 day) and longer (monthly) time frames. The precipitation data set used for this project is the Hadley Centre's HadUKP (MetOffice, 2011a), and has both a daily precipitation time series (dating back to at least 1931), and a monthly time series (dating back to 1871). HadUKP provides regional precipitation data which is split up into the nine precipitation regions of the United Kingdom, defined by Wigley et al (1984), and further extended to include the whole of the country by Gregory et al (1991) and Alexander and Jones (2000). Within each of the nine regions over the UK, defined by using principal components analysis, the precipitation is spatially coherent (Conway et al, 1996). These nine regions are presented in Figure 3.1, and for the purposes of this investigation, extreme events have been examined for the Northern Scotland and South East England regions of the UK. The data set is compiled by using a network of observational stations across the UK, in which some are automated and

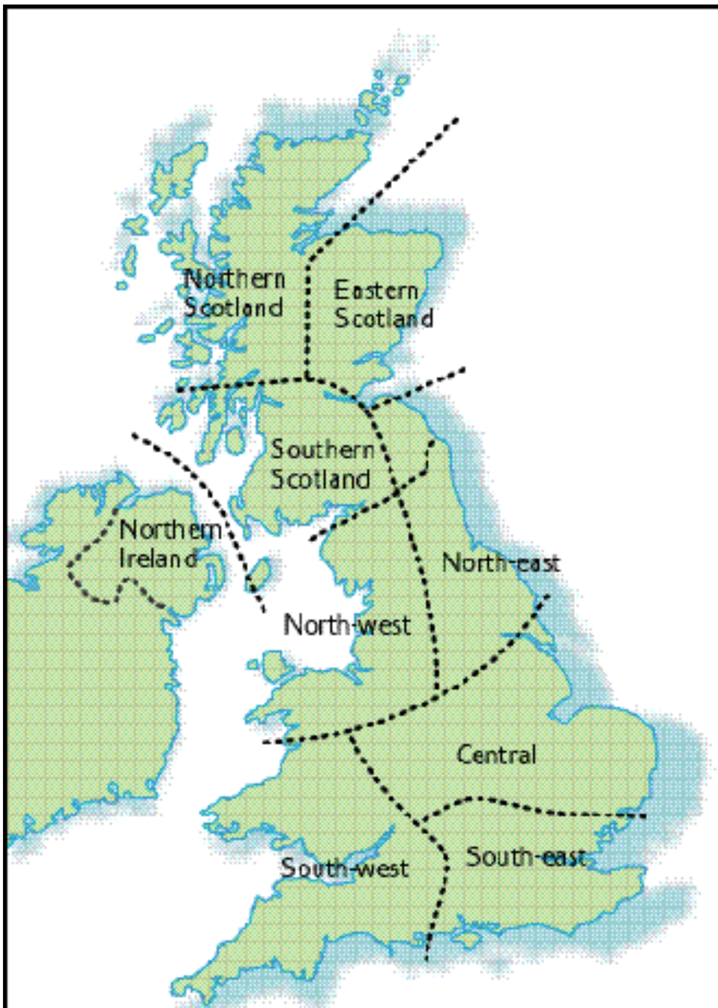

Figure 3.1. The nine precipitation regions of the UK. (Source: MetOffice, 2011a)

therefore can provide near real time data. Alexander and Jones (2000) however identified the disadvantages of using automated weather stations, due to the fact that a sensor may fail and provide a zero reading. Therefore quality controls are performed on the data before it is accepted into the MetOffice database. Other errors may arise if the type of rain gauge between observational sites is different or changed due to a fault. Rain-gauges can also provide spurious results if there is a strong wind, or if the precipitation is frozen.

As the data series only extends to 1931 in Northern Scotland, extreme events were only taken between the years 1931-2008. The reason that the analysis was not extended to the present day is due to the fact that the re-analysis data used to identify the weather patterns for each event only extends to the end of 2008 (the reanalysis data, and how it was used will be discussed further later in section 3.3).

Extreme monthly precipitation events in the two regions were identified as being two standard deviations from the regional monthly mean. Monthly means were used due to the fact that monthly rainfall varies significantly through the year, with generally wetter winter months, and drier summer months. Due to the differing nature of rainfall in these two regions, this meant that the number of events deemed to be extreme on the monthly timescale were different. 31 months exceeded two standard deviations from the mean in South East England, while there were 23 months in Northern Scotland. Daily events were identified by taking the top 0.1% rainfall totals, and this was also the case for the five day totals. Five day totals were calculated by taking a five day running sum using the daily precipitation series. Care was taken so as to produce a series of independent five day extreme events, so that no two events overlapped. This produced 28 extreme events for each region for both five day and one day totals.

3.2 The Northern Scotland and South East England regions

As has already been mentioned the regions of Northern Scotland and South East England have been chosen so that the causes of extreme rainfall and the links to flooding in these two regions can be compared and contrasted.

The Northern Scotland precipitation region comprises most of the Highland region as far west as Inverness, as well as northern parts of Argyll and Bute and western Perth and Kinross. It also includes the Western Isles, and Orkney and Shetland Islands. It therefore has a significant geographical span, as the Shetland Isles are situated approximately 100km to the North East of the mainland and therefore can experience significantly different weather to the rest of the region. Therefore this may be a limitation, as an extreme event across the Highlands may be reduced in scale by the fact that very little rainfall may have fallen in the Northern Isles.

The region includes two of the 15 largest river catchments in Scotland, these being the River Ness (drainage area of 1839km^2) and River Helmsdale (Black, 1996). However most of the river catchments are fairly small in size (less than 500km^2), draining the high ground of the North West Highlands or western Grampians.

The South East England catchment comprises the counties of Kent, East and West Sussex, Hampshire, Greater London, Surrey, Berkshire, as well as southern portions of Essex, Hertfordshire, Buckinghamshire and Oxfordshire. The main river catchment is the River Thames, with most of the region being drained by its tributaries. Other important rivers include the Medway in Kent and Stour in Hampshire.

These two regions were chosen for several main reasons. Firstly, these two region are located the furthest apart in the country and therefore are likely to exhibit differences in their weather regimes. This will be exacerbated by the fact that Northern Scotland is more exposed to south westerly/westerly winds and the jet stream, whereas the South East England will be more affected by continental weather systems. Secondly the topography and geology of the two regions is significantly different, with Northern Scotland characterised by mountains and narrow valleys of the Highlands, and impermeable bedrock. South East England by contrast is much flatter and low lying, with undulating hills (such as the South Downs and Chilterns) with much wider river valley systems and more permeable bedrock, most significantly Chalk. The seasonal distribution of such events and the weather patterns that tend to cause these events can then be compared between the north-west and south-east of Great Britain.

<u>3.3 Categorising weather types which produce extreme rainfall</u>

Once the extreme events had been compiled, the general weather pattern for each of the periods concerned was then analysed. Various weather and circulation variables were collected from NOAA's 20th century reanalysis product. This is a global gridded reanalysis product, which uses surface observations and data assimilation techniques to provide an atmospheric data set between 1871 and 2008, with a resolution of 2x2 degrees (Compo et al, 2010; NOAA, 2011). Mean sea level pressure (MSLP), vector wind at 250mb (to determine jet stream strength and direction), and geopotential height anomaly at 500mb were all indentified initially as the key parameters.

Climate fields were created for each of the events identified, for each of the variables chosen above. Then by visually comparing each event, categories and composites were identified for events which showed similar characteristics in MSLP, vector wind at 250mb and geopotential height at 500mb. The characteristics of the plotted fields of each of these variables were looked at as follows:

- Location of low pressure centre in relation to the UK
- Presence of a storm track, or a more stationary low pressure system
- Position of low pressure track in relation to the UK
- Presence of a blocking high over Central and Eastern Europe
- Direction of surface flow over the specific region in question
- Shape, location and strength of the vector wind maximum at 250mb (jet stream). i.e. is the jet stream straight or curved, and where is it situated in relation to the UK.
- Location of high/low geopotential anomalies in relation to the UK
- Presence and location of low geopotential troughs extending down from the north

The prevalence of events within each month and season was noted, as well as which category or categories of events were more likely at different times of year. To support the visual analysis of categorising events, lamb circulation type analysis was undertaken on the daily events. The Jenkinson objective system of classifying the circulation pattern of each day was used (Climate Research Unit, online, 2001). This provides a much longer time series which extends from 1880-July 2007, and therefore covers the majority of the years looked at in this project (all one day events occurred before July 2007). Once the assigned Lamb circulation type had been found for each event, these were then matched up with the categories formed in this project to determine whether there is any association between the differing categorisations.

<u>3.4 Links with past flooding events and flow data using two example river catchments</u>

Using the BHS (British Hydrological Survey) chronology of British Hydrological events, which compiles hydrological records including flood events from sources such as newspaper reports, online material and journals, flood events between the periods 1931-2008 in both Northern Scotland and South East England were compiled (University of Dundee, online, 2011). Other sources were also used such as literature on flood events in the country, such as Acreman's (1989) study into historical UK flooding and Black's (1988) investigation into flood frequency in Scotland. This list of flooding events for the two regions being studied was then compared to the list of extreme rainfall events previously compiled to determine whether the extreme events identified were connected with flooding, or whether flooding was always caused by extreme rainfall on either monthly, five day or daily timescales. Comparisons of the causes of flooding between the two regions being investigated were also assessed.

This investigation is focusing on the effects climate and precipitation has on fluvial flooding, i.e. flooding caused by the overtopping of a river or stream; reports of just pluvial (or surface) flooding was not considered.

In addition to relating the identified extreme precipitation events to recorded events across the whole region, two small catchments were selected, one in each region, so that flow data from these catchments could provide a more detailed analysis of the relationship between river flows and extreme events. The River Ewe catchment was selected for the Northern Scotland region, with the Great Stour catchment in South East England.

The River Ewe catchment is 441 km^2 in area and is located within the western Highlands, with the river flowing west and draining into Loch Ewe at Poolewe (where the gauging station is located) some 30km to the south west of Ullapool. It is classified as being very wet and mountainous, with impermeable bedrock which is overlain with superficial deposits (Lavers et al, 2010). Figure 3.2 indicates the topography of the catchment. The main land use within the catchment is moorland and rough grazing with some forestry also. The River Great Stour in South East England is of a similar size to the Ewe catchment being 342km^2 in total area. It flows East into the English Channel at Pegwell Bay, just to the north of Sandwich, Kent. The geology is dominated by chalk, but with clay in the east and west tributaries of the river (Lavers et al, 2010). It is a mainly rural catchment, with fairly mixed land use, with the only significant urban centre being Ashford. The topography of the catchment is shown in figure 3.3, and it can be seen that the landscape is at a much lower level, with the river valley much less steep.

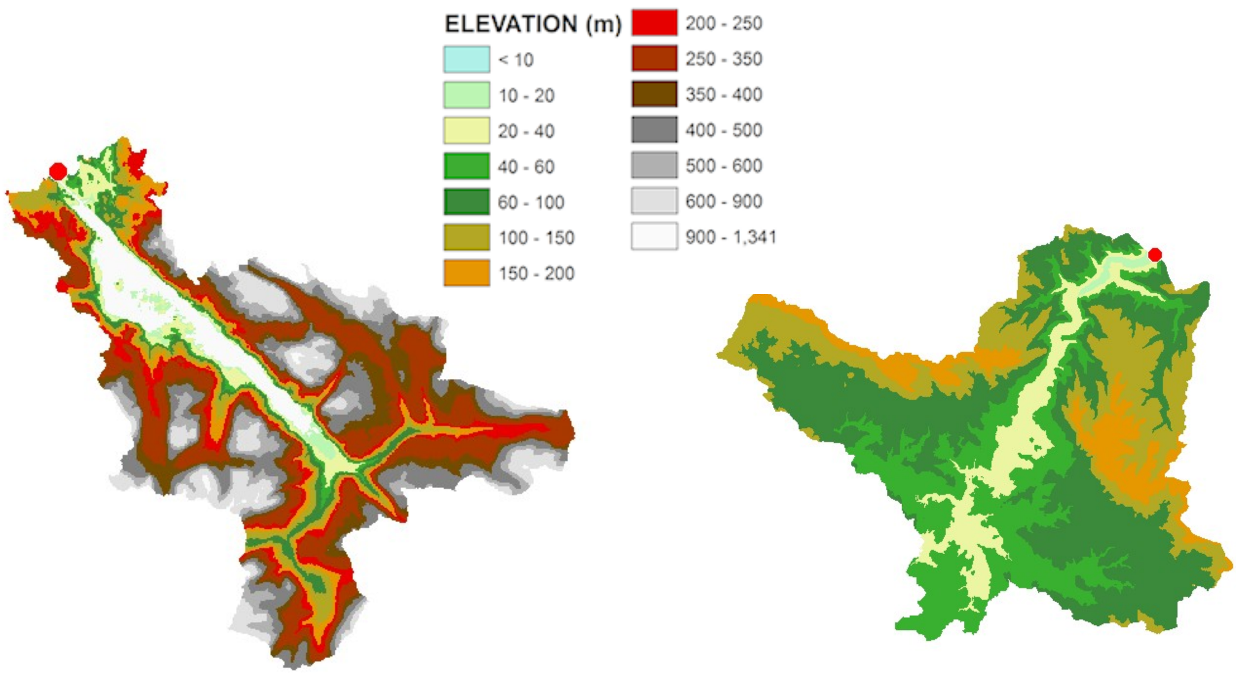

Figure 3.2 Ewe Catchment Topography

Figure 3.3 Great Stour Catchment Topography

These two catchments were chosen as they have been deemed to be near natural basins, and therefore have minimal impacts on the catchment due to human activities, and therefore links between the climate and river flows have not been affected by human water management (Lavers et al, 2010). They were also chosen as they are of comparable size in respect to their catchment area, and also have fairly long and uninterrupted records of flow data, with the Great Stour record beginning in 1962 and the Ewe in 1971. River flows over 1971-2008 were studied, and therefore provides a serious limitation as data is not available for the entire study period from 1931. However as mentioned earlier, long precipitation and river flow records are very rare and these catchments provided some of the longest and most comprehensive flow records available.

The top ten independent peak flows were identified from the start of 1971 until the end of 2008, and then these peak flows were compared to the extreme rainfall events to determine whether there was any link between extreme precipitation over the timescales looked in to and these high river flows.

4. Results

This chapter will discuss the results of the investigation. Firstly the extreme rainfall events that were identified at the one day, five day and monthly timescales will be discussed for both Northern Scotland and South East England. A breakdown of each of the categories used to group events with similar weather patterns will be outlined, and the distribution of events within each category will be discussed. Finally the list of fluvial flooding events which has been compiled from various sources will also be presented, linking these events to any of the extreme rainfall events which fall at the same time as any reported flooding.

4.1 Extreme rainfall events

Appendix A lists the extreme rainfall events that have been identified for the period 1931-2008 on the one day, five day and monthly timescales. Figures 4.1-4.3 show the monthly distribution of events for each of the event timescales. On daily timescales (fig 4.1), both Northern Scotland and South East England have peaks in the number of events in the autumn months, especially October. However extreme events occur through the winter months in Northern Scotland. In contrast South East England experiences events during the summer months. Extreme daily rainfall events are very unlikely in spring months in both regions of the UK.

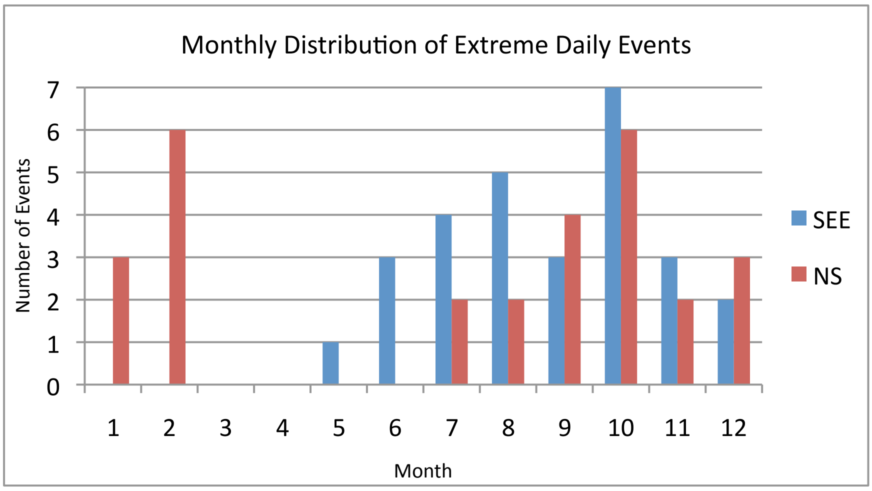

Fig 4.1. Monthly distribution of extreme events in Northern Scotland (NS) and South East England (SEE)

On the five day timescale (fig 4.2), the distribution of events is fairly similar. However there is an indication that extreme events are less likely during the summer months, and more likely during the autumn and early winter. October once again is the month with the highest number of extreme events in the South East England region. In Northern Scotland, all events occur in autumn, winter and in March, with the most events by far occurring during the months of October and December. There are fewer five day events occurring in winter in comparison to one day events in Northern Scotland also.

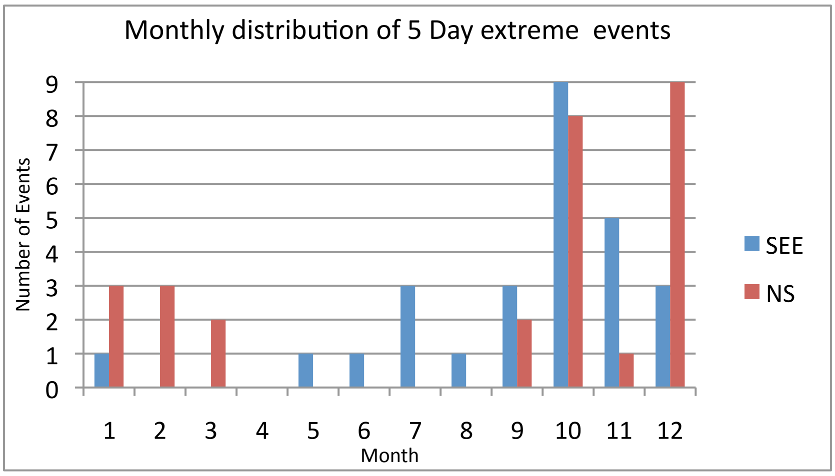

Fig 4.2. Monthly distribution of five day events in Northern Scotland (NS) and South East England (SEE)

For monthly extreme events, the monthly distribution is shown in figure 4.3. Due to the fact that extreme monthly events were determined in relation to the monthly mean (and not the annual monthly mean), the distribution of events cannot be compared as such to those on the five and one day timescales. However figure 4.3 shows that during certain times of the year, extreme monthly rainfall is more prevalent that at other times. In the South East England region, most events occurred between the months of October and May, with very few in the summer months. In comparison most of the extreme events in Northern Scotland occurred mainly in the months of February, March, May, June-September. However unlike the five day and one day events, an extreme event was observed for every calendar month of year for both regions during the period, potentially due to the differing way in which extreme monthly events were determined.

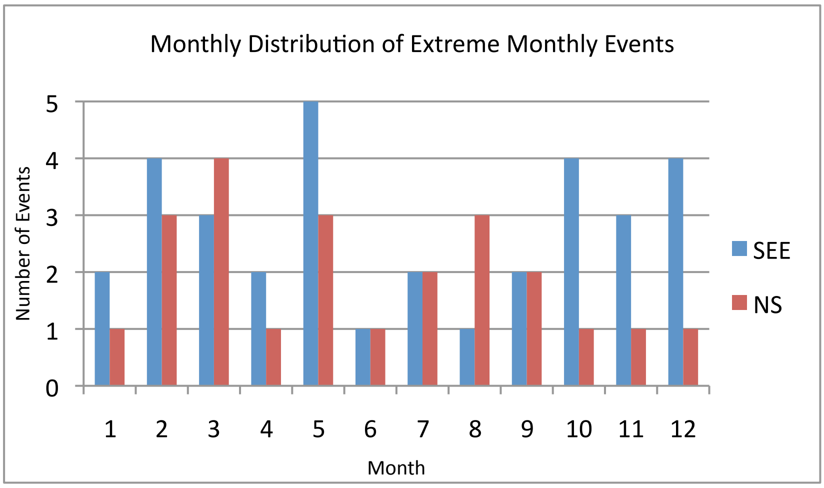

Fig 4.3. Monthly distribution of monthly events in Northern Scotland (NS) and South East England (SEE)

4.2 Categorising weather patterns in association with extreme rainfall events

The eight categories which were identified in relation to the weather patterns associated with the extreme rainfall events in both South East England and Northern Scotland will now be presented. A composite field of (MSLP) (in Pa), vector wind at 250mb (in ms-1), and 500mb geopotential height anomalies of the daily events which fall within each specific category is provided. The seasonal and geographic distribution of the number of events within each category will also be noted, as well as the top Lamb circulation types noted for each category. The key to Lamb Classification Types can be found in Appendix D.

They are listed as follows:

1. Category A: Strong Icelandic Low
2. Category B: Strong Icelandic Low with strong Scandinavian Blocking
3. Category C: Displaced Icelandic Low south towards the Faroe Islands
4. Category D: Low centre south of UK
5. Category E: Static Low over UK
6. Category F: Low west of UK, with Scandinavian Blocking
7. Category G: Low centre in North Sea
8. Category 0: Other

4.2.1 Category A: Strong Icelandic Low

The first category explains events that show a weather pattern that is close to the climatology of the region, with a low situated over the Icelandic region and high pressure to the south over the Azores and southern Europe. However with a more intense Icelandic Low and a stronger high pressure, the pressure gradient over the British Isles has been intensified leading to stronger westerly flow. The associated jet stream is from west to east, situated just to the north of Scotland. With these factors, increased south-westerly flow off the Atlantic would provide increased levels of moisture laden air especially to western facing coasts and mountains.

Number of one day events in category composite: 11

Top Lamb Circulation Types: W, SW

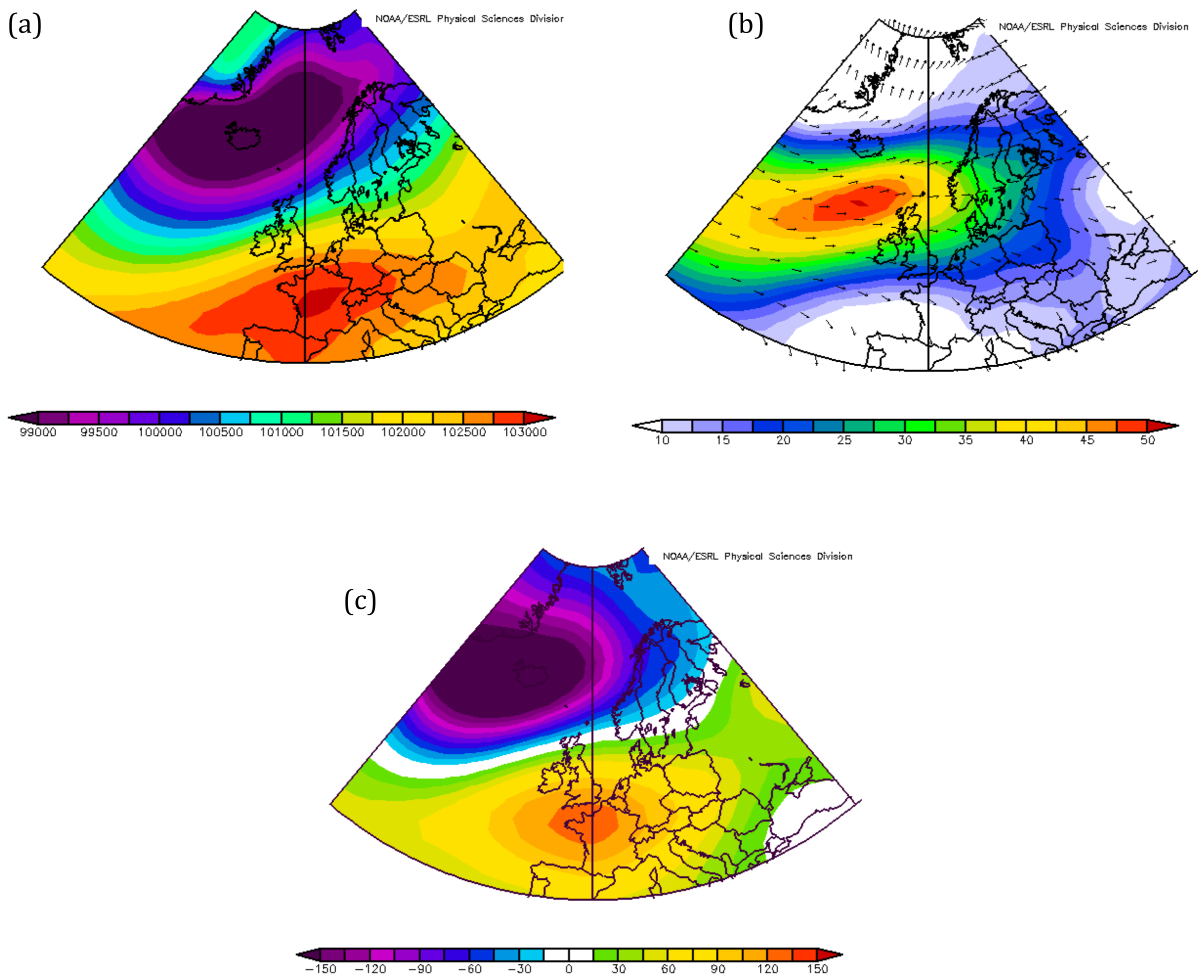

Figure 4.4. MSLP pressure field (a) [in mb], 250mb Vector wind (b) [in ms^{-1}], and Geopotential height anomalies at 500mb (c) [in dm] plots for Category A events composites

4.2.2 Category B: Icelandic Low with Scandinavian Blocking

This is similar synoptic situation to category A, except for the fact that the high pressure system usually to the south of the UK is displaced, north east over Central Europe and Scandinavia. This has an effect on Low pressure systems, in which they are prevented from taking their usual track through the Norwegian Sea, and therefore become much slower and stall around the Iceland area (see fig4.5a/b). This is associated with a more curved jet stream which curves to the north. Therefore the wind direction over the UK is much more south westerly, and therefore would be expected to bring warmer temperatures and potentially more moisture. This is also accompanied with a trough of low geopotential extending south to the west of the British Isles, but a ridge of increased geopotential directly over the country.

Number of one day events in category composite: 5   Top Lamb Circulation Types: ASW, S

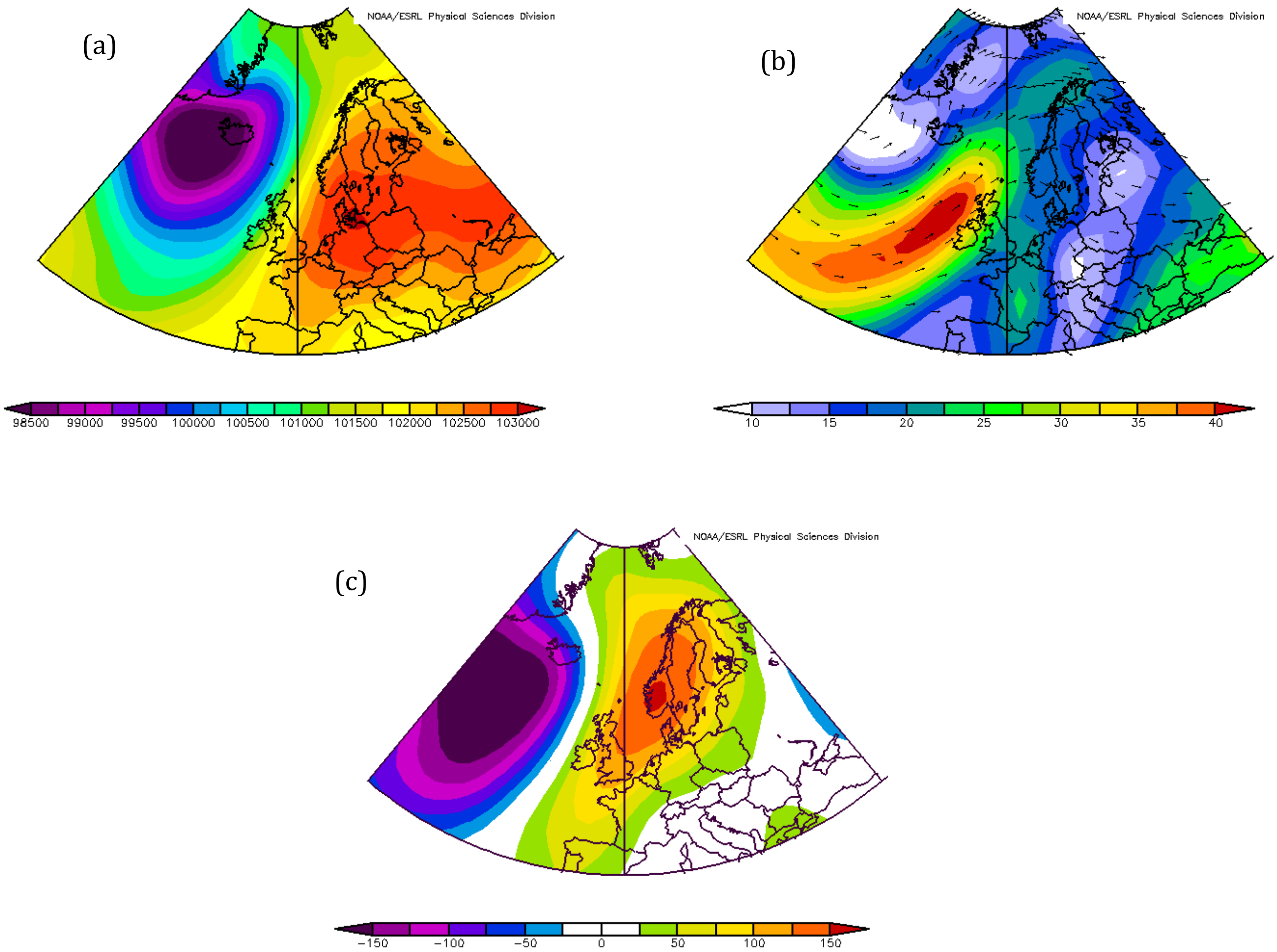

Figure 4.5. MSLP pressure field (a) [in mb], 250mb Vector wind (b) [in ms^{-1}], and Geopotential height anomalies at 500mb (c) [in dm] plots for Category B events composites

4.2.3 Category C: Southerly displaced Low towards Faroe Islands

This category is similar once again to A, except for the fact that the Icelandic Low and its associated track is displaced further south and therefore is closer to Northern Scotland and the rest of the UK. This is associated with a southerly displaced jet stream which is situated directly over the UK, and this drives low pressure systems between Iceland and Northern Scotland, directly over the Faroe Islands. This allows more westerly flow over the UK, and therefore potentially cooler temperatures compared to category A and B. In relation to this is a reduction in geopotential directly to the north of the UK.

Number of one day events in category composite: 18

Top Lamb Circulation Types: W, SW, CW

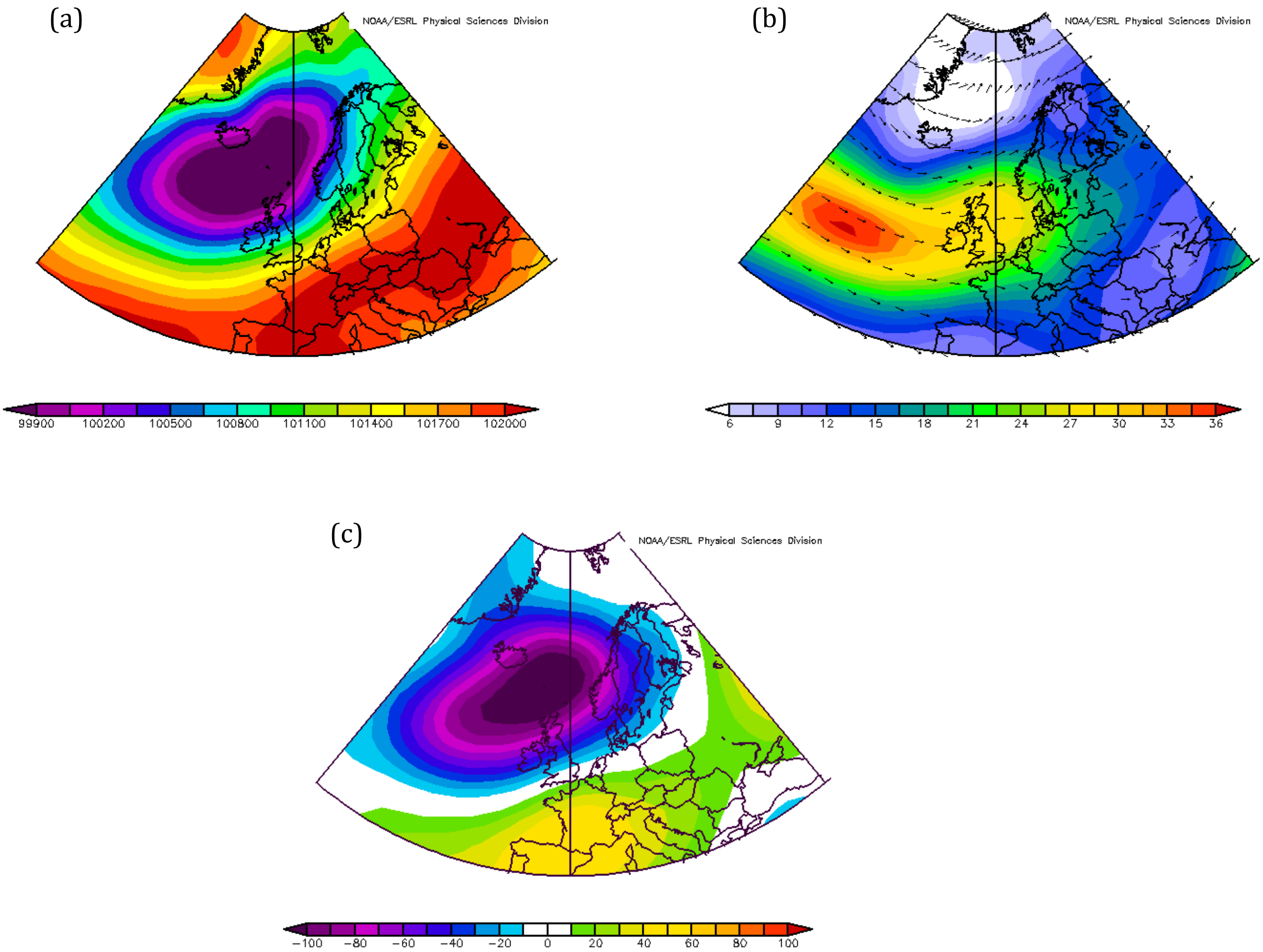

Figure 4.6. MSLP pressure field (a) [in mb], 250mb Vector wind (b) [in ms^{-1}], and Geopotential height anomalies at 500mb (c) [in dm] plots for Category C events composites

4.2.4 Category D: Low centred to the south of the UK

This category explains events which show a reversal in the usual pattern of Low and High pressure over the region, with a low system situated to the south of the UK and high pressure to the west or north of the country. This produces north easterly to south easterly flow over the UK, and with the low system to the south, it is likely that rainfall will be confined more to the southern and eastern United Kingdom, with moisture off the North Sea. This pattern is associated with a jet stream which is significantly displaced to south, curving round to the south of the UK through Iberia and France. With this situation, a trough of low geopotential is evident across the country.

Number of one day events in category composite: 6

Top Lamb Circulation Types: E, CE

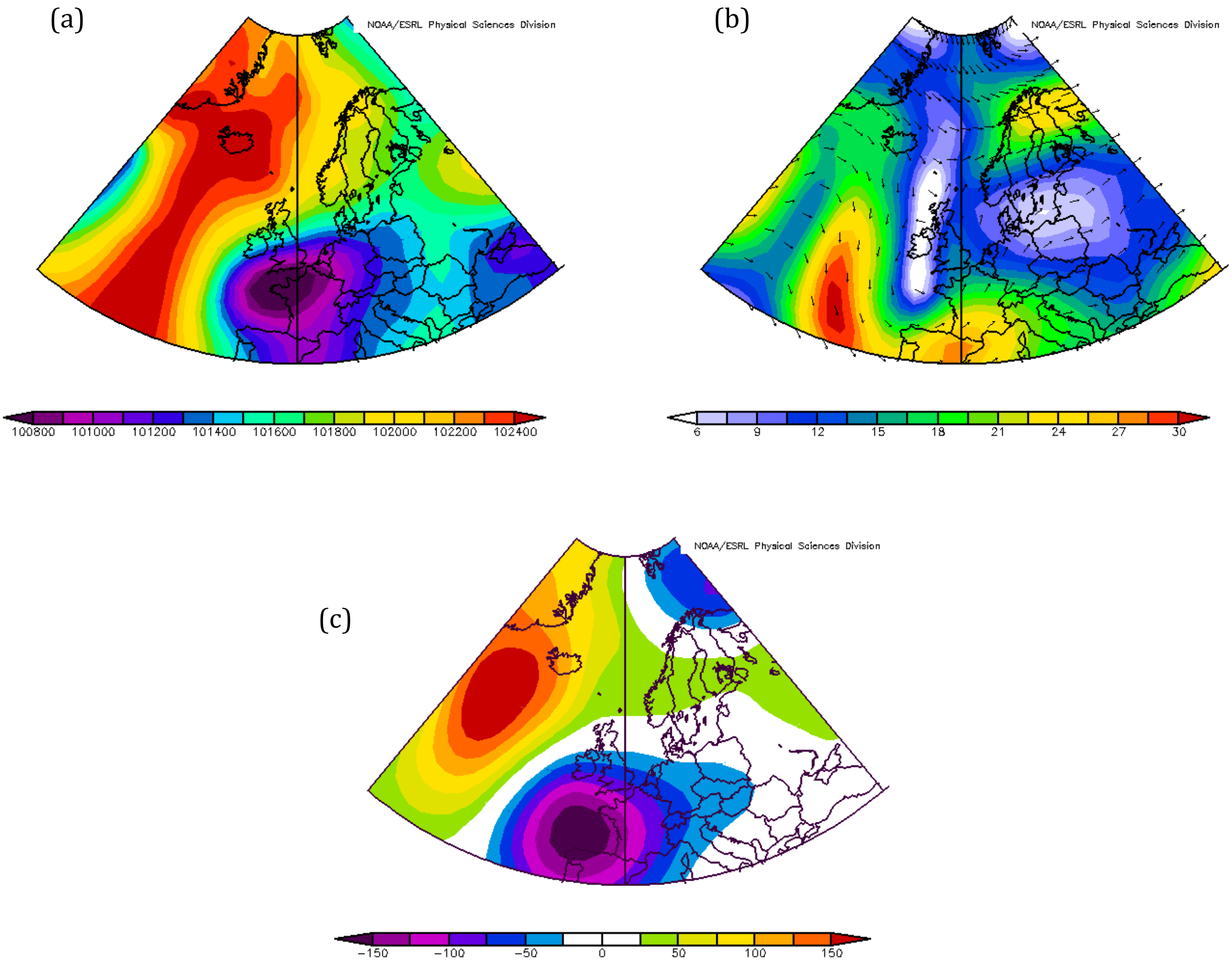

Figure 4.7. MSLP pressure field (a) [in mb], 250mb Vector wind (b) [in ms^{-1}], and Geopotential height anomalies at 500mb (c) [in dm] plots for Category D events composites

4.2.5 Category E: Stationary Low over the UK

This category is very similar to that of D, except for the fact that the low pressure system is situated directly over the UK itself, and therefore the flow over the country can be deemed to be cyclonic. The jet stream shows a similar shape to that of category D also, but is situated slightly closer to the UK, curving round from the west of the UK, around the south through France and into Germany. Like category D, a trough of low geopotential heights is evident across the whole of the UK. This is the least common weather situation in relation to extreme one day rainfall. As there is one daily event categorised as this, the plots represent this one event only.

Number of one day events in category composite: 1

Top Lamb Circulation Types: C

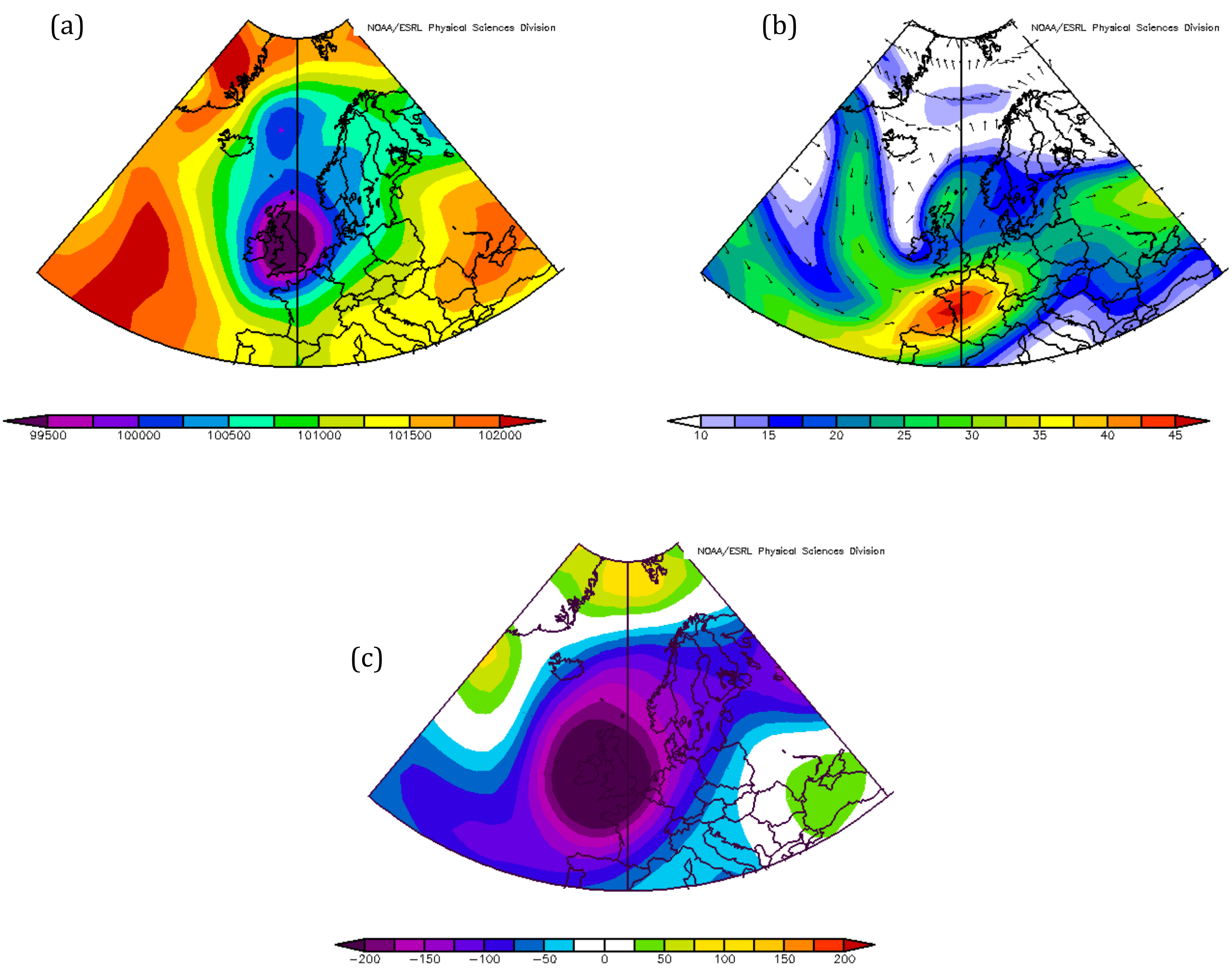

Figure 4.8. MSLP pressure field (a) [in mb], 250mb Vector wind (b) [in ms^{-1}], and Geopotential height anomalies at 500mb (c) [in dm] plots for Category E events composites

4.2.6 Category F: Low to the West of the UK, with Scandinavian Blocking

This category is similar to B, with high pressure to the East of the UK over Scandinavia and central Europe prevents the usual westward movement of low pressure systems. This category however identifies events where the Low pressure system is directly to the west of the British Isles, with a jet stream which curves around the low pressure and curves northwards across the UK as it comes up against the blocking high pressure. This situation provides a mores southerly airflow across the country, with a slight rise in geopotential to the east, and reduction in geopotential to the west.

Number of one day events in category composite: 7

Top Lamb Circulation Types: SE, CS

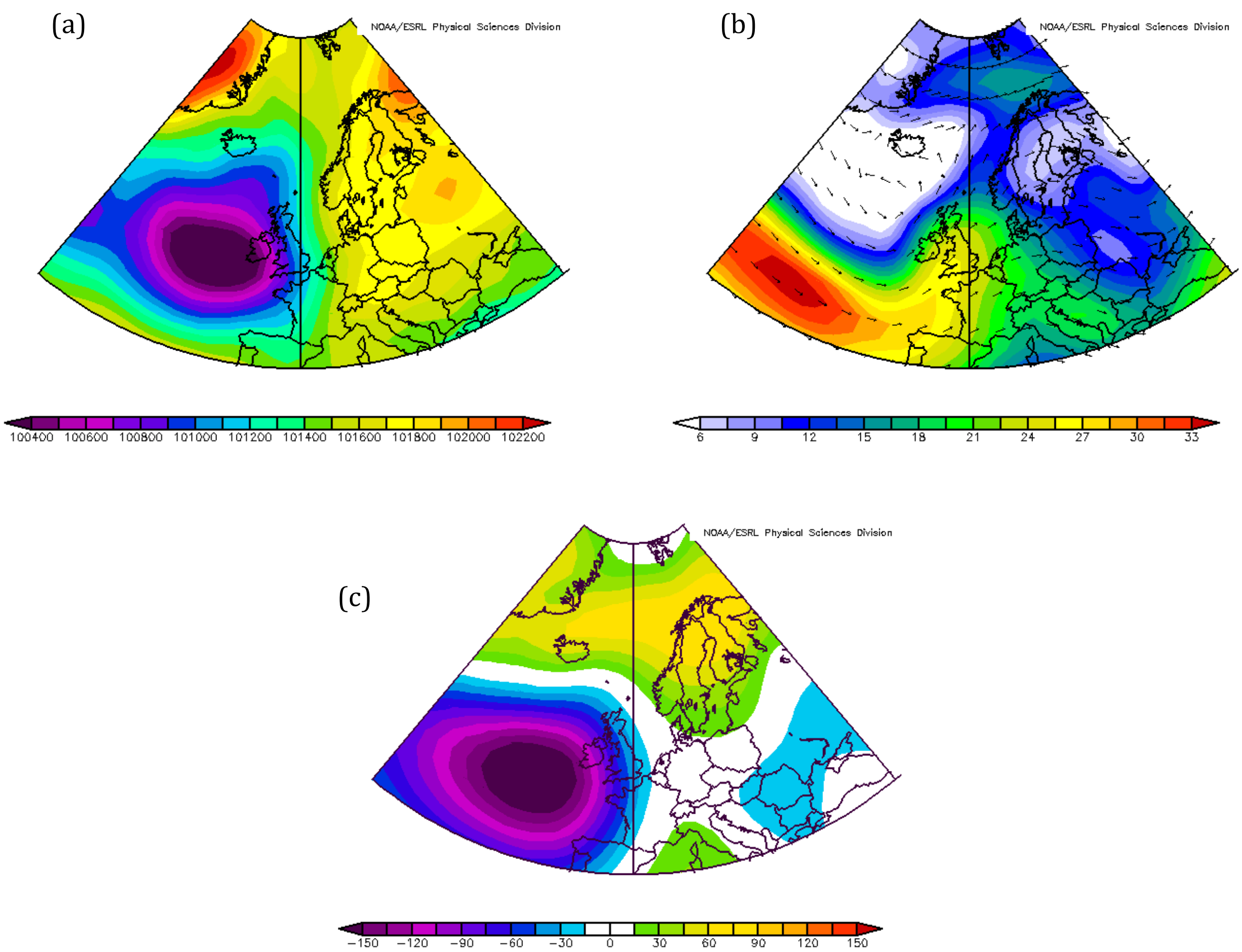

Figure 4.9. MSLP pressure field (a) [in mb], 250mb Vector wind (b) [in ms^{-1}], and Geopotential height anomalies at 500mb (c) [in dm] plots for Category F events composites

4.2.7 Category G: Low tracking directly across the UK

This is a similar situation to that shown in category F, except for the fact that the lack of blocking over Scandinavia allows the low pressure systems to track straight across the UK and are therefore much faster. This is associated with a much more zonally orientated jet stream situated over the southern parts of the UK and northern France, which drives low pressure systems across the central parts of the country. A trough of low geopotential heights extends south across the whole country from the north. This situation produces cyclonic flow over the UK, and then northerly flow as the low pressure systems has tracked across the country.

Number of one day events in category composite: 7

Top 2 Lamb Circulation Types: C, CNW, CE

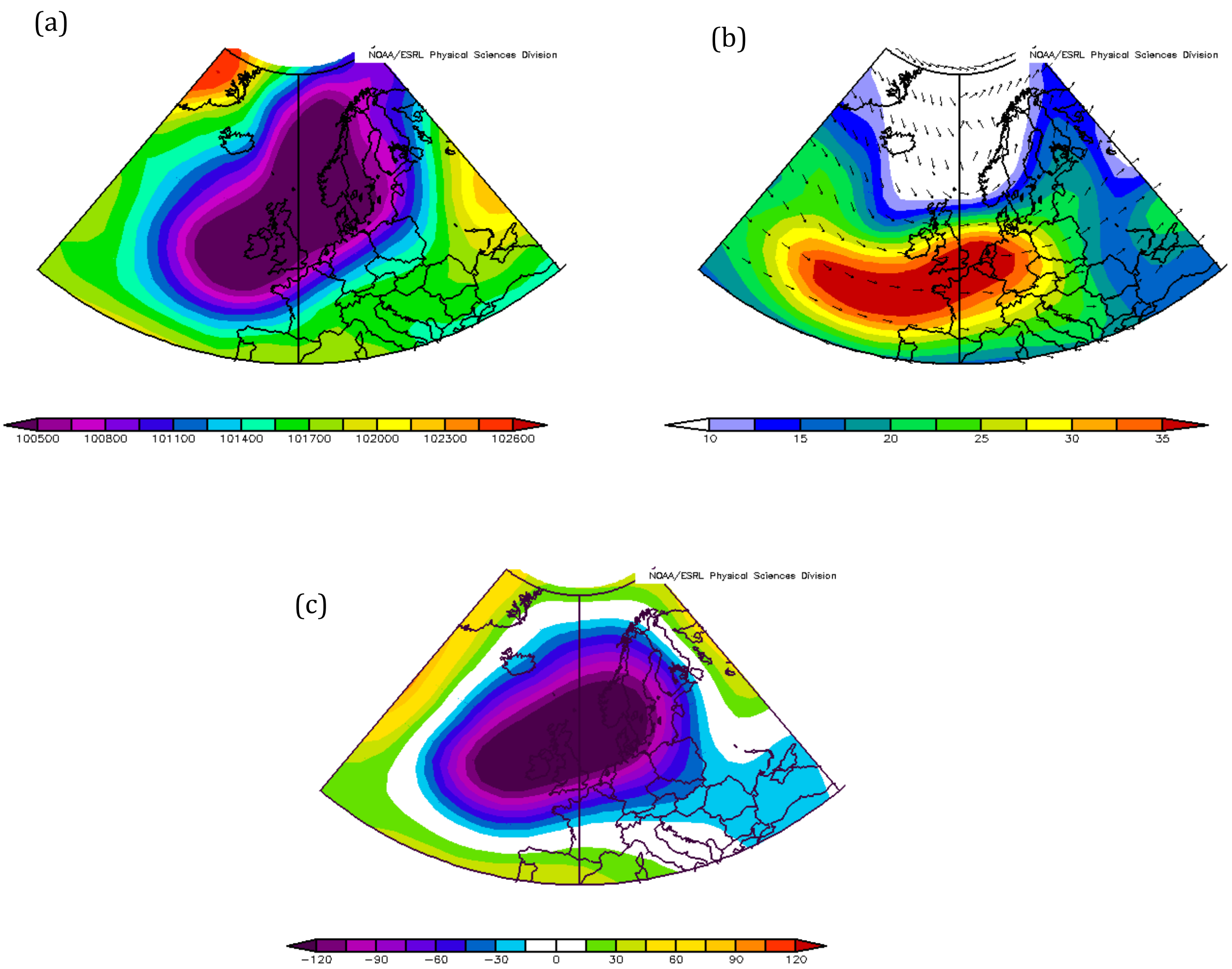

Figure 4.10. MSLP pressure field (a) [in mb], 250mb Vector wind (b) [in ms^{-1}], and Geopotential height anomalies at 500mb (c) [in dm] plots for Category G events composites

4.2.8 Category O: Other

Although most events fall within one of the seven categories listed above, there were several events which don't fully match and showed characteristics of more than one category. These only occurred with five events, all in the South East England region, and are classified as 'O' events for other within charts and text. Three of these events were classified as C/F which meant they showed characteristics of both categories.

4.3 Distribution of categories between Northern Scotland and South East England

The distribution of events within each category for one day, five day and monthly events will now be presented. The category assigned to each individual extreme rainfall event can also be found in Appendix A.

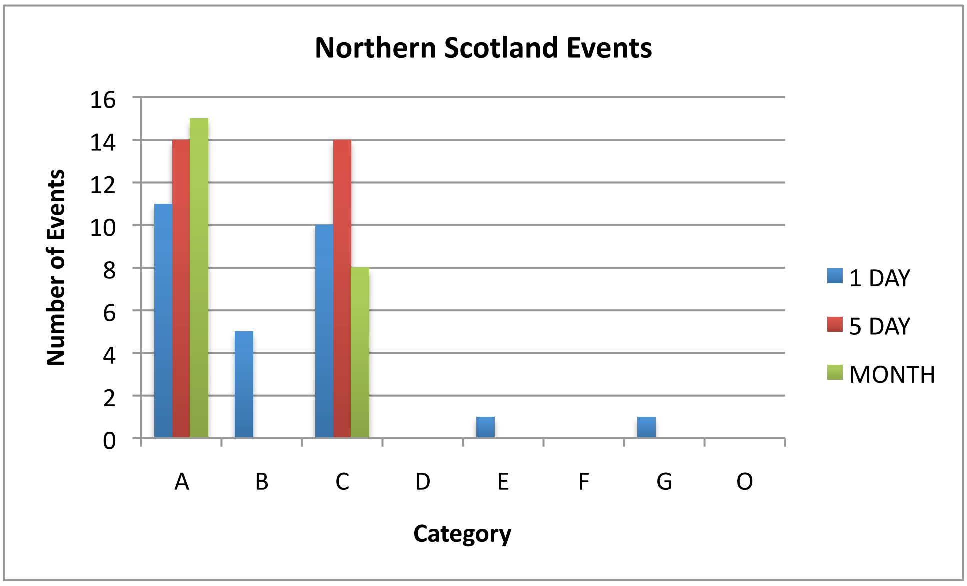

Figure 4.11. The number of events in each category for Northern Scotland

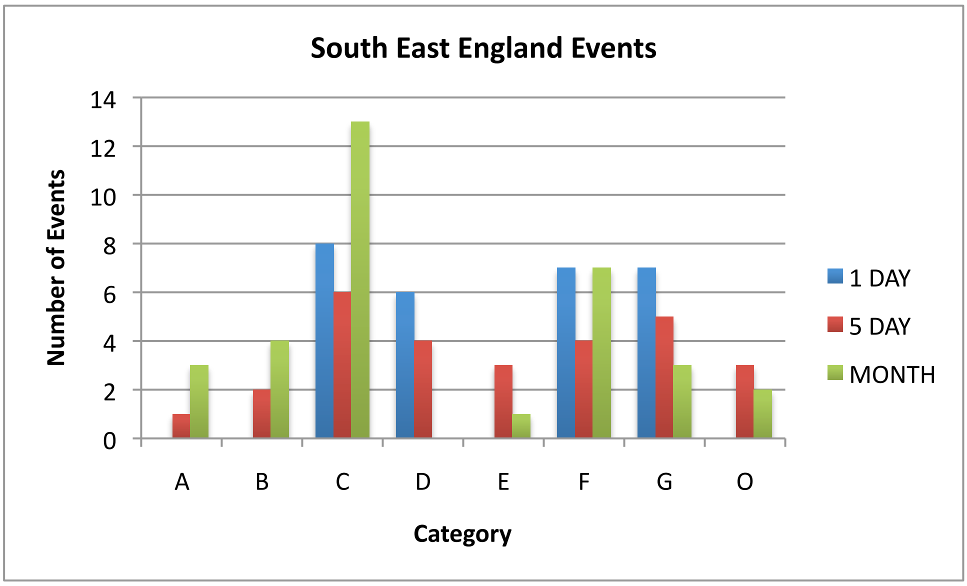

Figure 4.12. The number of events in each category for South East England.

It can be seen in figures 4.11 and 4.12 that the distribution of events within each category is significantly different for Northern Scotland extreme rainfall events, as opposed to those in the South East of England. In Northern Scotland, most events fall within category A and C which shows that most extreme rainfall in this region are related to low pressure systems to the north west of the UK situated over Iceland or the Faroe Islands. Therefore westerly or south westerly airflow dominates during extreme rainfall events on all timescales. This allows a long fetch and thus can pick up considerable moisture off the Atlantic Ocean. On daily timescales of extreme rainfall, although category A and C weather types still dominate, it is more likely that an event may be caused by slightly different weather patterns (such as category B, blocking high to the east slowing down the track of Icelandic low pressure systems). Although other weather patterns can lead to extreme rainfall over Scotland, these events are rare, and do not produce the heaviest rainfall events.

In comparison, in South East England a much larger range of weather pattern can lead to extreme rainfall in the region, especially at the five day and monthly timescales, with at least one event within each category (see fig. 4.12). Categories C, D, F and G however are the more likely weather patterns associated with extreme rainfall in this region and at these timescales. However one day events are confined to just four categories, with a fairly equal amount of events associated with categories C, D, F or G. All of these categories are associated with low-pressure systems much closer to the UK than usual and in particular to South East England. But generally figure 4.12 shows that extreme rainfall in the South East of England can be associated with and caused by significantly different weather patterns between events.

Therefore extreme rainfall in Northern Scotland is more likely to be caused by weather patterns that are associated with a more 'usual' Icelandic Low pressure system to the north west of the region. In comparison extreme rainfall in South East England is more likely to be associated with a southerly displacement of the jet stream, and therefore a more southerly track of systems across the UK. High pressure systems over Scandinavia and Central Europe can act to slow low pressure systems to the north west or west of the UK and produce extreme rainfall, in the form of slow moving frontal systems, as in category B and F. But it is generally more likely that extreme rainfall is associated with a more mobile situation, in which a zonally orientated and strong jet stream allows a series of low pressure systems to move across the country. This is definitely the case on the five day and monthly timescales in Northern Scotland.

4.4 Seasonal distribution of categories of events associated with extreme rainfall.

This section will outline the time of year in which certain categories of weather types are likely to cause extreme rainfall across the three different timescales in both Northern Scotland and South East England. A seasonal approach will be taken, with each season being looked at separately. MAM refers to Spring, JJA to summer, SON to October and DJF to winter.

4.4.1 Seasonal distribution of categories in Northern Scotland events

Figure 4.13 shows that there are certain times of the year when certain weather types dominate in the formation of extreme rainfall events. For example in autumn category C is by far the dominant weather type which causes extreme rainfall events on all three timescales with all 5 day events being attributed to this category. In contrast, in winter category A is the more dominate weather type. This indicates that weather patterns where the jet stream is further south and therefore low pressure systems track closer to north west Scotland are more likely to cause extreme rainfall events in Autumn, with the strong Icelandic low synoptic situation (A) more likely to cause extreme rainfall in the winter months. In spring and summer due to the reduction in total number of events during this part of the year it is more difficult to determine the dominate weather types which drive extreme events during this time of year.

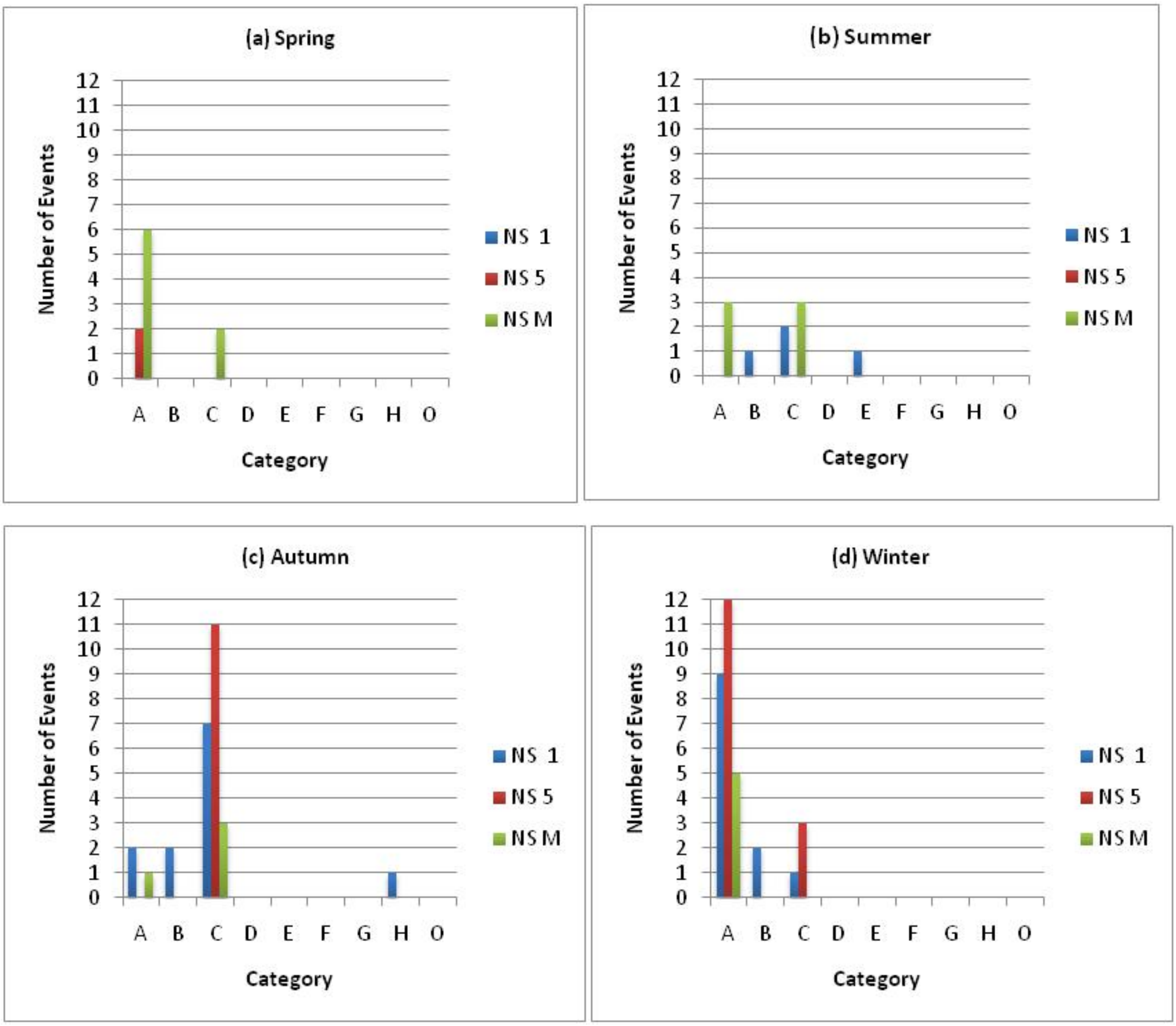

Figure 4.13. Seasonal distribution of events within each category for Northern Scotland. (a) Spring, (b) Summer, (c) autumn and (d) winter.

<u>4.4.2 Seasonal distribution of categories in South East England events</u>

In South East England there is much less seasonal variation in terms of the times of year in which certain weather categories dominate the production of extreme rainfall events. Most categories of weather type have contributed to extreme rainfall during most seasons. However certain categories do still dominate within some certain months but due to the limited number of events these results may not be significant. For example category F is the most likely weather type to have caused extreme one day rainfall in summer, along with C and D. In Autumn category C is also a significant contributor to extreme rainfall over all three timescales.

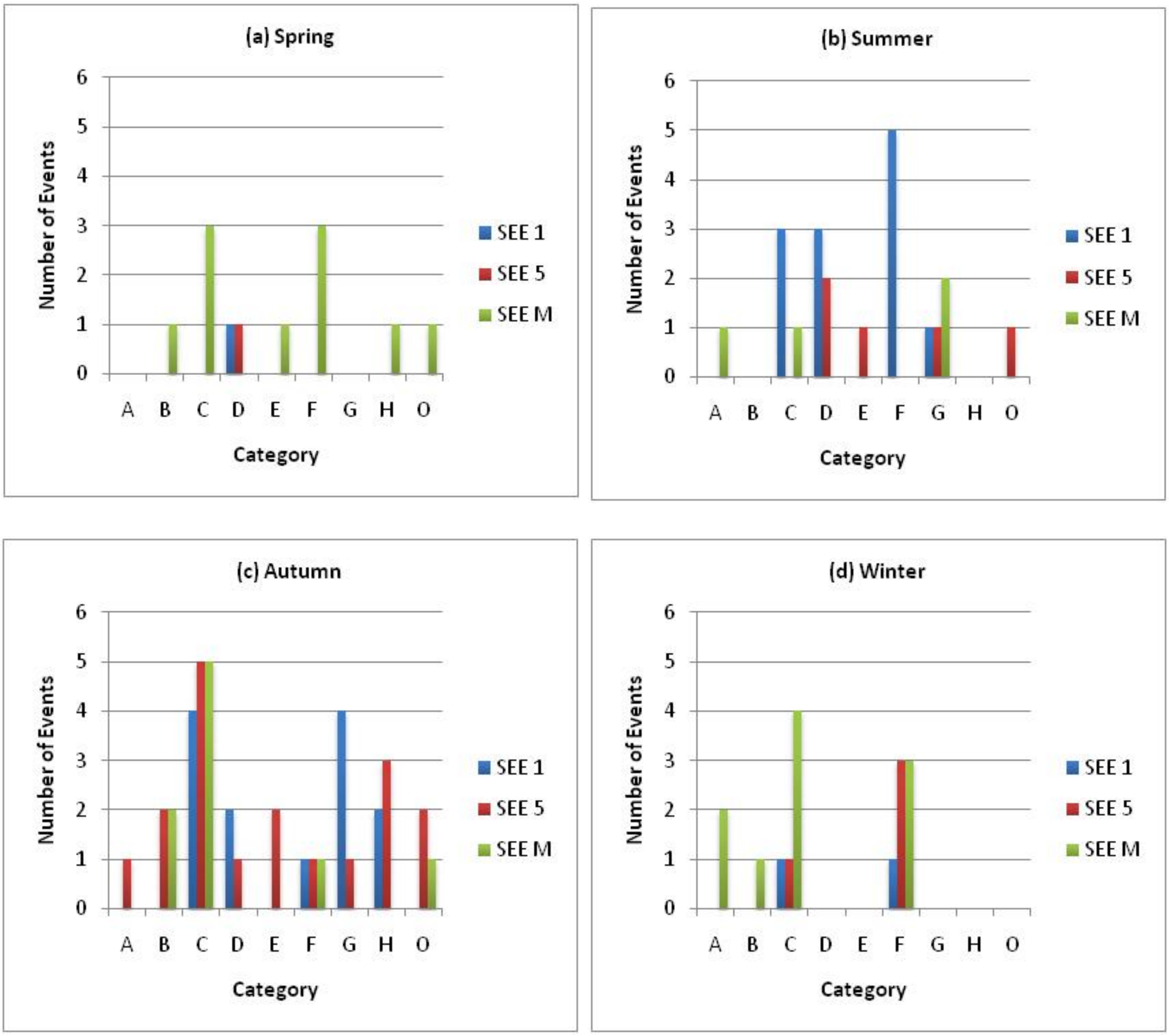

Figure 4.14. Seasonal distribution of events within each category for South East England. (a) Spring, (b) Summer, (c) autumn and (d) winter.

However generally there is little evidence of certain categories dominating extreme rainfall events. This indicates that extreme rainfall in South East England is much less predictable in terms of the weather patterns that have caused such events in comparison to Northern Scotland.

4.5 Relating extreme rainfall events to past flooding and the river flow record.

The list of flood events which have been documented in various sources as discussed in the Methodology can be found in Appendix B. The results of the number of flood events which related to one of the extreme rainfall events which were found in the study can be seen in figure

4.15. Twenty-five fluvial flooding events were found in the South East England region, with 21 in Northern Scotland.

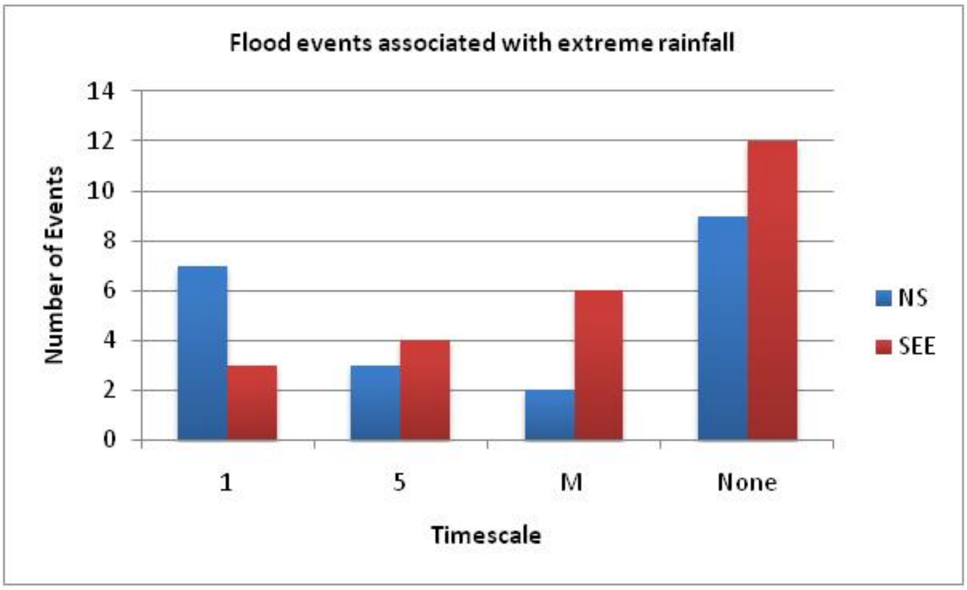

Figure. 4.15. The number of recorded flood events associated with any identified extreme rainfall events in Northern Scotland and South East England.

The interesting result that comes from figure 4.15 is the fact that there is evidence that different timescales of extreme rainfall are more likely to cause flooding within the two different regions. In Northern Scotland the largest number of floods that are associated with extreme rainfall, are on the one day timescale. In comparison, flooding events associated with extreme rainfall in South East England, are mainly linked to extreme monthly events. It is also notable that a significant number of flood events are not associated with extreme rainfall events which have been identified by this investigation, with nearly half of all recorded flood events in South East England not being related to any extreme rainfall event indentified in this research.

As well as looking at flood events over the entire two regions, as mentioned in the Methodology, two catchments were identified, one for each region, and the highest river flow peaks were then linked to the extreme rainfall events to also see whether there is any relationship between the two (for 1971-2008). The results of this can be seen in figure 4.16. Although the top ten flow events were chosen for each catchment, the number of events in figure 4.16 exceeds ten for each catchment. This is because some high flow events were associated with extreme rainfall on more than one timescale (for example with a one day and a five day event).

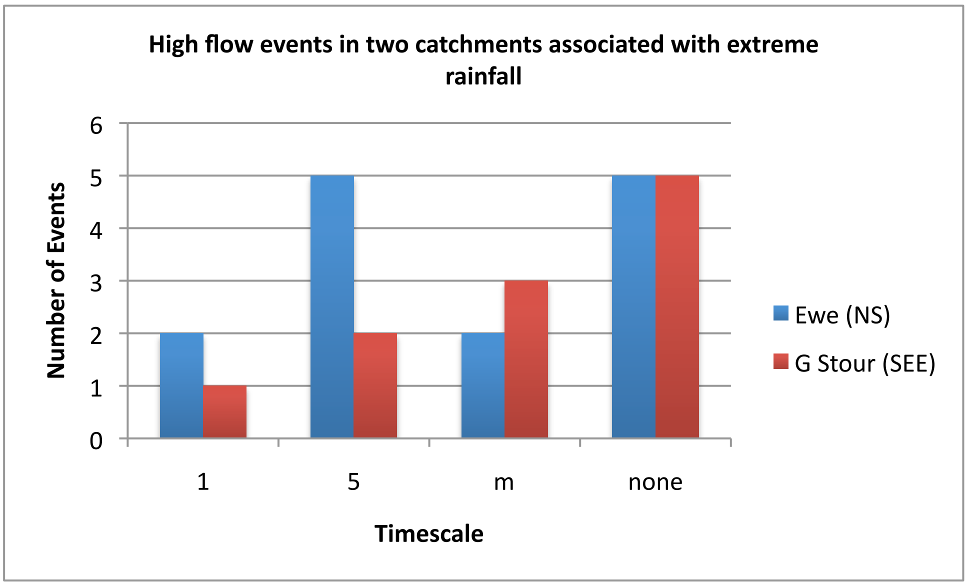

Figure. 4.16. The number of top ten flow events in the Ewe and Great Stour catchments associated with any of the identified extreme rainfall events.

The Great Stour in South East England shows a similar pattern to that of the rest of the South East England region, with more high flow events associated with longer extreme rainfall periods at the monthly timescale as well as a significant number of events that are not associated with extreme rainfall whatsoever. In the Ewe catchment a slightly different pattern to that shown to the rest of the Northern Scotland region is evident, with 5 day extreme rainfall events dominating the highest peak flows and not one day events. But once again half of the highest peak flow events are not associated with any of the extreme rainfall events identified by this investigation.

5. Discussion of the Results

This chapter will discuss the results of this investigation in relation to past research undertaken into the field of extreme rainfall events and flooding. Firstly the categorisation of weather types that lead to extreme rainfall will be discussed, before looking into the relationship between extreme rainfall events and flooding/high river flows. Finally the implications of this research will also be argued.

5.1 Categorising the weather patterns associated with extreme rainfall and links to the NAO

The first results of the analysis of extreme events shows that there is a marked seasonal distribution of events, especially at the short 1 day and 5 day timescales. Hand et al (2004) found that short extreme rainfall events (less than 60 hours), were very unlikely to occur in the UK during February to April. This relates fairly well to the findings of this report, except for the fact that there was a significant number of events in Northern Scotland in February. However the Hand et al (2004) study looked generally at low land stations and therefore very few events were found to occur in the uplands of Scotland, with most of them in England. However the study did conclude that orographic events were more likely in the winter months, and as the Northern Scotland region generally has steep orography which would be susceptible to such processes, it is not a surprise that a significant number of one day and five day events do occur in the winter months in the Northern Scotland region. Hand et al (2004) concluded that these type of events were associated with strong west or south west winds over the country in association with a strong high over the Bay of Biscay or Spain. Figure 5.1 shows the MSLP composite for category A events, and indicates a high pressure system over this exact area, with a stong pressure gradient over the UK producing south westerly flow. This category A type of weather is the most common cause of extreme one day and five day events, especially in the winter months, and therefore like the Hand et al (2004) study is an indication that orographic enhancement during this period can be a significant causal factor of extreme precipitaion events in the

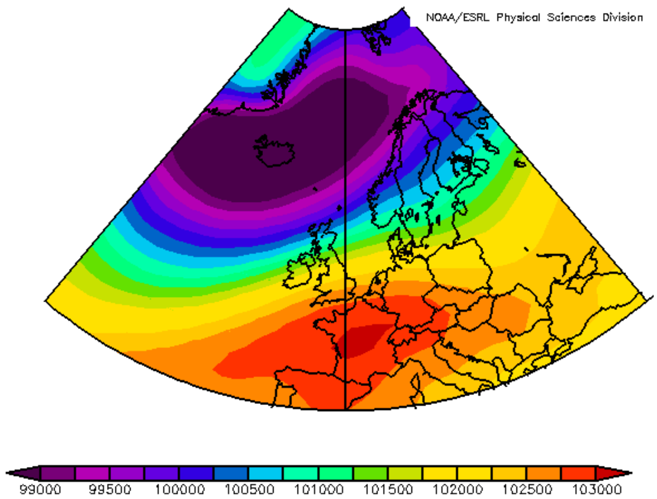

Figure 5.1 MSLP composite for category A events. Units: Pa (Source: NOAA, 2011).

region.

In South East England, extreme rainfall events were more likely to occur in the summer than in Northern Scotland. Hand et al (2004) also concluded that most convectively produced extreme rainfall events occurred in the summer months and were least likely to occur in the winter, with most of the convectively driven events occurring in the Midlands and the south of England. Therefore this compares well to the fact that many more one day and five day events occur in the South East in the summer and early autumn. This also explains the reason why there are a considerable number of type D and F events on these timescales. Type D and F produce southerly or south-easterly flow over the South East of England, and would allow moist and warm air to travel northwards which may have allowed deep convection to occur, and this may relate to the Spanish Plume effect. This occurs when hot dry air aloft, originating from the Iberian Plateau, caps warm moist air underneath as it travels northwards. This produces considerable instability in the atmosphere and can lead to the formation of intense multi-cell thunderstorms. This was the case on the 31/07/1978, a category D event with low pressure just to the south of the UK.

The results of this investigation show that there are several types of weather pattern which lead to extreme rainfall events within the United Kingdom, and shows that certain weather types have repeatedly occurred since 1931 to give the highest rainfall totals on the three timescales investigated. What is evident is the fact that in Northern Scotland a much smaller number of weather categories actually cause extreme rainfall in comparison to South East England where a wide variety of synoptic weather situations can cause heavy rainfall on varying timescales. In Northern Scotland nearly all events are produced by a deep Icelandic Low situation, with westerly or south westerly flow and a mobile jet stream which would allow a succession of storms to pass close to the north and west of Scotland. It has been previously found that there is a strong significant correlation between the NAO and precipitation in Northern Scotland. It has been found in the Ewe catchment that the correlation is as strong 0.81 in January, and is strong throughout the winter months. It also shows a slightly weaker but still significant correlation in the autumn (see fig. 5.2)(Lavers et al, 2010).

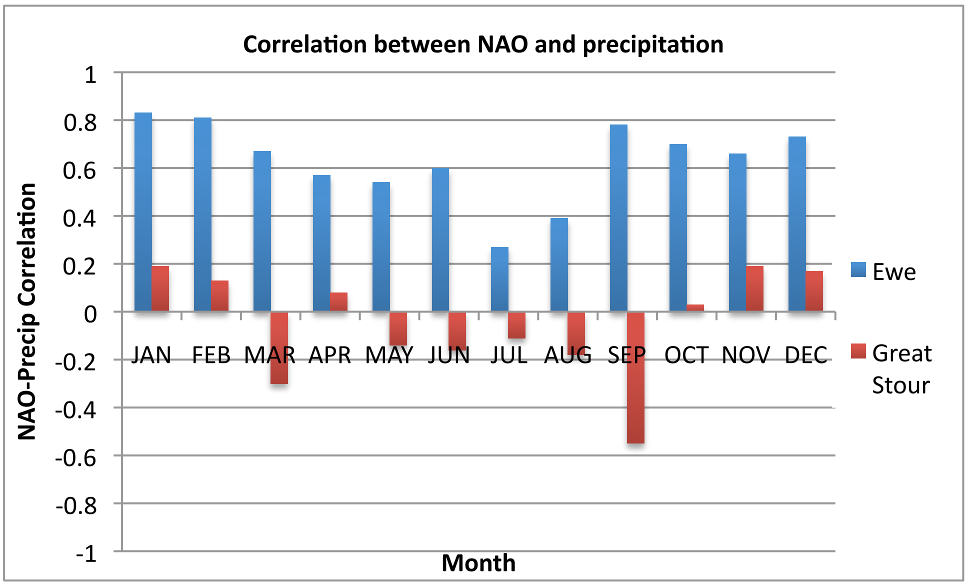

Figure 5.2 The correlation between NAO and precipitation in the two catchments (Data source: Lavers et al (2010)).

This links well with the findings of this investigation, with type A events dominating in the winter (strong Icelandic low) which would indicate that a strong NAO would lead to more precipitation. In the autumn months type C weather types dominate extreme events, which indicates a southward shift of the Icelandic low, and therefore would weaken the NAO index. The weakening of the correlation between the NAO and precipitation in the summer has been argued to be down to the fact that equator-north pole temperature gradient weakens during this time, and this weakens westerly flow, with a shift in pressure centres further north (Lavers et al, 2010; Lamb, 1972). This therefore is an explanation for the fact that extreme events are less likely in the summer in Northern Scotland. With weakened westerly flow and a less intense Icelandic low, the westerly flow of moisture-laden air towards the Scottish mountains would weaken, and therefore would reduce orographic precipitation.

The Great Stour at Horton in contrast does not show a significant positive or negative correlation between the NAO and precipitation (except in the month of September), and this relates to the fact that a wide variety of weather types can lead to heavy precipitation over the South East of England. It is also an indication that the area is sheltered from westerly winds and the moisture these can bring, with the strength of these heavily managed by the NAO.

5.2 Linking to Lamb circulation types

As shown in table 2.1, that certain lamb airflow types were identified to cause higher rainfall than others in Northern Scotland and South East England (Sweeney and O'Hare, 1992). In Northern Scotland, westerly and south-westerly lamb airflow categories produced the highest precipitation yields in this region. Appendix A lists the assigned lamb weather type for each extreme day events. All events were associated with a lamb weather type which was either southerly, south-westerly or westerly, whether this was associated with cyclonic or anticyclonic flow.

In South East England it was found that the Lamb weather types associated with the most precipitation were dominated by cyclonic types, with many having an easterly component (Sweeney and O'Hare, 1992). Of the 28 events, 14 were classified as having cyclonic flow, with a further seven classified partly as being either north-easterly, easterly or south-easterly. However several extreme events showed different Lamb types, and this relates to the fact that a wide variety of weather patterns and air flows can lead to extreme rainfall in this region. It may also be due to the limitations of such a classification scheme identified in chapter two, such as the possibility of two different air masses affecting the country at any one time.

This has shown that the research carried out into Lamb weather types and the precipitation yields from them by Sweeney and O'Hare (1992), links well to the extreme rainfall events determined by this investigation. Although there are many drawbacks of using classification systems such as Lamb weather typing, it can be argued that such systems allow comparison to be made between weather events in the United Kingdom.

5.3 Eastward and South-Eastward displacement of the jet stream

As discussed in chapter two, one of the main drivers of the exceptional autumn rainfall in 2000, was due to the eastward displacement of the jet stream towards the UK (Blackburn and Hoskins, 2001). What was evident when looking at the weather patterns associated with all of the extreme rainfall events was the fact that the jet stream was often displaced further to the east than normal, and in many cases in the South East of England, further south than normal often being situated directly over, or to the south of the UK.

Figure 5.3 shows the composite plot of the position of the jet stream (vector wind at 250mb) for the period 1931-2008. It shows that the peak intensity of the jet is situated towards 40W and 40N, a significant distance from the UK and at a maximum of 26 ms^{-1}. For category C, which the autumn 2000 event was classified as being, the jet stream is both much more intense, and much closer to the UK. The jet stream winds maximum is greater than 36ms^{-1} and is situated at 20W and 50N, much closer to the UK (see figure 4.6b). In all categories however the maximum winds within the jet stream for each composite are significantly faster than those of the average climatology. Therefore it can be argued that the increased intensity of the jet stream can act to cause extreme rainfall events, with eastward movement causing events in Northern Scotland,

and a south-eastward movement helping to develop events in the South East of England. The position of the jet stream determines the position and track of low pressure systems, and their associated rain bearing fronts, as well as westerly winds and associated moisture transport off the Atlantic Ocean (Marsh and Dale, 2002).

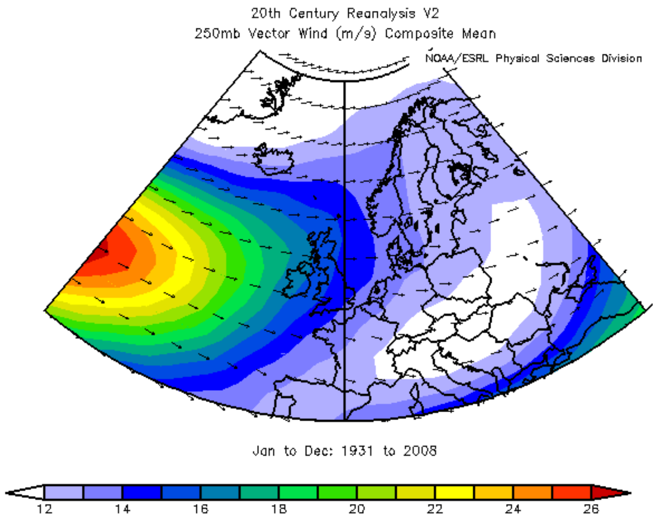

Figure 5.3. 250mb vector wind composite for 1931-2008 period. Units: ms^{-1} (Source: NOAA, 2011)

5.4 Extreme rainfall events and links to flooding in the UK

It is argued that extreme daily and five day events are more likely to cause flooding in the North of Scotland, with longer extreme events on the monthly timescales more likely to cause flooding in South East England. Lavers et al (2010) found that basins in western Britain have similar precipitation and river discharge patterns in relation to large-scale circulation. This means that the relationship between large-scale circulation and precipitation is also found in river discharge, and arguably means that the catchments in this region are highly responsive to rainfall events, and therefore in terms of the Ewe catchment, that there is also a strong relationship especially in the autumn and winter between river flows and the NAO. It was argued that the lower base flow index of catchments in Northern Scotland compared to the South East of England would mean that catchments in this area are more responsive. The Base Flow Index (BFI) is the proportion of river flows produced by longer stored water sources (for example groundwater stores), and the impermeable bedrock of the catchments of the North of Scotland would mean less water would enter such stores and would instead directly flow into the channel. However the Ewe catchment has a large loch along the channel which can act to store water flow, which has increased the BFI of the catchment to values close to the Great Stour. This has been argued to moderate storm flows on daily timescales, but due to the size of the loch, monthly extreme rainfall is less attenuated (Lavers et al 2010). This may help to explain why unlike the rest of the Northern Scotland region, that most of the high flow events in this catchment were not caused merely just by one day extreme rainfall events (see figures 4.15 and 4.16).

Ultimately the response of the differing responses of the catchments in Northern Scotland and South East England can be related to differences in the geology and topography of the two regions. As described in chapter 3, the geology of Northern Scotland including the Ewe catchment, is dominated by impermeable bedrocks with a shallow surface soil layer, with valleys that are narrow and have steep valley sides. This reduces the amount of rainfall which can infiltrate, and speeds up the development of channel flows. Therefore it would be expected that short extreme events would dominate floods in this area. In contrast, in South East England much of the area's geology is dominated by more permeable geology such as chalk, which allows large stores of water in the sub surface layers. Therefore for flooding to occur, these subsurface stores will have to be at capacity before surface runoff would occur. This would indicate that much longer periods of above average rainfall would require flooding, unless short-term extreme rainfall events were intense enough to exceed infiltration capacity.

However many flood events were not associated with extreme precipitation events identified in this investigation and there may be several factors why this may be the case. All of the high flow events on the River Ewe that are not associated with extreme rainfall are in the winter and early spring (See Appendix C). Therefore potentially some of these events may have been caused by snowmelt, due to warming from a change in wind direction and air mass. However although some of the flooding events across the whole of Northern Scotland are also during this time of year, many of the events not associated with an extreme rainfall event are found in the Summer and Autumn and are therefore unlikely to be due to snowmelt. These events, as well as those in South East England may have been produced instead by local intense rainfall produced by convective or localised orographic enhancement, falling on already saturated ground. These localised events may not have been picked up in a regional precipitation series as the event may have only fallen on one or even none of the rain gauges used to formulate the data series, and shows one of the major drawbacks of using a regional precipitation data series. This therefore underlines the potential drawbacks of the use of regional precipitation data sets, and the need to also look at individual rain gauge stations, similar to the methods used by Hand et al (2004).

5.5 Implications of this Research

Arguably this research has identified the types of weather patterns associated with extreme rainfall over two opposing regions of the UK, and how extreme rainfall generation differs between these two areas. With this knowledge of past events, it allows for a better understanding of what may cause extreme rainfall into the future. If the types of weather patterns that lead to extreme rainfall are better understood, then better forecasting of flood risk may be possible if certain weather regimes are expected to affect the country. With this, areas at risk may be given more accurate warnings of potential flooding, and more time to be able to prepare for them. If more time is given to prepare for flood events, then the financial costs may be lowered and the risk to human life reduced. This would allow for artificial flood defences to be put in place, sand bags prepared, movement of property to higher levels, and potentially the evacuation of people from at risk areas.

With future climate change, it has already been discussed that there is evidence that the intensity of precipitation events has increased over the past 100 years (Osborn and Maraun, 2008),and is likely to continue to increase into the future especially during the winter months. With global climate model simulations of the future climate indicating that anthropogenic forcing will increase the intensity of the storm track over North West Europe (Ulbrich and Christoph, 1999), it is expected that category A and C events will become potentially more common and more intense. This would have implications on extreme precipitation events, especially in Northern Scotland where most events were associated with category A and C weather types. They also found that the NAO centres (i.e. the low pressure minimum and high pressure maximums), were likely to move north-eastwards with low pressure centred further into the Norwegian Sea (Ulbrich and Christoph, 1999). This may indicate that type A to C events would be less likely to cause extreme rainfall in South East England, as the low pressure systems and strong westerly flow would shift north-eastwards. This could therefore reduce the number of extreme rainfall events in this region especially during the Autumn and Winter.

Ultimately this research has allowed the identification of dominant weather patterns that are associated with extreme rainfall events, by looking at an extended precipitation data set and identifying a series of extreme events instead of focusing on them singly. Therefore the next step is to determine whether these same weather patterns are represented well in Global Climate Models (GCM's), and whether these models are able to determine whether such weather patterns are likely to increase into the future.

6. Conclusions

Flooding in the United Kingdom is a significant issue which impacts on the nation's infrastructure, property and ultimately can cause injury and death in the most extreme cases. Therefore with this, and the potential risks of increased flood frequency into the future, it is paramount that the weather systems which lead to extreme rainfall events and flooding are better understood. This investigation has been able to combine the precipitation, 20th century reanalysis, flood archive and flow data sets to be able to better assess the links between atmospheric dynamics, rainfall, river flow and ultimately flooding.

This investigation found that the weather systems associated with extreme rainfall on various timescales were able to be grouped into eight main categories, in relation to mean sea level pressure fields, the jet streams location and shape, and geopotential anomalies over Western Europe and the North Atlantic. In Northern Scotland, nearly all extreme precipitation events were associated with a strong Icelandic Low pattern which was either in its usual position or slightly displaced towards the north of Scotland. This was associated with a strong jet stream which directed low pressure systems to the north of the UK and provided strong westerly flow which brought increased moisture transport to the north west coast of the north of Scotland. In contrast the South East of England has experienced a much wider range of weather systems which produce extreme rainfall in the region. In general a much further displaced jet stream across the central parts of the country, or much further south over Iberia, can drive low pressure systems much further south and impact on the region.

Importantly this research has indicated the weather patterns that are most likely to cause extreme rainfall, and increase the risk of flooding occurring. It can be concluded that:

- In Northern Scotland certain categories of events are more likely to cause extreme rainfall at different times of the year at different timescales. The most significant trend is that category A weather patterns are most likely to cause extreme events in winter, and category C weather is the dominant driver of autumn extreme events. However in South East England, almost any category of event can cause extreme rainfall at different times of the year and at different timescales.
- Extreme events are unlikely to occur in the Spring and Summer in Northern Scotland, and less likely to occur in the winter and spring in South East England
- Not all flood events across the whole of the region and high flow events on the case study catchments were associated with extreme events, and not all extreme events were associated with flooding

- Flooding was more likely to occur in Northern Scotland due to short one day or five day events with flooding in South East England more likely to occur due to longer monthly extreme events. It is argued that this was down to the geology and topography of the catchments and the response times of the rivers in each region.

6.2 Limitations and potential for future study

As discussed in chapter 2 there can be drawbacks from trying to categorise the weather of the British Isles, as it can be highly complex and variable even on daily timescales. Therefore by trying to categorise the weather associated with extreme rainfall on the large scale can mean that smaller features which may be different between events can be ignored. Especially on monthly timescales, different weather category types may combine to produce the extreme event. Even on daily timescales different weather patterns and flow can be experienced over different parts of the UK (Sweeney and O'Hare, 1992). However producing composites of daily events, which show similar characteristics, produced plots which showed clear signals of the structure of the mean sea level, pressure field, jet stream and geopotential anomalies. This suggests that this method in trying to categorise events was appropriate. Despite this however, it must be noted that no two events were exactly the same.

By using regional precipitation data, it allows us to be able to determine the extent at which an event impacted across a whole region. However this means that many local events which may have only impacted on a small area may not have been evident within the data set. This has implications for both of the regions studied. In Northern Scotland for example, the region has a large geographic extent, including the Western Isles as well as Orkney and Shetland which are a considerable distance from the mainland. An extreme event in Shetland may not be identified in the regional data set, and in contrast and extreme event which may have affected the mainland may be reduced in intensity within the data set my low precipitation levels in the Northern and Western Isles. In South East England, where it has been argued that convective systems can be important in producing extreme events, can be very localised in nature. Such events once again may not be identified in a regional precipitation data set.

Also by restricting the timescales at which extreme events were looked at, would ultimately mean that many rainfall events which took place over different timescales would not be identified. This as well as the fact that regional data sets were used, may explain the fact that not all flood events in both regions were associated with extreme rainfall events. The rainfall associated with these events may have been localised or associated with timescales not looked into within this study.

Therefore with this in mind, further work into this field should firstly look into using point source measurements, like that done in studies of short term extreme events undertaken by Hand et al (2004) and extend this to five day and monthly timescales, potentially first looking at measurements within the Ewe and Great Stour catchments. Secondly extreme precipitation events should be extended to include bi-monthly or seasonal timescales, as this may be a factor in causing flood events especially in the South East of England where antecedent moisture conditions can have a significant impact on whether a shorter term rainfall event will or will not cause flooding.

Finally it would also be useful to look at extreme events and determine whether the categories that have been produced for Northern Scotland and South East England can be extended across the whole of the United Kingdom, and whether there are any other weather types which create extreme rainfall events in other parts of the country.

7. 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.

Alexander, L; Jones, P (2000). Updated precipitation series for the UK and discussion of recent extremes. *Atmospheric Science Letters* **1** (2) p.142-150

Allan, R (2011). Human influence on rainfall. *Nature* **470** p.344-345

Black, A (1995). Major flooding and increased flood frequency in Scotland since 1988. *Physics and Chemistry of the Earth.* **20** (5-6) p.463-468

Blackburn, M and Hoskins, B (2001). Atmospheric Variability and extreme Autumn rainfall in the UK. University of Reading

Burt, T and Horton, B (2007). Inter-decadal variability in daily rainfall at Durham (UK) since the 1850s. *International Journal of Climatology.* **27** p.945-956

Centre for Ecology and Hydrology (2011a). 94001-Ewe at Poolewe: Catchment Characteristics Available at: http://www.ceh.ac.uk/data/nrfa/data/spatial.html?94001 [Accessed: 1st August 2011]

Centre for Ecology and Hydrology (2011b). 40011-Great Stour at Horton: Catchment Characteristics. Available at: http://www.ceh.ac.uk/data/nrfa/data/spatial.html?40011 [Accessed: 1st August 2011]

Compo, G; Whitaker, J; Sardeshmukh, P; Matsui, N; Allan, R; Yin, X; Gleason, B; Vose, R; Rutledge, G; Bessemoulin, P; Bronnimann, S; Brunet, M; Crouthamel, R; Grant, N; Groisman, P; Jones, P; Kruk, M; Kruger, A; Marshall, G; Maugeri, M; Mok, H; Nordil, O, Ross, T; Trigo, R; Wang, X; Woodruff, S; Worley, S (2010). The Twentieth Century Reanalysis Project. *Quarterly Journal of the Royal Meteorological Society.* **137** (654) p1-28

Conway, D; Wilby, R; Jones, P (1996). Precipitation and air flow indices over the British Isles. *Climate Research.* **7** p.169-183

DEFRA (2011). *Future funding of flood and coastal erosion risk management in England*. Available at http://www.defra.gov.uk/environment/flooding/funding-outcomes-insurance/ [Accessed on 16th July 2011]

Durman, C; Gregory, J; Hassell, D; Jones, R, Murphy (2001). A comparison of extreme European daily precipitation simulated by a global and regional climate model for present and future climates. *Quaterly Journal of the Royal Meteorological Society.* **127** p.1005-1015

Environment Agency (2011). Flood. Available at: http://www.environment-agency.gov.uk/homeandleisure/floods/default.aspx [Accessed on 2nd July 2011]

European Environment Agency (2003). Mapping the impacts of recent natural disasters and technological accidents in Europe. *Environment Issue Report No.35.*

Fowler, H and Kilsby, C (2005). Implications of changes in seasonal and annual extreme rainfall. *Geophysical Research Letters.* **30** (13) p.1720-1723

Gregory, J; Jones, P; Wigley, T (1991). Precipitation in Britain: an analysis of area-average data updated to 1989. *International journal of climatology.* **11** p. 331-345

Hand, W, Fox, N; Collier, C (2004). A study of twentieth-century extreme rainfall events in the United Kingdom with implications for forecasting. *Meteorological Applications.* **11** p.15-31

Haylock, M; Cawley, G; Harpham, C; Wilby, R; Goodess, C (2006). Downscaling heavy precipitation over the United Kingdom: A comparison of dynamical and statistical methods and their future scenarios. *International Journal of Climatology.* **26** p.1397-1415

IPCC (2007). *Climate Change 2007-The Physical Science Basis: Contribution of working group I to the fourth assessment report of the IPCC.* Cambridge University Press

Jenkinson, A and Collison, F (1977). An initial climatology of gales over the North Sea. *Synoptic Climatology Branch Memorandum No. 62.* Meteorological Office, Bracknell.

Lamb, H (1950). Types and spells of weather around the year in the British Isles: annual trends, seasonal structure of the year, singularities. *Quarterly Journal of the Royal Meteorological Society.* **76** p.393-429

Lamb, H (1972). British Isles weather types and a register of the daily sequence of circulation patterns 1861-1971. *Meteorological Office, Geophysical Memoir no. 116.* HMSO, London

Lavers, Dl Prudhomme, C; Hannah, D (2010). Large-scale climate, precipitaion and British river flows: Identifying hydroclimatological connections and dynamics. *Journal of Hydrology*. **395** p. 242-255

Limbrick, K; Whitehead, P; Butterfield, D; Reynard, N (2000). Assessing the potential impacts of various climate change scenarios on the hydrological regime of the River Kennet at Theale, Berkshire, south-central England, UK: an application and evaluation of the new semi-distributed model, INCA. *The Science of the total Environment.* **251** p.539-555

Local Government (2011). Managing flood risk. Available at http://www.idea.gov,uk/idk/core/page.do?pageId=13058274 [Accessed on 6th July 2011]

Macklin, M; Rumsby, B (2007). Changing climate and extreme floods in the British uplands. *Transactions of the Institute of British Geographers.* **32** (2) p168-186

Marsh, T and Dale, M (2002). The UK floods of 2000-2001; A Hydrometeorological appraisal. *Water and Environment Journal.* **16** (3) p.180-188

Marsh, T (2004). The January 2003 flood on the Thames. *Weather* **59** (3) p.59-62

Mayhew, S (2004). *Oxford Dictionary of Geography.* Oxford University Press, UK.

MetOffice (2011a). MetOffice Hadley Centre observational datasets: HadUKP. Available at: http://www.metoffice.gov.uk/hadobs/hadukp/ [Accessed on 1st July 2011]

MetOffice (2011b). UK Mapped Climate Averages. Available at http://www.metoffice.gov.uk/climate/uk/averages/ukmapavge.html [Accessed on 2nd August 2011]

NOAA (2011). 20th Century Reanalysis. Available at: http://www.esrl.noaa.gov/psd/data/20thC_Rean/ [Accessed on 1st July 2011]

Osborn, T and Hulme, M (2002). Evidence for trends in heavy rainfall events over the UK. *Philosophical Transactions of the Royal Society A.* **360** p.1313-1325

Osborn, T and Maraun, D (2008). Changing intensity if rainfall over Britain. *Climatic Research Unit.* Information Sheet no.15. Available at: http://www.cru.uea.ac.uk/cru/info/ukrainfall/ [Accessed on 28th June 2011]

Pall, P; Aina, T; Stone, D; Stott, P; Nozawa, T; Hilberts, A; Lohmann, D and Allen, M (2011). Anthropogenic greenhouse gas contribution to flood risk in England and Wales in autumn 2000. *Nature* **470** p.382-386

Robson, A (2002). Evidence for trends in UK flooding. *Philosophical Transactions of the Royal Society A.* **360** p.1327-1343

Sweeny, J and O'Hare, G (1992). Geographical variations in precipitation yields and circulation types in Britain and Ireland. *Transactions of the Institute of British Geographers.* **17** p.448-463

Thompson, R (1999). A time-series of the changing seasonality of precipitation in the British Isles and neighbouring areas. *Journal of Hydrology* **224** p.169-183

Ulbrich, U and Christoph, M (1999). A shift of the NAO and increasing storm track activity over Europe due to anthropogenic greenhouse gas forcing. *Climate Dynamics.* **15** p.551-559

United States Geological Survey, USGS (2004). The world's largest floods, past and present: Their cause and magnitudes. Available at: http://pubs.usgs.gov/circ/2004/circ1254/ [Accessed on 2nd July 2011]

University of Dundee (2011). *Chronology of British Hydrological Events.* Available at http://www.dundee.ac.uk/geography/cbhe/ [Accessed 5th July 2011]

Wigley, T; Lough, J; Jones, P (1984). Spatial patterns of precipitation in England Wales and a revised, homogeneous England and Wales precipitation series. *International Journal of Climatology* **4** p.1-25

Zolina, O; Simmer, C; Gulev, S; Kollet, S (2010). Changing structure of European precipiation: Longer wet periods leading to more abundant rainfalls. *Geophysical Research Letters.* **37**

8.1 Appendix A: Extreme Precipitation Events

ONE DAY EVENTS						
	South East England			Northern Scotland		
	Date	Rainfall (mm)	Category	Date	Rainfall (mm)	Category
1	29/10/2000	41.95	C	28/02/1955	53.50	B
2	27/05/2007	41.02	D	19/12/1936	50.20	A
3	17/07/1945	41.00	F	29/10/2001	47.91	A
4	13/09/1975	40.87	G	02/01/1992	47.09	A
5	09/10/1987	40.38	C	18/09/1990	46.20	C
6	10/06/1971	38.40	D	03/11/1932	43.74	C
7	31/07/1978	35.80	D	20/11/1947	42.22	C
8	27/12/1979	35.44	C	11/02/1962	42.17	A
9	22/06/1966	34.43	F	06/12/1938	42.02	A
10	16/08/1977	33.43	D	30/10/1940	40.54	B
11	25/08/1986	33.34	F	21/09/1969	40.44	A
12	14/08/1980	32.99	F	27/08/1933	40.25	B
13	15/09/1968	32.98	D	26/09/1948	40.12	C
14	31/10/1998	32.62	G	10/08/1935	39.80	C
15	19/06/1973	32.49	C	12/07/1939	39.62	C
16	04/09/1974	32.24	C	25/10/1987	39.59	B
17	13/11/1940	31.78	C	21/10/1971	39.04	C
18	20/10/1987	31.53	F	18/02/1935	38.88	A
19	03/11/1940	31.28	G	24/10/1998	38.85	C
20	13/10/1939	31.18	H	14/01/1932	38.27	A
21	05/11/2000	31.17	G	25/02/1938	38.14	B
22	29/08/1966	31.03	F	19/12/1987	37.97	A
23	15/10/1980	30.87	D	04/02/1933	37.90	C
24	23/10/1949	30.82	H	29/07/1956	37.62	E
25	06/08/1962	30.72	G	30/01/1962	37.56	A
26	13/12/1989	30.62	F	06/02/1989	37.48	A
27	25/07/1954	29.94	C	25/10/2006	37.44	E

FIVE DAY EVENTS						
	South East England			Northern Scotland		
	Start Date	Rainfall (mm)	Category	Start Date	Rainfall (mm)	Category
1	22/10/1949	85.15	G	13/12/1940	113.40	A
2	21/11/2003	78.46	A	01/11/1996	111.27	C
3	13/11/1940	74.26	H	15/12/1936	107.80	C
4	13/11/1974	71.54	C	12/01/1932	106.22	A
5	12/12/1989	70.99	F	01/10/1943	105.67	C
6	30/10/1940	70.24	H	14/12/1932	105.35	A
7	11/10/1939	69.86	D?	30/12/1991	104.03	A
8	13/09/1968	69.56	F	15/02/1935	102.24	A
9	29/10/1960	68.48	C/F	05/03/1990	101.98	A
10	06/10/1987	68.12	C	04/12/1938	101.84	A
11	10/06/1971	67.70	D	03/01/1934	99.52	A
12	10/07/1945	66.90	E	26/10/2001	98.67	C
13	16/10/1949	66.23	C	25/10/2006	97.08	C
14	24/05/2008	66.11	D	24/09/1948	97.05	C
15	28/12/2002	65.79	F	24/10/1998	97.00	C
16	19/10/1932	65.56	C	26/12/1983	96.26	A
17	19/12/1995	65.20	F	29/10/1940	96.07	C
18	31/10/1957	63.41	C	31/01/1993	95.27	C
19	01/09/1974	63.37	B	23/10/1952	95.05	C
20	07/10/2000	62.59	B	02/02/1989	94.62	A
21	29/07/1978	62.07	B/D	02/02/1990	94.52	A
22	07/08/1960	61.94	G	29/12/1980	94.34	A
23	30/09/1993	61.61	E	02/10/1938	94.13	C
24	09/07/1968	61.70	D	10/12/1956	94.13	C
25	30/01/1990	61.34	C	06/12/1942	93.70	A
26	14/11/1963	61.10	H	22/09/1952	93.56	C
27	17/11/2007	59.06	E	15/03/1938	92.73	C
28	21/10/1945	58.76	C/F	17/10/1984	92.66	C

MONTHLY EVENTS						
	South East England			Northern Scotland		
	Month	Rainfall (mm)	Category	Month	Rainfall (mm)	Category
1	04/2000	290.1	E/F	05/1986	203.9	C
2	03/1947	291.7	F	02/1990	359.8	A
3	12/1934	244.3	F	06/1938	206.9	A
4	06/1971	260.4	G	04/1947	220.2	A
5	09/1974	262.3	C	03/1990	339.6	A
6	10/1987	262.9	C/F	07/1985	221.1	A
7	11/1940	252.1	C	08/1985	263.2	C
8	02/1951	275.5	C	07/1988	211.8	C
9	03/1981	253.9	C	08/1992	257.0	C
10	10/1949	250.5	C	12/1986	364.1	A
11	10/2000	182.0	C	08/1989	255.2	A
12	05/1932	119.9	H	11/1938	331.6	C
13	11/1970	186.4	C	03/1994	288.6	A
14	08/1977	132.8	A	03/1967	284.9	A
15	07/2007	112.6	G	02/1989	278.6	A
16	03/2001	122.4	F	09/1950	275.2	C
17	02/1937	124.9	C	01/1993	332.2	A
18	02/1990	122.3	A	05/1963	155.3	A
19	01/1988	143.8	C	10/1983	333.4	A
20	11/2002	175.4	B	09/1980	270.4	C
21	01/1995	143.1	A	05/1964	152.0	C
22	05/2007	110.6	C	03/1938	260.3	A
23	05/1955	110.5	C	02/1997	264.6	A
24	12/1978	144.9	F			
25	02/1950	117.3	C			
26	10/1960	167.0	F			
27	04/1966	105.4	F			

28	12/1989	143.8	F
29	09/1968	135.5	B
30	07/1950	105.5	C
31	05/2000	109.3	B
32	12/1959	143.4	B
33	05/1967	108.9	E

8.2 Appendix B: Significant Fluvial Flooding 1931-2008

Northern Scotland

Date	River	Region	M	5	1	Source
Jun 1931	Wick, Shin	NW Highlands				BHS
Aug 1933	Stornoway	Western Isles				BHS
Dec 1936	Moriston	SE Highlands		*	*	Acreman (1989)
Nov 1947	Glen Cannich	SE Highlands			*	Acreman (1989)
Sep 1953	Allt Uaine	Western Grampians			*	Acreman (1989)
Jan 1955	Tirry	Northern Highlands				Acreman (1989)
Jul 1957	Ness	Southern Highlands			*	BHS
Feb 1962	Allt Larig nan Lunn	Western Grampians			*	Acreman (1989)
	Loch Awe	Western Grampians			*	
	Lyon	Western Grampians			*	
	Beauly	SE Highlands			*	
Oct 1978	Oykel	Northern Highlands				Acreman (1989)
Sep 1981	Ardessie	Western Highlands				Acreman (1989)
Dec 1985	Helmsdale	NW Highlands				Black (1995)
Feb 1989	Ness	Southern Highlands	*		*	BHS
Nov 1989	Ness	Southern Highlands			*	Black (1995)
Feb 1990	Ness	Southern Highlands	*	*		BHS
Sep 2003		Shetland Isles				BHS
Jan 2005	Ness	Southern Highlands				BHS
Oct 2006	Thurso	Northern Highlands		*	*	BHS
	Halladale	Northern Highlands		*	*	
	Naver/Clachan Burn	Northern Highlands		*	*	
	Willow and Durkadale Burn	Orkney Isles		*	*	

South East England

Date	River	Region	M	5	1	Source
May 1932	Thames (catchm.)	Oxfordshire	*			BHS
Feb 1933	Ock (Thames)	Oxfordshire				Marsh and Dale (2002) BHS
Jun 1936	Wey	Surrey				BHS
Aug 1936	Wandle	Greater London				BHS
Dec 1936	Thames	Oxfordshire				BHS
Jun 1946	Colne	Hertfordshire				BHS
Mar 1947	Thames	Oxfordshire, Berkshire, Greater London	*			Marsh and Dale (2002) BHS
Apr 1951	Thames tribs.	Oxfordshire, Surrey				BHS
Mar 1953	Brent, Perivale	Greater London				BHS
Dec 1954	Colne	Hertfordshire				BHS
Aug 1958	Medway	Kent				BHS
Nov 1960	Winterbourne	Sussex		*		BHS
Dec 1960	Lavant, Sussex	Sussex	*			BHS
Sep 1968	Wey	Surrey	*	*		BHS
Dec 1979	Stour	Hampshire			*	Acreman (1989)
Feb 1990	Medway	Kent		*		BHS
Jan 1994	Lavant	Sussex				BHS
May 2000	Sussex	Sussex	(*)			BHS
Oct 2000	Sussex	Sussex	*		*	BHS
Nov 2000	Wey	Surrey			*	Marsh and Dale (2002)
Jan 2003	Thames	Oxfordshire, Berkshire, Greater London		*		Marsh (2004), BHS
Jul 2006	Wey	Surrey				BHS
Jul 2007	Ock, Thames,	Oxfordshire	*			BHS

8.3 Appendix C: Top Flow events in Ewe and Great Stour catchments

EWE-Northern Scotland					
	Date	Flow	M	5	1
1	06/02/1989	227.1	*	*5	*
2	13/12/1998	179.9			
3	01/01/1984	164.0		*+2	
4	15/12/1992	161.7			
5	03/01/1992	148.9		*5	*-1
6	11/03/1990	148.1	*	*+2	
7	07/01/2005	146.3			
8	20/01/2004	141.8			
9	02/01/1981	138.5		*5	
10	04/12/2006	135.7			

-1=day before

5d=on 5th day of 5 day event

+2=2 days after eve

*=on day

GREAT STOUR-South East England					
	Date	Flow	M	5	1
1	07/11/2000	30.92	*+1m		
2	09/02/2001	30.71			
3	05/11/1967	28.85			
4	29/12/1979	28.34			*+2
5	29/01/1988	28.05	*		
6	23/11/1974	27.24		+6	
7	31/12/2002	26.82	*+2m	*4	
8	27/12/1985	26.05			
9	21/02/1969	25.79			
10	29/10/1966	25.74			

8.4 Lamb Classification Key

U	Unclassified
A	Anticyclonic
ANE	Anticylonic North-Easterly
AE	Anticyclonic Easterly
ASE	Anticyclonic South Easterly
AS	Anticyclonic Southerly
ASW	Anticyclonic South Westerly
AW	Anticyclonic Westerly
ANW	Anticyclonic North Westerly
AN	Anticyclonic Northerly
NE	North-Easterly
E	Easterly
SE	South Easterly
S	Southerly
SW	South Westerly
W	Westerly
NW	North Westerly
N	Northerly
CNE	Cyclonic North-Easterly
CE	Cyclonic Easterly
CSE	Cyclonic South Easterly
CS	Cyclonic Southerly
CSW	Cyclonic South Westerly
CW	Cyclonic Westerly
CNW	Cyclonic North Westerly
CN	Cyclonic Northerly