Joint Defra/EA Flood and Coastal Erosion
Risk Management R&D Programme

Extreme event recognition project Phase 2

Analysis of less-extreme events and recent extreme events

R&D Project Report FD2208/PR

Environment Agency

defra
Department for Environment
Food and Rural Affairs

Work Package 1 Final report

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Will Hand (January 2006)

1. Aims of the package

The main aim of this work package was to identify and study a set of point rainfall events which were "less extreme" than those studied in Phase 1 [1]. The purpose was to ascertain whether there were any significant differences in the meteorology associated with extreme and less extreme rainfalls. In addressing this it was expected that some conclusions could be made as to whether the meteorological conditions that cause extreme rainfalls are "unusual" or whether the conditions form part of a continuum. The work was intended to be as objective as possible drawing largely on using established statistical techniques to explore differences between the sets of data. Extreme point rainfall cases occurring after 31/12/1999 were to be included in the study, noting any major differences from the 20th Century set.

2. Definitions used for "Extreme" and "Less Extreme" point rainfall events

2.1 Extreme Events

The Extreme Rainfall threshold (ET) used in Work Package 1 (WP1) was the same as that used for Phase 1. For point rainfall durations of 24 hours or greater the ET values were the published FSR Vol II [2] 1:100 year return period rainfalls for AAR (average annual rainfall) regime 1400-2800 mm. For durations of 1 hour or less the FSR "maximum fall possible" was used. In FSR this was expressed as percentages of the estimated 2-hour maximum rainfall which was conveniently taken to be 100mm for the purposes of Phase 1. ETs for a range of durations were then derived by log-linear interpolation from the ETs at 15 min, 30 min, 1h, 24h, 48h, 72h and 96h durations. The complete set of ETs used in WP1 is shown in Table 3.

The ETs for durations of 24 hours and above are FSR 1:100 year rainfalls (M100). Return periods for durations less than 24 hours were calculated from published FSR rainfall growth factors from estimated M5 rainfalls. M5 rainfalls were estimated using information in Tables 3.4, 3.6 and 3.10 in FSR. Growth factors for M100, M1000 and M10000 were averages calculated from FSR Tables 2.7 (England and Wales) and 2.9 (Scotland and Northern Ireland). The results of this analysis are shown in Table 1.

	15 min	**30 min**	**1h**	**2h**	**6h**	**12h**	**24h**
Estimated M5 rainfall (mm)	11	15	21	30	50	68	94
M100 growth factor	1.95	1.99	1.97	1.91	1.77	1.66	1.57
M1000 growth factor	3.19	3.30	3.27	3.09	2.69	2.43	2.17
M10000 growth factor	5.19	5.49	5.42	5.00	4.10	3.57	3.01
M100 rainfall (mm)	21	30	42	57	88	113	148
M1000 rainfall (mm)	35	49	69	93	135	165	204
M10000 rainfall (mm)	57	82	114	150	205	243	283
ET (mm)	45	62	79	94	117	132	152

Table 1. M100, M1000 and M10000 rainfalls from growth factors of M5 rainfall derived from published tables in FSR.

For durations less than 2 hours the ET lies between M1000 and M10000, at 2 hours it is M1000 and lies between M100 and M1000 from 2 to 24 hours. The ETs were therefore consistent with the aim of Phase 1 which was to look at *extreme point* rainfall events. In this context it is interesting to note that at *short* durations M100 events are not extreme but very common. Generally atmospheric disturbances show a time-space scaling such that storms lasting about 1 hour have a typical scale of 10 km, while those lasting about 12 hours have a typical scale of 100 km and those lasting 3 days have a typical scale of 1000 km. Extreme storms occur not when these scales are violated, but rather when the storm is quasi-stationary, so that the area over which the rain falls is minimised. One should therefore expect that in a given area there might be 100 (10 squared) times as many 100 year events at 1 hour as at 12 hours, and 100 times as many 100 year events at 12 hours as at 3 days. Thus the choice of M1000 as the extreme threshold for 2 hour durations and decreasing to M100 at and above 24 hours duration was very reasonable.

2.2 Less Extreme Events

For consistency it was decided that FSR information should also be used for the selection of Less Extreme event rainfall thresholds. It was desirable that the set of Less Extreme events was distinct from the Extreme set. However, it was recognised that if the chosen upper and lower rainfall thresholds were too low then the number of occasions for analysis would be unmanageably large. To some extent, however, the choice of thresholds was somewhat arbitrary. The Project Board decided that the Less Extreme set should consist of rainfalls with a return period between 1:20 and 1:50 years (M20 - M50). This was fine for event durations over 24 hours where the ET was M100, however, for shorter durations the ET greatly exceeded the M100 value. So for the specific durations of 15 minutes and 2 hours, figures 2.2 and 2.3 in FSR were used to estimate the ratios M20/M100 and M50/M100. These ratios were then multiplied by the ET value to give lower (LETL) and upper rainfall amount (LETU) thresholds for the Less Extreme set for 15 minute and 2 hour durations. For durations of 24 and 48 hours LETL and LETL are M20 and M50 values respectively, see Table 2. LETL and LETU for other times were estimated using log-linear interpolation/extrapolation.

	15 min	**2h**	**24h**	**48h**
ET	45	94	152	193
M20/M100	0.73	0.79	x	x
M50/M100	0.87	0.91	x	x
LETL	33	74	120	157
LETU	39	85	137	178

Table 2. Extreme Rainfall threshold (ET), ratio of M20 and M50 to M100 rainfall and lower (LETL) and upper (LETU) rainfall thresholds for Less Extreme events for durations of 15 minutes, 2, 24 and 48 hours.

The complete set of thresholds; ET, LETL and LETU used in WP1 are tabulated in Table 3.

Duration (mins)	15	20	25	30	35	40	45	50	55	60
ET (mm)	45	53	58	62	66	70	73	75	77	79
LETU (mm)	39	46	51	55	59	62	64	67	69	71
LETL (mm)	33	39	43	47	50	53	55	57	59	61
Duration (hours)	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
ET (mm)	94	103	109	113	117	120	123	125	127	129
LETU (mm)	85	94	100	104	108	111	114	117	119	121
LETL (mm)	74	81	87	91	94	97	100	102	104	106
Duration (hours)	**12**	**15**	**18**	**21**	**24**	**48**	**72**	**96**		
ET (mm)	132	137	142	147	152	193	219	247		
LETU (mm)	123	127	131	134	137	178	201	229		
LETL (mm)	107	111	115	118	120	157	183	210		

Table 3. Extreme Rainfall threshold (ET), Less Extreme Rainfall Lower threshold (LETL) and Less Extreme Rainfall Upper threshold (LETU) as a function of duration of rainfall.

Comparing Tables 1 and 3 it can be seen that for durations up to 1 hour LETL and LETU span the 1:1000 year return period rainfall. By 12 hours duration they are bridging the 1:100 year return period.

3. Selection of "Less Extreme" cases

The lower and upper thresholds presented in Table 3 were used as a reference for identifying Less Extreme cases from historical records. This was achieved by manually searching rainfall data records and meteorological publications from 1900 to 1999 held in the National Meteorological Library (NML) in Exeter; for example, "British Rainfall" and the "Monthly Weather Report". Dates when rainfall amounts and durations fell within the upper and lower thresholds were noted. Whilst doing the search the opportunity was taken to identify any Extreme events missed in Phase 1. The full list of Less Extreme cases identified by this procedure is given in Appendix 1 and a revised list of twentieth Century Extreme cases is presented in Appendix 2. It is important to remember that the Extreme cases only included those lasting up to 72 hours. An analysis of important meteorological parameters in the twentieth Century Extreme cases is provided in Appendix 5. The revised list of Extreme cases gave an additional 10 instances (5 frontal and 5 orographic) making a total of 60. In order to do a detailed comparison between the Less Extreme and Extreme samples from a synoptic perspective with the resources available, it was desirable to select a random sample of 60 Less Extreme cases (35 convective, 15 frontal and 10 orographic). This was achieved by assigning each Less Extreme case with a unique number and allowing colleagues to draw the required quota of numbers out of a box as per a raffle. There were three boxes, one each for convective, frontal and orographic types. The randomly selected case dates are shown in bold type in Appendix 1 and a detailed analysis of these cases with some references is shown in Appendix 3.

4. Comparison of "Less Extreme" cases with "Extreme cases"

Synoptic analyses of the random set of Less Extreme cases were carried out in a similar way to that done for the Extreme cases in Phase 1. The distribution according to rainfall duration, amount and synoptic type is shown in Figure 1a. Appendix 3 lists the synoptic classifications for individual cases. The classifications follow the same convention used in Phase 1. For comparison the Extreme cases are shown in Figure 1b.

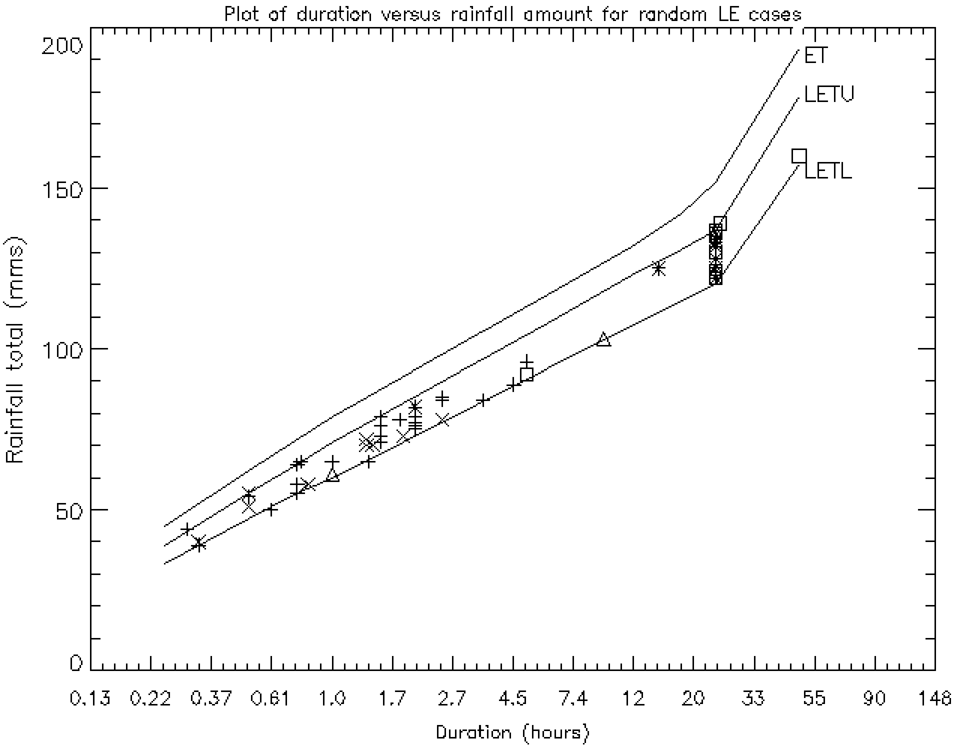

Figure 1a. Extreme rainfall threshold (ET), upper and lower Less Extreme rainfall thresholds (LETU and LETL) for the 60 randomly selected LE cases represented by a symbol according to rainfall duration and amount and synoptic type. '+' = convective, 'X' = convective with frontal forcing, ж = orographic, Δ= frontal with embedded convection and □ = frontal.

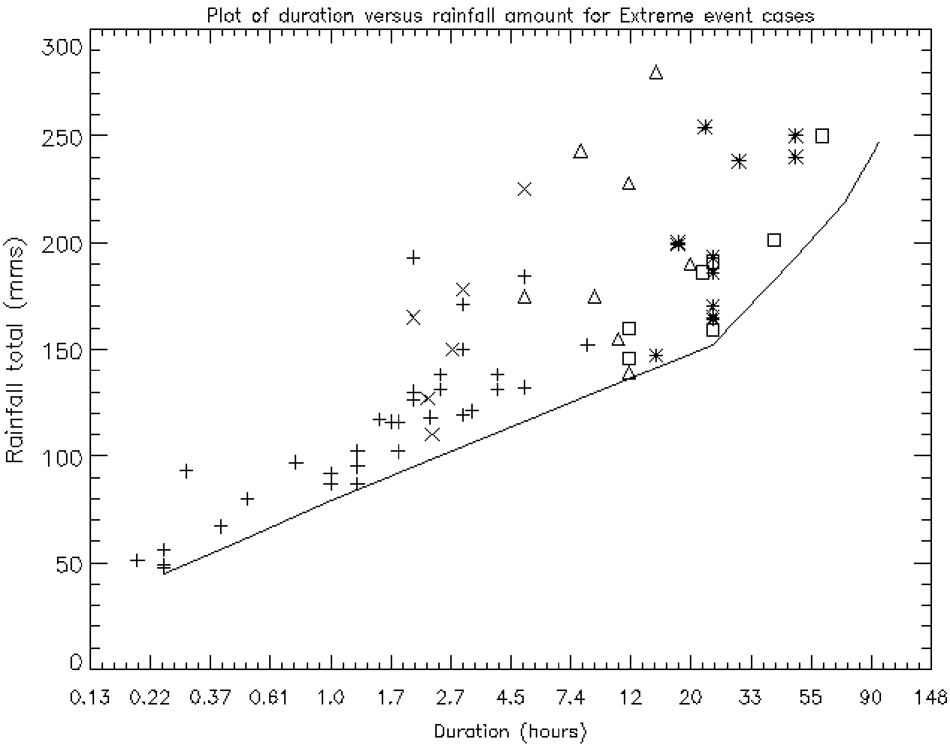

Figure 1b. Extreme rainfall threshold line, all 20th and 21st Century Extreme cases represented by a symbol according to rainfall duration and amount and synoptic type. '+' = convective, 'X' = convective with frontal forcing, ж = orographic, Δ= frontal with embedded convection and □ = frontal.

The cluster of orographic and frontal Less Extreme cases at 24 hour duration shown in Figure 1a is due to the practice of publishing rainfall data as daily amounts. Generally the convective events are of shorter duration than the frontal or orographic events. However, there is very little pattern with all of the convective types intermingled unlike the Extreme cases shown in Figure 1b. Out of the 15 frontal cases just two had embedded convection whereas in the Extreme dataset eight had embedded convection. Conversely, 10 convective cases had frontal forcing whereas there were 5 in the Extreme set.

4.1 Monthly distribution of events

The monthly distributions of all the Less Extreme (LE) and revised list of Extreme (E) cases are shown in Figures 2a and 2b respectively.

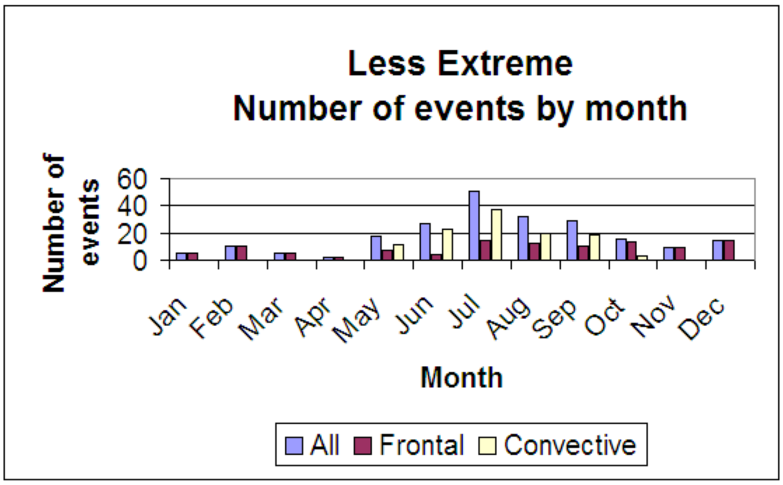

Figure 2(a). Monthly distribution of number of Less Extreme events according to synoptic type. (Frontal category includes Orographic).

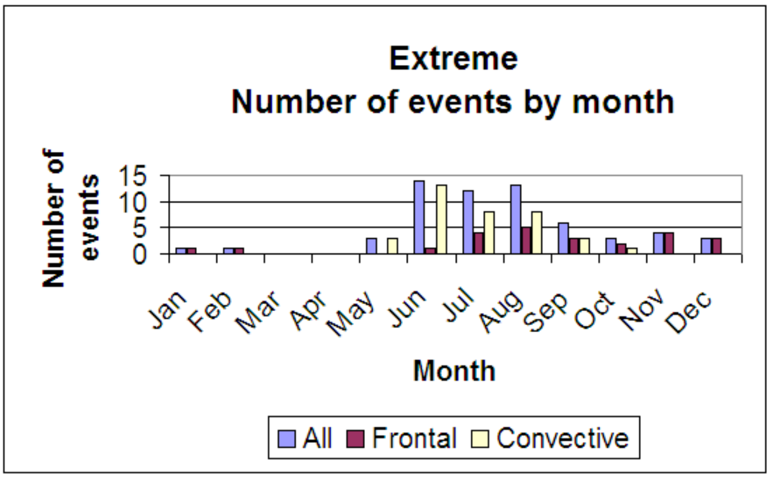

Figure 2(b). Monthly distribution of number of Extreme events according to synoptic type. (Frontal category includes Orographic).

The two distributions are similar in that they both have a peak number of cases in the summer. However, the LE sample has a sharper peak in July. Both distributions are asymmetric having relatively more events in the second half of the year than in the first. In Phase 1 this was explained by the effect of warmer seas providing more moisture for rainfall in Autumn than in Spring. This would appear to still be the case for the LE events although clearly there is enough moisture to trigger some LE frontal or orographic events in March and April. Generally Frontal/Orographic events are more evenly distributed throughout the year in LE. The frequency of convective events peaked in June in the E sample but in July in the LE sample. The significance of this is not clear but is probably limited by the relatively small sample size of the Extreme events.

4.2 Decadal distribution of events

The decadal distributions of all the LE and E cases are shown in Figures 3a and 3b respectively.

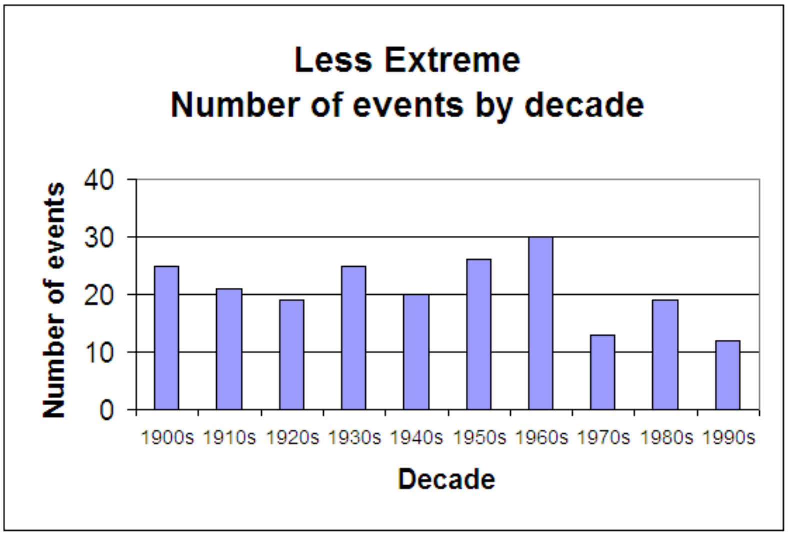

Figure 3(a). Decadal distribution of number of Less Extreme events.

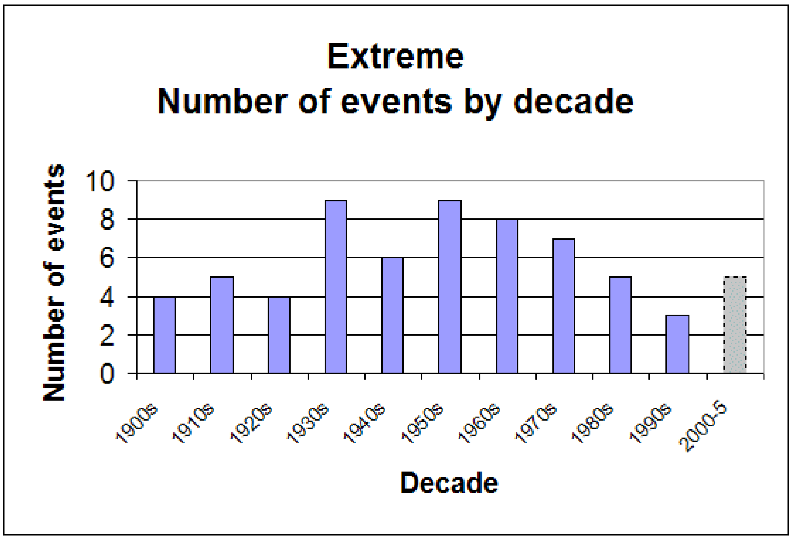

Figure 3(b). Decadal distribution of number of Extreme events.
(21^{st} Century number indicated by a dashed bar is to the end of 2005).

The two decadal distributions exhibit some similarities, however, the restricted sample size precludes drawing any firm conclusions. In LE there is a peak in the 1960s and minima in the 1970s and 1990s. The E set also has a minimum in the 1990s but the peaks are in the 1930s and 1950s with the 1970s having the fourth highest number of occasions. The 1900s saw relatively few E events but a relatively large number of LE events.

In order to try and understand the differences it was decided to look at a long term time-series of prevailing synoptic conditions, since in Phase 1 it was discovered that the Extreme events could be categorised according to synoptic type. The synoptic measure chosen was the North Atlantic Oscillation (NAO) Index. The NAO is a well-known empirical index of a primary mode of atmospheric circulation variability over the North Atlantic [3]. The NAO gives an indication of the strength of the westerlies across the northern North Atlantic and is usually derived from a difference in sea-level pressure between Iceland and the Azores or between Iceland and south-western Iberia. The resulting values are normalised to give a standardized series where positive NAO means enhanced westerlies, while negative NAO means weakened westerlies and enhanced blocking tendency with a greater opportunity for low pressure systems and associated fronts to become slow moving and anchored close to the UK.

For WP1 the NAO was derived from datasets of mean monthly sea-level pressure from Iceland, the Azores and Gibraltar from January 1900 to December 1999. Means and standard deviations for each of these locations for the whole century were then calculated. The NAO indices for each month were then derived as follows

$$NAOI_{Azores} = [\ (P_{Azores} - PBAR_{Azores})/\sigma_{Azores}\ ] - [\ (P_{Iceland} - PBAR_{Iceland})/\sigma_{Iceland}\ ]$$

$$NAOI_{Gib} = [\ (P_{Gib} - PBAR_{Gib})/\sigma_{Gib}\ ] - [\ (P_{Iceland} - PBAR_{Iceland})/\sigma_{Iceland}\ ]$$

where NAOI is the monthly NAO index, P is the mean monthly pressure, PBAR is the mean pressure for the century and σ is the standard deviation.
Decadal NAO indices were then calculated by averaging the monthly values.
The decadal NAO indices were then compared with the decadal frequency of E and LE events. The results are summarised in Tables 4 and 5.

Decade	Number of Extreme events	Number of Less Extreme events	Gibraltar – Iceland Decadal NAO index	Azores – Iceland Decadal NAO index
1900s	4	25	0.073	0.067
1910s	5	21	0.051	0.065
1920s	4	18	0.192	0.233
1930s	9	25	-0.038	0.058
1940s	6	20	-0.040	-0.117
1950s	9	26	-0.028	0.001
1960s	8	30	-0.222	-0.436
1970s	7	13	-0.104	-0.001
1980s	5	19	-0.026	-0.052
1990s	3	12	0.143	0.183

Table 4. Number of Extreme and Less Extreme cases per decade. Decadal NAO indices for Gibraltar-Iceland and Azores-Iceland mean sea level pressures.

The largest index values (stronger westerly average flow) occurred in the 1920s and 1990s; both of these decades had relatively low incidences of Extreme rainfall. The lowest index value was in the 1960s which had the highest frequency of LE events and a relatively high frequency of E events.

Correlations and percentage probability of chance occurrence				
	Number of Extreme events	Number of Less Extreme Events	Gibraltar - Iceland Decadal NAO index	Azores – Iceland Decadal NAO index
Number of Extreme events		0.57 (8)	-0.74 (1)	-0.52 (12)
Number of Less Extreme events			-0.47 (17)	-0.58 (8)

Table 5. Correlation and the probability that the correlation occurred by chance (percentages in brackets) between the number of Extreme and Less Extreme cases per decade and the decadal NAO indices for Gibraltar-Iceland and Azores-Iceland.

The number of E events is loosely correlated with the number of LE events at 0.57 possibly indicating some similarity of causes but also differences as well.
For the E events the Gibraltar-Iceland index has the highest correlation and the probability of this correlation occurring by chance using a Student's t-test is 1% making this a very significant result. The correlation is negative indicating a relationship between the frequency of Extreme events and the frequency of synoptic regimes with a lower westerly component than normal.

For the E events the correlation with the Gibraltar-Iceland index is very much higher than with the Azores-Iceland index. This would tie in with the findings from Phase 1 that frontal and convective E events are more likely with low pressure that is slow moving either over the UK or to the south of the UK. In those situations pressure will often be lower than average over Gibraltar but not necessarily lower than average over the Azores.

In interpreting this result one has to be somewhat cautious as the number of events in each decade in the E sample is relatively small. Nevertheless there is an indication that the NAO Gibraltar-Iceland index may have some value in predicting the relative frequency of E events over a decadal time period if the index itself can be predicted.

4.3 Frontal cases

All of the LE frontal cases with additional data are listed in Appendix 4. There were 54 LE frontal cases 32 of which were within 450 km of the centre of a depression. The bearings and distance of each of these events from the depression centres are plotted in Figure 4a. These should be compared with a similar set of Extreme events shown in Figure 4b.

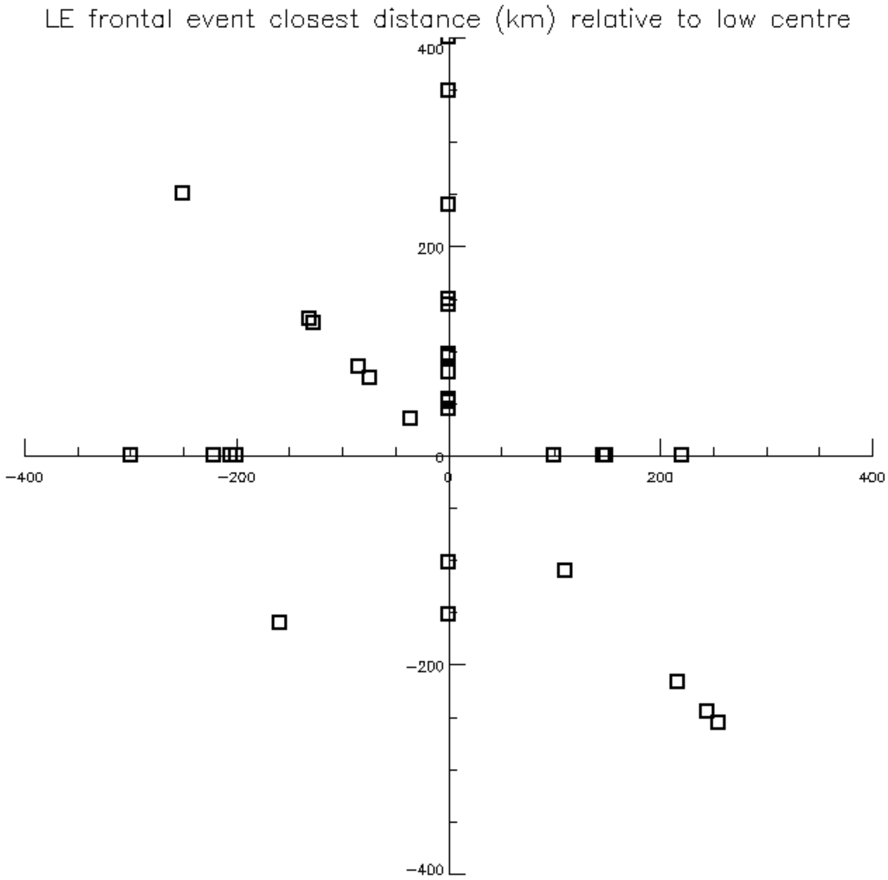

Figure 4a. Direction and distance of each LE frontal event from closest approach of depression centre (0 on compass cross). Note that events further than 400Km from a low centre are not shown.

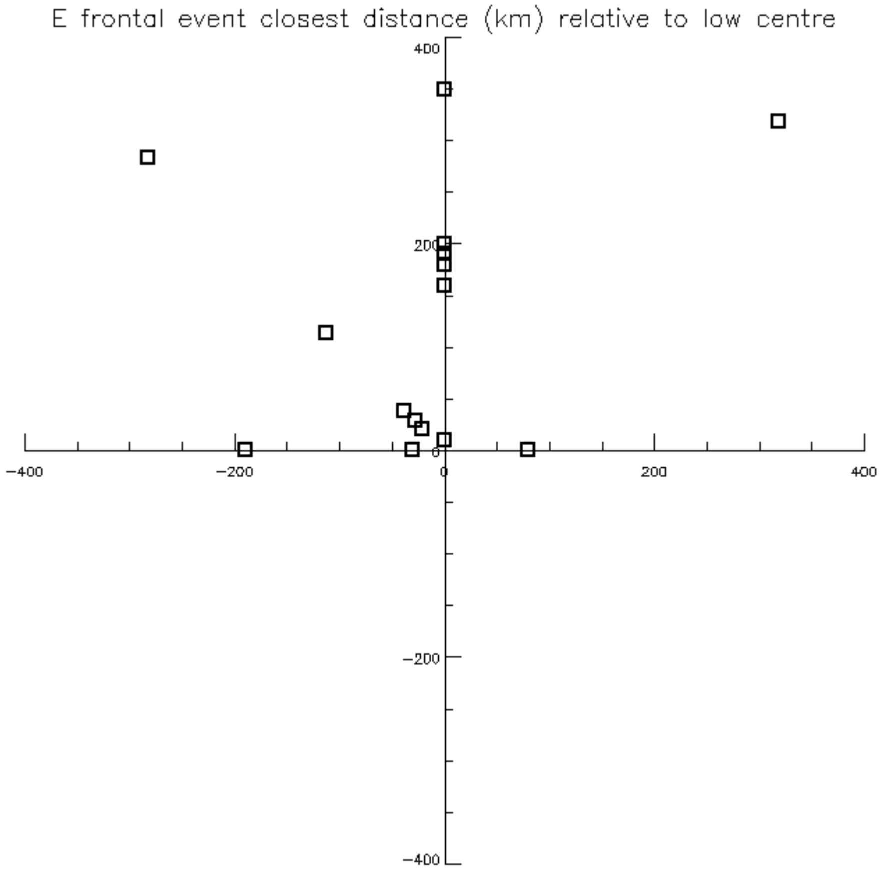

Figure 4b. Direction and distance of every E frontal event from closest approach of depression centre (0 on compass cross).

The main differences between the LE and E sets are that all of the E frontal events were within 450 km of a low centre and all of them were north of the low centre with the majority in the NW sector relative to the low. However, the LE events less than 450 km from a low were more evenly distributed spatially but still with the majority in the NW quadrant. The data are tabulated in more detail in Tables 6 and 7.

Aspect	**N**	**NE**	**E**	**SE**	**S**	**SW**	**W**	**NW**
Extreme	6	1	1	0	0	0	2	5
Less Extreme	11	0	4	4	2	1	4	6

Table 6. Aspect of Extreme and Less Extreme events to centre of a depression provided closest approach of the centre is less than 450 km.

Distance from low centre (km)	**<240**	**240 or more**
Extreme	12	3
Less Extreme	24	30

Table 7. Closest distance of a depression centre from an Extreme and Less Extreme event.

Chi-square statistics were calculated for the data in Tables 6 and 7. Differences in aspect (Table 6) were found to be insignificant with a Chi-square statistic of 6.76 and 7 degrees of freedom. However, for closest distance from a low (Table 7) the Chi-square statistic was 5.95 which is significant at the 2.5% level with 1 degree of freedom. The main difference between the E and LE data is that a frontal Extreme event has never occurred when the location has been more than 450 km from a low centre (see Appendix 4). 55% of LE cases were at least 240 km from a depression centre as opposed to only 20% of E cases.

The next aspect to consider was the speed of the depression at closest approach to an event. Slow-moving depressions were one of the key factors found in Phase 1 in Extreme frontal events. This comparison is shown in Table 8.

Depression speed (m/s)	**<5**	**5-10**	**>10**
Extreme	7	4	4
Less Extreme	15	8	9

Table 8. Speed of depression closest to rainfall event provided closest approach of depression centre is less than 450 km.

The chi-square value for this table is 0.02 with 2 degrees of freedom which is not a significant result. This would imply that the speed of a depression alone would not be enough to distinguish an Extreme from a Less Extreme event.

To summarise the results in this section; a frontal rainfall event at a location has a greater probability of being Extreme as opposed to Less Extreme the closer it is to a low centre. For locations less than 450 km from a low centre the speed of the depression and aspect of location will not be helpful in distinguishing Extreme from Less Extreme. For locations more than 450 km from a low centre a frontal Extreme event is unlikely to occur.

4.4 Convective cases

The analysis of the convective cases was done using the random sample of LE convective events. The analyses were conducted using data available in the NML and over the Internet. A number of meteorological parameters important for convection were studied.

4.4.1. CAPE

(Note this was only done for cases where CAPE could be calculated from upper air observations).

Convective Available Potential Energy (CAPE) is a measure (in Joules per kilogramme of air (J/kg)) of the amount of energy available/released by a rising parcel of air in the unstable part of the atmosphere. A comparison between E and LE cases is shown in Table 9.

CAPE	**<200 J/kg**	**200-800 J/kg**	**>800 J/kg**
Extreme	7	6	9
Less Extreme	2	10	10

Table 9. Ranges of CAPE for Extreme events and the random sample of Less Extreme events.

A Chi-square test on this contingency table gave an insignificant result regarding differences between E and LE events with CAPE. However, it is interesting that 32% of the E events were initiated with a CAPE less than 200 J/kg. This would indicate that CAPE per se is not a good indicator of the amount of rainfall that can be expected at a point. This conclusion is to some extent borne out by the Boscastle event (16 Aug. 2004) where CAPE values were modest at around 170 J/kg. However, for the LE events it would appear that there is a signal that larger CAPE values are required. So something special must be happening to initiate an Extreme convective rainfall event. The next parameter that was investigated was moisture availability close to the ground.

4.4.2 Surface dewpoints

Surface dew point measured in a Stevenson screen at 1.2 metres above ground was chosen since at least some records were available throughout the 20th Century. The dew point just prior to a convective event was estimated from available data. To do the comparison between E and LE events actual values were used as opposed to ranges and a Student's t-test was carried out to determine whether there were was any significant difference in the two distributions. Results are shown in Table 10.

Dew point	Less Extreme	Extreme
Average	14.5	14.9
Standard deviation	2.4	2.2
Number of cases	35	35

Table 10. Average and standard deviation of surface dew points prior to occurrence of Less Extreme and Extreme convective rainfall events.

This table clearly shows that there is no significant difference between the distributions of dew point. Dew points in the Extreme set of cases were slightly higher with less variability than in the Less Extreme set. However, it was thought that the availability of surface moisture may have a greater influence on the more short-lived convective cases. The analysis was therefore extended to distinguish events lasting less than an hour from those lasting an hour or more. These results are shown in Table 11.

	Less Extreme		**Extreme**	
Dew point	<1 hour duration	≥1 hour duration	<1 hour duration	≥1 hour duration
Average	15.4	13.9	15.4	14.7
Standard deviation	3.5	1.1	1.9	2.3
Number of cases	13	22	9	26

Table 11. Average and standard deviation of surface dew points prior to occurrence of Less Extreme and Extreme convective rainfall events categorised according to durations of less than one hour or greater than or equal to one hour.

As expected the average dew point was higher for cases with durations less than an hour in both the Extreme and Less Extreme samples. Interestingly the variation was higher in the Less Extreme cases than the Extreme cases although there were relatively fewer short-lived cases in the Extreme sample. The lowest average dew point occurred in the longer-lived LE cases, the next lowest was for the longer-lived E cases followed then by short-lived LE cases and short-lived E cases. This illustrates that dew point does have some importance for short-lived cases both Extreme and Less Extreme. The significance of this was investigated using a Student's t-test and the results are shown in Table 12.

Probability that dew point differences occurred by chance (%)	Extreme <1 hour duration	Extreme ≥1 hour duration	Less Extreme <1 hour duration	Less Extreme ≥1 hour duration
Extreme <1 hour duration		39	96	1
Extreme ≥1 hour duration			46	18
Less Extreme <1 hour duration				8
Less Extreme ≥1 hour duration				

Table 12. Comparison of dew point distributions in Extreme and Less Extreme convective samples using a Student's t-test. The probability that sample differences occurred by chance are shown.

The least probabilities of a chance result occur when samples are compared with the "Less Extreme ≥1 hour duration" set. The comparison between dew points in the "Extreme <1 hour duration" set and the "Less extreme ≥1 hour duration" shows a very significant difference with only a 1% probability that it could have occurred by chance. A tentative conclusion may be that a lower threshold of surface moisture is required to trigger a Less Extreme convective event that lasts an hour or more.

Clearly surface dew points are a measure of moisture near the ground only and moisture aloft is important too for storm development and characteristics. However, measuring moisture aloft for point locations from observational data is difficult as upper air soundings are too far apart to accurately measure moisture at point locations. To get round this problem it was decided to look at precipitable water content from NCEP NWP re-analyses available on the Internet dating back to 1950 [4].

4.4.3 Precipitable water content

(Note this was only examined for cases after 1950).

Precipitable Water content (in mm) is equivalent to the amount of liquid precipitation that would result if all the water vapour in a column of air instantaneously condensed. It is therefore a direct and rather convenient measure of moisture content aloft.

The analysis was conducted in the same way as for dewpoint by distinguishing cases according to duration of rainfall. The results are shown in Table 13.

	Less Extreme		Extreme	
Precipitable water (mm)	<1 hour duration	>1 hour duration	<1 hour duration	>1 hour duration
Average	24.9	21.9	27.1	24.0
Standard deviation	4.9	3.1	3.3	5.9
Number of cases	5	14	6	13

Table 13. Precipitable water content (mm) prior to occurrence of Less Extreme and Extreme convective rainfall events categorised according to durations of less than one hour or greater than or equal to one hour.

There is some consistency in these results. Average precipitable water (PW) contents are higher for short duration rainfalls than longer duration rainfalls both in the E and LE samples. Also average PWs are correspondingly higher in the E sample than in the LE sample. The latter result confirms that an Extreme event requires there to be more moisture aloft on average than a Less Extreme event. Also more moisture is necessary for short duration events than longer duration events. At Boscastle the PW was around 26 mm which exceeds the average values for LE events with only 2 short duration LE events exceeding this value in the 20th Century. The sample distributions were compared using a Student's t-test and the results are shown in Table 14.

Probability PW differences occurred by chance (%)	Extreme <1 hour duration	Extreme ≥1 hour duration	Less Extreme <1 hour duration	Less Extreme ≥1 hour duration
Extreme <1 hour duration		28	51	1
Extreme ≥1 hour duration			73	26
Less Extreme <1 hour duration				12
Less Extreme ≥1 hour duration				

Table 14. Comparison of precipitable water (PW) distributions in Extreme and Less Extreme convective samples (post 1949) using a Student's t-test.

These results are very interesting as they mirror those for dew point even though the analyses used completely independent data sources. From these results it appears that less moisture is required throughout the atmosphere to trigger a Less Extreme event that is going to last longer than an hour than either an Extreme event or a shorter duration Less Extreme event.

4.4.4 Duration of rainfall

The analyses for CAPE, dew point and PW have all shown that duration of a convective event seems to be an important factor. So this aspect was studied in more detail.

Event durations were split into three categories; <1 hour, 1-2 hours and >2 hours. The numbers of randomly selected Less Extreme and Extreme convective events falling into these categories are shown in Table 15.

Duration	0-1 h	1 h - 2h	>2h
Extreme	9	10	16
Less Extreme	13	16	6

Table 15. Duration (hours) of Less Extreme and Extreme convective rainfall events.

This table is very clear in showing a signal that Extreme convective events tend to last longer than Less Extreme events. The Chi-square value for the table is 6.66 which is significant at the 5% level.

The average durations with their standard deviations are shown in Table 16.

Duration	Extreme	Less Extreme
Average	2.23	1.58
Std. Dev.	1.68	1.09
Number of occasions	35	35

Table 16. Average and standard deviation of durations (hours) of convective events in the randomly selected Less Extreme sample and the Extreme sample.

The average duration of Extreme events was 0.65 hours (39 minutes) longer than Less Extreme events but with more variability. A Student's t-test gives a statistic of 1.93 which has a significance level of 5.8%. So there is a definite possibility that Less Extreme and Extreme events belong to different populations as regards duration of rainfall. In other words it may be that it is the duration of rainfall at a point that distinguishes an Extreme convective rainfall event from a Less Extreme one given equality in other factors.

4.4.5 Occurrence of "large hail"

The presence of large hail (stones >15 mm diameter) which can cause damage to crops, glasshouses, cars, aircraft and other structures was found in Phase 1 to be an important element in some Extreme convective events. In WP1 the number of occasions when large hail was reported in the Less Extreme random sample was compared with the number of reports in the Extreme sample. The results are shown in Table 17.

Large hail occurrences	Extreme	Less Extreme
Yes	12	9
No	23	21
Undecided	0	5

Table 17. Number of occurrences of large hail (stones >15 mm diameter) in the Extreme and random Less Extreme convection samples. The occasions where hail reports were inconclusive or non-existent have been designated as "undecided".

The Table shows that 52% of Extreme events had large hail and 30% of Less Extreme events where a positive identification either way could be made. Unfortunately a Chi-square test (excluding the "undecided" cases) shows that this result is not significant and so any differences between the categories in the contingency table may be due to chance. The conclusion is, therefore, that large hail may be just as likely to occur in Less Extreme events as in Extreme events.

4.5 Orographic cases

In the Phase 1 study it was found that all Extreme orographic events had specific synoptic conditions associated with them. The geostrophic wind (wind at approximately 600 m above ground) had a direction between 210 and 250 degrees with a speed of at least 16 m/s and an airmass source dew point greater than 14 deg C. The wind usually had a steady and long fetch extending thousands of kilometres with an anticyclone centred either in the Bay of Biscay or Spain and a low near Iceland. In order to objectively compare Less Extreme orographic events with Extreme ones three categories were devised:

A – The specific conditions identified in Phase 1 for Extreme orographic events were not present.

B – Specific conditions met with a geostrophic wind speed of 16-25 m/s

C – Specific conditions met with a geostrophic wind speed >25 m/s

The ten orographic events in the Extreme sample were then compared with the ten randomly selected Less Extreme events giving the categorisations listed in Table 18.

Orographic class	A	B	C
Extreme	0	3	7
Less Extreme	6	3	1

Table 18. Number of Extreme and Less Extreme events in each synoptic category A, B, C (see text for details).

The analysis shows six Less Extreme events did not meet the expected conditions for Extreme events and only one Less Extreme event occurred in the windiest synoptic scenario for an Extreme event. The Chi-square value for this table is 10.5 which is very significant at the 1% level. The conclusion is that an orographic event is more likely to be Less Extreme as opposed to Extreme if the prevailing synoptic conditions fall into category A. Figure 5 shows a typical example of synoptic conditions that gave a Less Extreme event. This case was for 23/3/68 when 132 mm was recorded in 24 hours at Llyn Eigiau in North Wales. The wind direction and speed are correct for a possible Extreme event but the tropical airmass was too cold in the warm sector as the fetch was rather short.

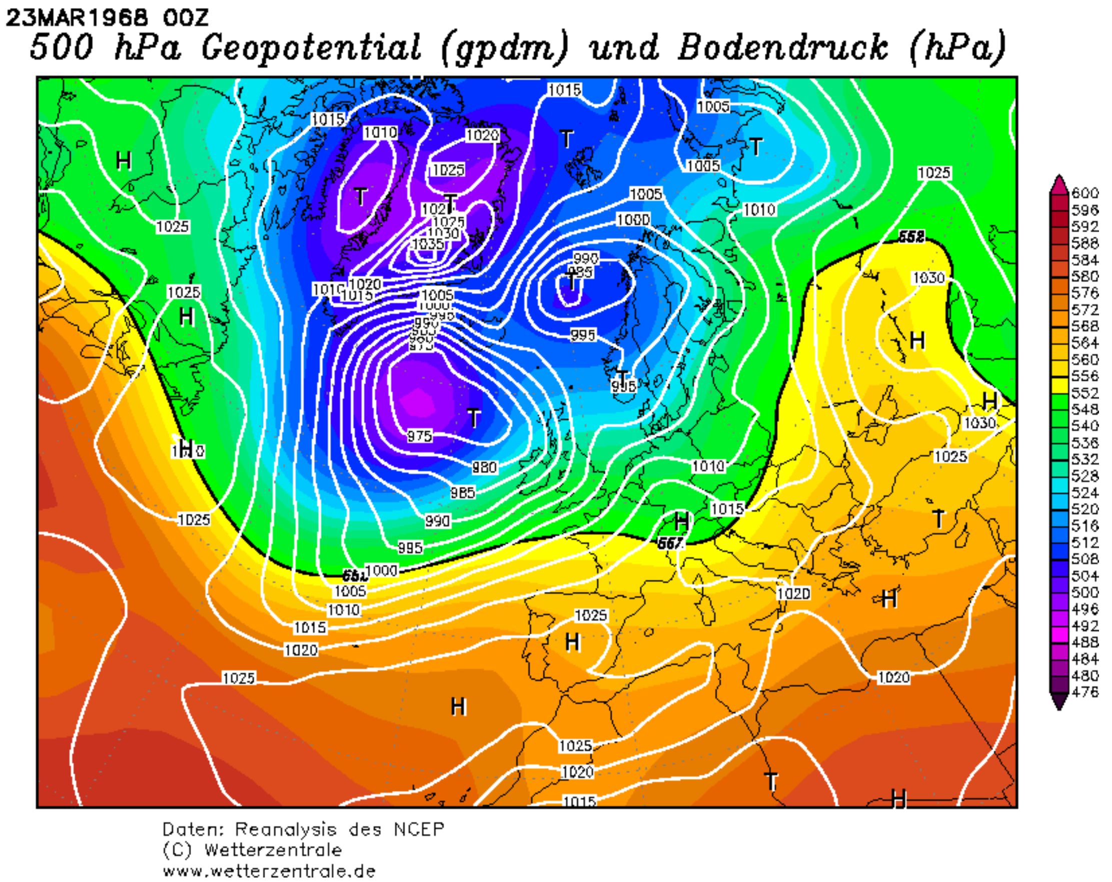

Figure 5. Re-analysis of 500 hPa height (shading) and mean sea-level pressure (white contours) by NCEP [4] for 0000 UTC 23/3/68. (Obtained from http://www.wetterzentrale.de/topkarten/).

5. Analysis of recent (21st Century) Extreme cases

The current list of cases is shown in Table 19.

Date	Location	Amount	Duration	Type	Published Reference
07/05/00	Bracknell	87	1.25	C	Weather Vol.57, Feb 2002 pp73-77
10/08/03	Carlton-in-Cleveland	49	0.25	C	Weather Vol.60, Mar 2005 pp60-65
02/02/04	Capel Curig	165	24	O	Weather Vol.59, Apr 2004 "Weather Log" insert.
16/08/04	Boscastle	184	5	C	Weather Vol.60, Aug 2005 pp219-227, 230-235
07/01/05	Honister (Carlisle floods)	164	24	O	

Table 19. List of Extreme point rainfall events occurring in the 21st Century. Date, location, rainfall amount (mm), duration (hours) and published references are indicated. For "type"; C= convective, O= orographic.

These cases were analysed in the same way as the 20th Century Extreme cases and the results are shown in Table 20.

Date	Type	CAPE class	Large hail?	Orog class	Precipitable water	Surface dewpoint
07/05/00	C	3	Y		27.0	13
10/08/03	C	6	Y		31.9	18
02/02/04	O			C		
16/08/04	C	2	no		25.9	16
07/01/05	O			C		

Table 20. Analysis of 21st Century Extreme cases. Type; 'C'= convective, 'O'= orographic. CAPE class; '2'= 101-200, '3'= 201-400, '6'= >1600 J/kg. Large hail; 'no'= hail reported but no large stones, 'Y'= hail > 15mm diameter reported. Orog class; 'C'= geostrophic wind direction 210-250 with speed > 25 m/s and airmass source dew point > 14 . Precipitable water is in millimetres for the convection cases and the surface dew point is in ºC estimated just prior to the onset of deep convection.

Average duration of the convective cases is 2.17 hours.This is quite close to the 20th Century case average of 2.23 (Table 16). The precipitable water values are all higher than the 20th Century average values (Table 13) and two dew points are higher too (10/08/03, 16/08/04 cases) compared with the average in Table 10. CAPE is inconclusive, but fits in with the 20th Century analysis and 2 out of 3 cases had large hail which again ties in. Both orographic cases fitted the synoptic conditions identified in Phase 1 as being common in all 20th Century Extreme events.

6. Summary and Conclusions

A method of selecting a sample of "less extreme" point rainfall cases occurring in the UK during the 20th Century was identified. Using this method 210 Less Extreme events were identified (Appendix 1). 54 were frontal cases, 104 were convective and 52 orographic. Whilst doing the selection an additional 10 Extreme events (5 frontal and 5 orographic) were found (Appendix 2) bringing the total number to 60. Random samples of 35 convective, 15 frontal and 10 orographic cases were then drawn from the Less Extreme set for deeper analysis and for comparison with the Extreme events. The distribution in time of the Less Extreme events was compared with the Extreme set. Statistical analyses of differences between the two sets in important meteorological factors were undertaken. The main conclusions of these parts of the study are as follows:

- *Differences between the monthly distributions of Extreme and Less Extreme events are small* with the Less Extreme sample having a slightly more even spread throughout the year peaking in July as opposed to June in the Extreme sample.

- *There is a significant link between the number of Extreme events in a decade and the decadal North Atlantic Oscillation index measured between Gibraltar and Iceland.* The implication is that the frequency of Extreme point rainfall events might have a relationship to changes in global weather patterns.

- *A frontal rainfall event has a greater probability of being Extreme as opposed to Less Extreme the closer it is to a low centre.* The speed of a depression and bearing of a location from the low centre cannot be used in isolation to distinguish an Extreme from a Less Extreme frontal event. However, an Extreme event is very unlikely from a depression passing to the north of a location.

- *Orographic situations that lead to Extreme orographic rainfall are significantly different to those that give Less Extreme values.* In all the Extreme cases winds at 600 m above ground had a trajectory between 210 and 250 degrees with a long fetch across the Atlantic at speeds greater than 15 m/s from a sub-tropical origin with dew points greater than 14 ºC. 60% of Less Extreme cases had conditions differing in some aspect from those prevailing in the Extreme cases.

- Convective events are complicated. *The main conclusion is that Extreme convective events last significantly longer on average than Less Extreme ones.* However, there are also some other differences. Less Extreme events tend to have higher CAPE on average than Extreme events. Less Extreme convective events lasting longer than one hour require less moisture near and above ground than those lasting less than that. They also require less moisture than all Extreme events. Extreme events lasting less than one hour require more moisture than those with a longer duration. The implication of all this is that Extreme convective events can be put into two categories;

    1. *Convective point rainfall events lasting less than an hour usually triggering in a very moist atmosphere with convective clouds forming rapidly (e.g. Carlton-in-Cleveland, Wisbech)..*

    2. *Convective point rainfall events lasting longer than one hour that do not necessarily require a very moist atmosphere nor high values of CAPE but do require an environment that will permit repeated generation of convective cells in the same place (e.g. Boscastle, Hampstead and Halifax storms).*

  In Phase 1 it was concluded that the presence of large hail (stones >15mm diameter) was an important indicator that a convective event could become Extreme. However, large hail has been found to occur in the Less Extreme cases and differences in number of occurrences between the two sets is insignificant. *So the presence of large hail by itself is not an indicator that a convective situation will become extreme.*

In a similar vein we have:

- CAPE per se is not a good indicator that an Extreme rainfall event will occur.
- Surface dew point by itself will not distinguish Extreme from Less Extreme rainfalls.
- Total precipitable water content by itself will not distinguish Extreme from Less Extreme rainfalls.

A general conclusion is that *an Extreme convective point rainfall event will occur either through the efficient and rapid conversion of a moisture rich atmosphere into heavy rainfall or by repeated generation of deep convective cells in the same area. The latter scenario would have a variety of causes often due to complicated interactions within and between the atmosphere and ground (e.g. Boscastle).* An implication of this is that the parameters presented in Phase 1, deemed to be important for Extreme convective rainfall, are far too simple and insufficient to distinguish an Extreme fall from a Less Extreme fall.

- By comparing all Extreme with all Less Extreme point rainfall events it has been discovered that the underlying causal meteorological conditions are part of a continuum. There seems to be no sudden "jump" from one condition to another that would cause an event to become Extreme. Many factors usually have to come together to provide the ingredients for an Extreme point rainfall.

Five Extreme point rainfall events occurring this century have been identified. All of them fitted into the framework of Phase 1 results and were consistent with the conclusions noted above.

7. Recommendations

1. Given the significant but modest differences in underlying meteorological conditions between Less Extreme and Extreme point rainfall events it is clear that the processes that must come together to trigger an Extreme event are still not fully understood. It is important; therefore, that Extreme and Less Extreme cases should be studied and compared in detail using high resolution NWP models that can best represent the non-linear processes that occur in these systems. Since most Extreme point rainfall events are convective, and that type is the least understood, then effort should be concentrated on those cases.

2. This study has briefly looked at possible links of Extreme event frequency with global climate indicators. Climatologists have mostly concentrated their work on understanding and predicting the winter NAO and its effect on weather. Much less has been published about the summer NAO and it is during the summer that most Extreme events have occurred. The link with the decadal NAO discovered in WP1 may point to a need to understand the summer NAO better, hence it could be fruitful to explore the tentative link found with the NAO further and also consider the possibility of other linkages, for example with hurricane frequency and intensity.

3. 21st Century Less Extreme rainfall events should continue to be identified and the database of Extreme and Less Extreme rainfall events should be maintained. It is recommended that this should be done in the Met Office.

8. Acronyms

AAR	Average annual rainfall
CAPE	Convectively available potential energy
E	Extreme (point rainfall events)
ET	Extreme rainfall threshold
FSR	Flood Studies Report
LE	Less Extreme (point rainfall event)
LETL	Less Extreme threshold (lower)
LETU	Less Extreme threshold (upper)
M5	1:5 year point rainfall
M20	1:20 year point rainfall
M50	1:50 year point rainfall
M100	1:100 year point rainfall
M1000	1:1000 year point rainfall
M10000	1:10000 year point rainfall
NAO	North Atlantic Oscillation
NAOI	North Atlantic Oscillation Index
NCEP	National Centers for Environmental Prediction
NML	National Meteorological Library (in Exeter)
NWP	Numerical weather prediction
WP1	Work package 1

9. References

1. Defra R&D Project Report FD2201 – Extreme Rainfall and Flood Event Recognition

2. Flood Studies Report – Volume II. Meteorological studies.; NERC; 1975

3. Hurrell, J.W., 1995, Decadal trends in the North Atlantic Oscillation - regional temperatures and precipitation. Science, 269, pp676-679.

4. NCEP Reanalysis data provided by the NOAA-CIRES Climate Diagnostics Center, Boulder, Colorado, USA, from their Web site at http://www.cdc.noaa.gov/

Appendix 1

Date	Place	Amount (mm)	Duration (hours)	Type
15/02/00	Borrowdale	126	24	F
02/07/00	Trool	80	2	C
11/08/00	Skye	125	24	F
20/08/00	Bradenhurst	58	0.75	C
14/12/00	Seathwaite	133	24	O
12/07/01	Wooburn	103	6	C
25/07/01	Farnham	83	2.2	C
10/08/01	N. Berwick	75	2	C
01/07/02	Ipswich	84	2	C
07/08/02	Limerick	92	5	F
10/09/02	Surbiton	51	0.5	C
18/07/03	Crewe	63	0.83	C
23/07/03	Dartford	111	15	F
26/07/04	Clifden	81	3	C
09/07/05	Enfield	62	0.83	C
25/08/05	Dublin	121	24	F
02/08/06	Guildford	29	0.2	C
21/07/07	Bath	63	1.2	C
16/10/07	Kingsbridge	124	24	F
09/07/08	Swansea	121	24	F
11/09/08	Canterbury	39	0.33	C
19/10/08	Brecon	122	24	F
02/02/09	Loch Arkaig	122	24	O
23/09/09	Castle Bytham	86	3	C
09/12/09	Loch Shiel	120	24	O
26/05/11	Fareham	82	2	C
24/06/11	Llyn Eigiau	130	24	F
04/08/11	Snowdon	126	24	O
29/10/11	Grasmere	125	24	O
12/07/12	Baslow	57	0.67	C
17/06/13	Gt. Paxton	71	1.5	C
17/09/13	Doncaster	134	24	F
14/06/14	Richmond	81	2	C
11/07/14	Mostyn	85	2.5	C
21/07/14	Kirkby Lonsdale	39	0.33	C
14/08/14	Guernsey	39	0.25	C
17/12/14	Borrowdale	124	24	O
06/05/15	Finsbury	79	1.5	C
04/07/15	Abergavenny	55	0.5	C
12/08/15	Carlisle	70	1.5	C
17/08/16	Cheshunt	89	2.5	C
11/10/16	W. Scotland	127	24	O
21/10/16	Killarney	127	24	F
17/05/18	Milton Bryant	78	2.5	C

Date	Place	Amount (mm)	Duration (hours)	Type
03/04/49	Snowdon	132	24	O
22/09/49	Presteigne	70	1.33	C
21/05/50	Ipsden	40	0.33	C
30/07/51	Cowes	64	0.75	C
07/09/51	Oxford	66	1.45	C
19/05/52	Honiton	65	0.77	C
01/07/52	Bredbury	44	0.4	C
06/08/52	Boreham Wood	123	24	F
25/06/53	Langham	54	0.6	C
30/09/53	Coniston	132	24	O
26/11/53	Snowdon	130	24	O
05/06/54	Wyton	78	1.75	C
21/08/54	Freshwater	66	1	C
18/10/54	Ulpha	43	0.4	C
28/02/55	W. Scotland	128	24	O
04/07/56	Snowdon	121	24	F
18/07/56	Hemingford Frey	83	1.5	C
19/07/56	Liskeard	76	2	C
30/07/56	Nairnshire	123	24	F
06/08/56	Arundel	44	0.3	C
21/01/57	Snowdon	125	24	O
03/07/57	Plymouth	66	1.25	C
19/07/57	Anstey	73	1.8	C
10/08/57	Anglesey	137	24	F
19/12/57	Glenleven	123	24	O
22/08/58	Minworth Greave	79	2	C
12/05/59	Hanham	76	1.5	C
10/08/59	Newquay	66	1.25	C
02/02/60	Grasmere	126	24	O
06/07/60	Yorkshire	127	24	F
07/08/60	Old Maldon	82	2	C
24/08/60	Portrush	122	24	F
03/12/60	Rhondda	137	24	O
11/02/62	Sloy	122	24	O
18/04/62	Douglas	125	24	F
16/05/62	Overscaig	132	24	O
04/08/62	Loch Merkland	127	24	O
10/08/62	Wastwater	127	24	O
07/06/63	Kensington	58	0.6	C
11/06/63	Lough Neagh	46	0.33	C
05/07/63	Hemyock	80	1.6	C
30/05/64	Manchester	123	24	F
26/07/64	East Ham	69	1	C
12/12/64	Lake Vyrnwy	121	24	O

17/07/18	Shad (Thames)	53	0.5	C
15/09/18	Snowdon	123	24	F
02/02/20	Loch Arkaig	122	24	O
09/02/20	Rydal	121	24	O
05/05/20	Blaneau Ffestiniog	123	24	O
09/05/20	Grasmere	130	24	F
26/05/20	Barnes	67	1.2	C
04/10/20	E. Scotland	123	24	F
15/03/21	Llandeusant	125	24	O
15/05/22	Mull	128	24	F
12/11/23	Snowdon	126	24	F
31/05/24	Hanmer	135	24	F
22/07/24	Guildford	60	0.95	F
12/12/24	Loch Quoich	120	24	O
26/12/24	Patterdale	125	24	O
22/07/25	Essex (Great Chesterford Mills)	40	0.35	C
10/06/26	Snowdon	136	24	F
04/11/26	Snowdon	137	24	O
18/11/26	County Mayo	125	24	F
11/07/27	Hammersmith	51	0.6	C
01/11/27	Snowdon	134	24	O
17/06/30	Nottingham	71	1	C
18/06/30	Nottingham	50	0.6	C
14/06/31	Stafford	60	0.6	C
07/07/31	Burwarton Hall	76	2	C
03/09/31	Co. Wicklow	124	24	F
05/01/32	Rhondda	125	24	O
30/06/32	Princetown	127	20	F
12/08/32	Rickmansworth	56	0.75	C
16/12/32	Buttermere	124	24	O
27/02/33	Inchnabobart	136	24	F
22/06/33	S. Devon (Poltimore Rectory)	56	0.75	C
21/07/33	Chatham	54	0.5	C
12/07/34	Bettws-y-coed	81	2	C
13/07/34	Wrexham	69	1	C
25/06/35	Sutton	53	0.67	C
29/06/36	Clifton	47	0.5	C
24/10/36	Keswick	133	21	O
13/12/36	Snowdon	133	24	O
19/12/36	Glenleven	137	24	O
07/08/38	Chichester	64	0.75	C
10/08/38	Ayr	62	1	C
10/02/39	Loch Quoich	128	24	O
06/07/39	Rhonnda	123	24	O
03/09/39	Antrim	72	1.25	C
14/07/65	Trevanson	137	24	F
17/12/65	Afon Mynach	127	24	O
22/07/67	Chard	61	1	F
30/07/67	Gwynedd	127	24	O
10/08/67	Wilford Hill Res.	68	1	C
16/10/67	Glamorgan	121	24	O
23/03/68	Llyn Eigiau	132	24	O
26/03/68	Spean Bridge	134	24	O
03/06/68	Prickwillow	83	2.33	C
12/09/68	E. Yorks (Craggs Lane Farm)	72	1.33	C
14/09/68	Wickford	69	1.5	C
14/06/69	Barnsley	59	0.75	C
15/06/69	Dudley	35	0.3	C
28/07/69	Plymouth	137	24	F
07/08/70	Harwell	65	1.35	C
19/07/72	Exeter	89	2.2	C
23/07/72	Farley	44	0.33	C
15/07/73	Derwent Dam	134	24	F
08/01/74	SW England	125	24	F
16/06/74	Ambrosden	96	5	C
16/06/75	Midhurst	72	1.5	C
11/09/76	NE England	125	24	F
28/09/76	Glasgow	84	3.5	C
14/06/77	Biggin Hill	57	0.7	C
16/08/77	Ruislip	113	9	F
01/06/78	Chipping Norton	82	2	C
26/12/79	Dartmoor	120	24	O
20/09/80	Worthing	95	6	F
10/10/80	Worthing	101	8	F
09/07/81	Holborn	58	0.82	C
06/08/81	London	71	1	F
12/07/82	Bruton	113	16	F
06/07/83	Lampeter	70	1	C
02/09/83	Capel Curig	135	24	F
15/08/84	Surbiton	55	0.75	C
26/07/85	Co. Tyrone	103	9.5	F
25/08/86	Aber	135	24	F
29/12/86	Dolgellau	120	24	O
26/03/87	Waen Sychlwch	127	24	F
17/07/87	Slapton	89	4.5	C
23/08/87	Stafford	114	9.5	F
18/10/87	Black mountains	160	48	F
31/12/87	Strathclyde	125	24	F
08/05/88	Uxbridge	87	3	C
19/10/88	Crosby	82	2	C

25/11/39	Blaenau	126	24	O
02/11/40	Glamorgan	125	24	O
05/10/41	Brecon	95	5	C
26/11/41	Argyll	124	24	O
30/06/42	New Malden	55	0.55	C
29/08/42	Burnham	58	0.8	C
04/09/42	Borrowdale	128	24	O
09/10/42	Rydal	120	18	F
29/05/44	Glossop	77	2	C
01/12/44	Blaenau	120	24	O
15/07/45	Neston	42	0.33	C
28/08/45	Newport	76	1.9	C
24/10/45	Borrowdale	128	24	O
23/06/46	Sutton Coldfield	70	1.4	C
02/07/46	Bury St Edmonds	51	0.5	C
19/07/47	Higham	39	0.25	C
20/11/47	Glenshiel	127	24	O
28/07/48	Holford	65	1	C
02/08/48	Silchester	51	0.6	C
11/09/89	Holsome	123	24	F
22/02/91	Llangmawddy	133	24	O
01/01/92	South Laggan	136	24	O
29/05/92	Chorleywood	74	2	C
09/06/92	Lewisham	67	1.25	C
30/06/92	Wrantage	84	2.5	C
22/09/92	Walcot	113	15	F
29/03/93	Doune	139	25	F
25/05/93	Lambourn	73	1.5	C
09/06/93	Culdrose	123	24	F
08/07/97	Leatherhead	23	0.1	C
05/01/99	Cumbria	125	15	O
05/07/99	Gt. Maplestead	73	1.5	C

Appendix 1. Complete list of twentieth Century Less Extreme cases. Dates in bold type were those randomly selected for deeper analysis. For the type of event; F=frontal, C=convective and O=orographic.

Appendix 2

Date	Place	Amount (mm)	Duration (hours)	Type
12/07/00	Ilkley	95	1.25	C
12/07/01	Maidenhead	92	1	C
30/05/03	Croydon	87	1	C
21/10/08	Portland	175	5	F
09/06/10	Reading	130	2	C
26/08/12	Norwich	186	22	F
25/09/15	Inverness	201	40	F
16/06/17	Kensington	118	2.3	C
28/06/17	Bruton	243	8	F
29/05/20	Louth	119	3	C
19/08/24	Brymore	225	5	C
28/06/28	Blaenau	193	24	O
11/11/29	Rhondda	200	18	O
19/07/30	N. Yorks	250	60	F
08/08/31	Boston	155	11	F
02/11/31	Western Britain	240	48	O
11/07/32	Cranwell	126	2	C
26/09/33	Fleet	131	4	C
22/07/34	West Wickham	116	1.66	C
25/06/35	Swainswick	150	2.75	C
15/07/37	Boston	139	12	F
04/08/38	Torquay	127	2.25	C
22/06/41	Newcastle	110	2.33	C
14/09/43	Ferriby	48	0.25	C
23/11/46	Princetown	170	24	O
16/07/47	Wisley	102	1.25	C
12/08/48	SE Scotland	160	12	F
15/07/49	March	102	1.75	C
15/08/52	Lynmouth	228	12	F
26/06/53	Eskdalemuir	80	0.5	C
17/12/54	Loch Quoich	254	22.5	O
18/07/55	Martinstown	280	15	F
11/06/56	Bradford	165	2	C
08/06/57	Camelford	138	2.5	C
05/08/57	Rodsley	152	8.5	C
05/09/58	Knockholt	131	2.5	C
11/07/59	Hindolveston	93	0.3	C
07/10/60	Horncastle	178	3	C
06/06/63	Southery	150	3	C
18/07/64	Bolton	56	0.25	C
17/12/66	Glen Etive	199	18	O
08/08/67	Dunsop Valley	117	1.5	C
10/07/68	Chew Stoke	175	9	F
15/09/68	Whitstable	190	20	F
31/10/68	Tollymore Park	159	24	F
11/06/70	Pershore	67	0.4	C
27/06/70	Wisbech	51	0.2	C
01/08/73	Norwich	138	4	C
20/09/73	W. Stormouth	191	24	F
09/11/73	Blaneau Ffestiniog	147	15	O
17/01/74	Loch Sloy	238	30	O
14/08/75	Hampstead	171	3	C
25/06/80	Sevenoaks	116	1.75	C
01/08/80	Orra Beg	97	0.75	C
05/08/81	Tarporley	132	5	C
05/02/89	West Highland	186	24	O
19/05/89	Halifax	193	2	C
10/06/93	N. Weald	121	3.25	C
31/08/94	Bungay	146	12	F
10/12/94	Loch Sloy	250	48	O

Appendix 2. List of twentieth Century Extreme cases used in Phase 1 with additional cases (bold) found in WP1. For the type of event; F=frontal, C=convective and O=orographic.

Appendix 3

Date	Type	CAPE class	Large hail?	Orog class	Precipitable water (mm)	Surface dewpoint (ºC)	References
20/08/00	C	N/A	No			14	
10/08/01	C	N/A	Y			14	
07/08/02	F	N/A	No				
10/09/02	C***	N/A	Y			14	
16/10/07	F	N/A	No				Met. Mag. Nov.1907 p196
11/09/08	C	N/A	No			7	Met. Mag. Oct 1908 pp172,173
19/10/08	F	N/A	No				
24/06/11	F	N/A	No				
29/10/11	O	N/A	No	B			
17/06/13	C	N/A	No			14	
11/07/14	C	N/A	No			13	
06/05/15	C	N/A	No			11	Met. Mag. Jun 1915 p77
04/07/15	C***	N/A	Y			15	Met.Mag. Jul 1915 pp98-99, Aug 1915 p109
17/05/18	C***	N/A	Y			14	.
31/05/24	F***	N/A	No				
10/06/26	F	N/A	No				
01/11/27	O	N/A	No	C			
18/06/30	C	N/A	No			20	Met. Mag. 1930 pp129-131.
05/01/32	O	N/A	No	B			
27/02/33	F	N/A	No				
21/07/33	C	N/A	No			18	
13/12/36	O	N/A	No	A			
07/08/38	C	N/A	No			17	
04/09/42	O	0	No	A			.
29/05/44	C	5	Y			15	
23/06/46	C***	4	Y			16	
28/07/48	C	5	No			20	.
22/09/49	C***	3	No			15	
21/05/50	C***	5	Y		27.9	14	Met. Mag. Vol 79 pp245-256
19/05/52	C	4	Y		22.9	15	Met. Mag. 1952 p249.
05/06/54	C	4	No		15.2	14	Met. Mag. 1954

							pp247-248
19/07/56	C	4	No		20.3	14	
06/08/56	C	5	No		17.8	12	Met. Mag. 1956 pp297-299
19/07/57	C***	4	No		20.3	14	
10/08/57	F	0	No				
22/08/58	C	5	No		22.9	13	
12/05/59	C	6	No		25.4	15	
07/08/60	C***	5	No		22.9	13	
24/08/60	F	0	No				
11/02/62	O	0	No	A			
18/04/62	F***	1	No				
16/05/62	O	3	No	A			
14/07/65	F***	3	No				
22/07/67	F***	4	No				
23/03/68	O	0	No	A			.
26/03/68	O	0	No	A			
12/09/68	C***	4	N/A		22.9	13	
07/08/70	C	5	N/A		22.9	15	
16/06/74	C	6	N/A		25.4	14	
28/09/76	C	5	N/A		17.8	14	
01/06/78	C	4	N/A		20.3	15	
09/07/81	C***	5	No		30.5	18	
15/08/84	C	4	Y		25.4	16	
26/07/85	F***	2	Y				
17/07/87	C	2	No		20.3	12	
18/10/87	F	0	No				
30/06/92	C	2	No		25.4	15	
29/03/93	F	0	No				
05/01/99	O	0	No	B			
05/07/99	C	5	No		25.4	14	

Appendix 3. Analysis of the randomly selected set of sixty Less Extreme cases. Type; 'C'= convective, 'C***'= convective with frontal forcing, 'F'= frontal, 'F***'= frontal with embedded convection, 'O'= orographic. CAPE (Convective available potential energy) class; '0'= <1, '1'= 1-100, '2'= 101-200, '3'= 201-400, '4'=401-800, '5'=801-1600, '6'= >1600 J/kg, 'N/A'= information not available. Large hail; 'no'= hail reported but no large stones, 'Y'= hail >15 mm diameter reported, 'N/A'= insufficient information available. Orog class; 'A'= geostrophic wind direction not in range 210-250 or airmass source dew point <15 ºC or geostrophic wind speed < 16m/s, 'B'= geostrophic wind direction 210-250 with speed 16-25 m/s and airmass source dew point >14 ºC, 'C'= geostrophic wind direction 210-250 with speed > 25 m/s and airmass source dewpoint >14 ºC. Precipitable water; (mm) for convection cases. Surface dewpoint; is in ºC estimated just prior to the onset of deep convection.

Appendix 4

Date	**Low Velocity range**	**Aspect To low**	**Closest distance to low** (Km)	**Date**	**Low Velocity range**	**Aspect to low**	**Closest Distance to low** (Km)
15/02/00	3	E	220	**10/08/57**	3	N	50
11/08/00	nil			06/07/60	1	SW	220
07/08/02	1	N	350	**24/08/60**	3	W	200
23/07/03	nil		0	**18/04/62**	2	W	200
25/08/05	1	NW	50	30/05/64	nil		
16/10/07	1	NW	120	**14/07/65**	1	E	100
09/07/08	nil			**22/07/67**	1	N	240
19/10/08	nil			28/07/69	3	NW	100
24/06/11	1	W	300	15/07/73	1	N	100
17/09/13	nil			08/01/74	3	S	150
21/10/16	nil			11/09/76	2	N	50
15/09/18	nil			16/08/77	nil		
09/05/20	nil			20/09/80	2	E	150
04/10/20	nil			10/10/80	2	E	150
15/05/22	nil			06/08/81	1	NW	350
12/11/23	nil			12/07/82	nil		
31/05/24	1	N	50	02/09/83	3	S	100
22/07/24	2	N	150	**26/07/85**	2	W	220
10/06/26	1	SE	150	25/08/86	2	N	100
18/11/26	1	N	150	26/03/87	3	SE	300
03/09/31	1	NW	180	23/08/87	2	N	80
30/06/32	nil			**18/10/87**	nil		
27/02/33	nil			31/12/87	3	SE	350
09/10/42	nil			11/09/89	nil		
06/08/52	nil			22/09/92	1	NW	180
04/07/56	3	SE	360	**29/03/93**	nil		
30/07/56	nil			09/06/93	1	N	400

Appendix 4. Analysis of all frontal Less Extreme cases. Dates marked in bold correspond to those in the randomly selected sample. Low velocity range; 1=less than 5 m/s, 2= 5-10 m/s, 3= 11-20 m/s, nil= low centre more than 450 km from event location. Aspect; compass bearing of event location from low centre at closest approach. Closest distance to low; this is an estimate in kilometres from the low centre to the event location.

Appendix 5

Date	Amt.	Dur.	Type	CAPE class	Large Hail?	Orog class	Precip. water	Dew Pt.	Low vel. range	Aspect	Close. Dist. low
	(mm)	(hours)						(ºC)			(Km)
12/07/00	95	1.25	C	N/A	no			12			
12/07/01	92	1	C	N/A	no			14			
30/05/03	87	1	C	N/A	no			14			
21/10/08	175	5	F***						1	E	80
09/06/10	130	2	C	N/A	Y			15			
26/08/12	186	22	F						1	W	30
26/09/15	201	40	F						1	W	190
16/06/17	118	2.3	C	N/A	Y			17			
28/06/17	243	8	F***						3	N	180
29/05/20	119	3	C	N/A	no			14			
19/08/24	225	5	C***	N/A	Y			10			
28/06/28	193	24	O			B					
11/11/29	200	18	O			C					
22/07/30	250	60	F						1	NW	30
08/08/31	155	11	F***						2	N	200
03/11/31	240	48	O			C					
11/07/32	126	2	C	N/A	Y			17			
26/09/33	131	4	C	N/A	no			12			
22/07/34	116	1.66	C	N/A	no			16			
25/06/35	150	2.75	C***	N/A	Y			20			
15/07/37	139	12	F***						3	N	160
04/08/38	127	2.25	C***	3	Y			16			
22/06/41	110	2.33	C***	2	no			14			
14/09/43	48	0.25	C	2	Y			15			
23/11/46	170	24	O			C					
16/07/47	102	1.25	C	1	no			16			
12/08/48	160	12	F						2	NW	400
15/07/49	102	1.75	C	5	no			15			
15/08/52	228	12	F***						1	NW	40
26/06/53	80	0.5	C	4	no		27.9	16			
18/12/54	254	22.5	O			C					
18/07/55	280	15	F***						2	N	350
11/06/56	165	2	C***	6	no		30.5	15			
08/06/57	138	2.5	C	6	Y		17.8	13			
05/08/57	152	8.5	C	5	no		22.9	15			
05/09/58	131	2.5	C	6	Y		30.5	18			
11/07/59	93	0.3	C	1	Y		25.4	17			
07/10/60	178	3	C***	1	no		20.3	12			
06/06/63	150	3	C	4	Y		20.3	14			
18/07/64	56	0.25	C	3	no		30.5	16			
17/12/66	199	18	O			C					
08/08/67	117	1.5	C	5	no		20.3	14			
10/07/68	175	9	F***						4	N	190
15/09/68	190	20	F***						1	N	10

31/10/68	159	24	F						1	NE	450
11/06/70	67	0.4	C	5	no		25.4	17			
27/06/70	51	0.2	C	1	no		33.0	18			
01/08/73	138	4	C	5	no		20.3	15			
20/09/73	191	24							3	NW	55
09/11/73	147	15	O			B					
17/01/74	238	30	O			C					
14/08/75	171	3	C	5	no		30.5	16			
25/06/80	116	1.75	C	4	Y		17.8	10			
01/08/80	97	0.75	C	2	no		20.3	12			
05/08/81	132	5	C	N/A	no		30.5	15			
05/02/89	186	24	O			B					
19/05/89	193	2	C	5	no		17.8	14			
10/06/93	121	3.25	C	3	no		33.0	17			
31/08/94	146	12	F						2	NW	160
10/12/94	250	48	O			C					

Appendix 5. Analysis of the revised list of Extreme point rainfall cases. Amt.; rainfall amount (mm). Dur.; Rainfall duration (hours). Type; 'C'= convective, 'C***'= convective with frontal forcing, 'F'= frontal, 'F***'= frontal with embedded convection, 'O'= orographic. CAPE class; '0'= <1, '1'= 1-100, '2'= 101-200, '3'= 201-400, '4'=401-800, '5'=801-1600, '6'= >1600 J/kg, 'N/A'= information not available. Large hail; 'no'= hail reported but no large stones, 'Y'= hail > 15mm diameter reported. Orog class; 'B'= geostrophic wind direction 210-250 with speed 16-25 m/s and air-mass source dewpoint > 14 ºC, 'C'= geostrophic wind direction 210-250 with speed > 25 m/s and airmass source dewpoint > 14 ºC. Precip. water; (mms) for convection cases. Dew pt.; is dew point in ºC estimated just prior to the onset of deep convection. Low vel. range; 1=less than 5 m/s, 2= 5-10 m/s, 3= 11-20 m/s, 4= >20 m/s. Aspect; compass bearing of event location from low centre at closest approach. Close. Dist. to low; this is an estimate in kilometres from the low centre to the event location at closest approach.

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