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A study of twentieth-century extreme rainfall events in the United Kingdom with implications for forecasting

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Rainfall events in the United Kingdom during the twentieth century have been surveyed and those identified as extreme by the Flood Studies Report (1975) standards have been examined for common features. Events of duration up to 60 hours were considered in order to investigate those that could cause flash floods. More than half of the 50 events identified were short-period convective storms. The rainfall events were classified by meteorological situation, location and season, allowing the identification of conditions under which extreme rainfall occurred.

Suitable conditions for extreme rainfall were split into three categories: orographic, frontal and convective. The frontal and convective classes were then divided into two sub-classes according to whether significant embedded instability was present in the frontal cases and the nature of the convection in the convective cases. The study revealed a lot of commonality between the cases. For example, all of the orographic events occurred in winter in moist west to southwest airflows, and 80% of the frontal cases involved a slow-moving depression to the south or east and also a slow moving frontal system. A conceptual airflow diagram has been developed for some of the frontal cases. The key result, however, was the discovery that each category of meteorological situation occupied a unique space in a rainfall amount versus duration diagram for each extreme event. This offers exciting opportunities for applying the results of this study and a framework for studying future events.

1. Introduction

The most extreme hydrometeorological events that are likely to be experienced in the United Kingdom have received only limited study from the point of view of underlying consistency and predictability. Practically all such rainfall and associated flood events that have occurred in the past 100 years or so have been described, and in some cases have been analysed in order to seek their causes. However, guidance to forecasters to help identify these events remains skeletal. It is vital that signals of the possibility of such events be recognised as early as possible, preferably 24 hours or more in advance. Many events were described by sources in the first half of the twentieth century and have not been revisited, even though analytical methods and basic meteorological theory have developed immensely since that time. Some surveys have been published in *British Rainfall* and *Weather*, many of which have listed heavy rainfall events for particular periods (e.g. decades), but have not proceeded to determine the meteorological features common to those events. Acreman (1989a and 1989b) presents an overview of extreme UK floods, but approaches the subject from a wholly hydrological perspective.

In this study we identified and examined extreme rainfall events with the aim of identifying common underlying meteorological characteristics. Clearly, given that such events will always lead to a possibility of severe flooding, an improved understanding could be very beneficial. Events were identified using published return periods and expected maxima for point rainfall amounts as a function of time. Simple classifications according to location and the time of year and the main rainfall-producing mechanism were then carried out. These were refined to obtain a categorisation of extreme rainfall events by rainfall amount and duration according to four distinct and measurable meteorological regimes.

Table 1. *Maximum point rainfalls possible for durations less than one hour and the one in one hundred year return period for durations greater than one hour as a function of average annual rainfall (AAR). Note that the amounts for greater than one hour correspond to the top of the AAR range.*

Average annual rainfall (AAR) mm	Duration (hours)						
	0.25	0.5	1	24	48	72	96
	Maximum fall possible			Amount for 1:100-year return period			
500–1400	47	65	83	100	123	135	150
1400–2800	**45**	**62**	**79**	**152**	**193**	**219**	**247**
>2800	43	59	75	228	309	356	410

2. Selection, classification and analysis of events

2.1. Selection and classification

Rainfall events that could give rise to serious flooding involve four main ingredients: intensity of precipitation, duration of precipitation, the wetness of the ground and the response of the rainfall catchment. The key items considered in this study were the first two, which are the meteorological ones. Hydrological contributions and other factors were noted when applicable.

Criteria for event selection were established by making use of the point rainfalls estimated in the *Flood Studies Report Volume II* (1975) (*FSR*) as the 'maximum' falls possible for durations of less than 1 hour, and the one in one hundred year return period for durations greater than one hour. Values are shown in Table 1.

Because orographic enhancement generally leads to higher average annual rainfall (AAR) totals in mountainous areas, and preliminary results indicated that most extreme rainfalls occur over lowland UK, it was decided to use the middle range of AAR in Table 1 as a definition of the lower limit of extreme rainfalls. It is useful to compare this classification with the 'classification of heavy falls in short periods' by Bilham (1935) published in *British Rainfall*. Bilham puts falls into three categories: 'noteworthy', 'remarkable' and 'very rare' as shown in Table 2. Comparing Tables 1 and 2 it can be seen that the lower limit chosen for extreme events is substantially greater than that for the 'very rare' category in the Bilham classification.

Table 2. *Lower limits of point rainfall amount in mm as a function of duration for three categories of event according to Bilham (1935). (Note that the original article has a duration resolution of 10 minutes).*

Time (mins)	Noteworthy	Remarkable	Very rare
5 or less	10.9	17.3	26.8
10 or less	13.8	21.6	33.2
20 or less	17.3	26.8	40.9
30 or less	19.7	30.3	46.2
60 or less	24.5	37.6	56.8
90 or less	27.8	42.4	64.0
120 or less	30.4	46.2	69.4

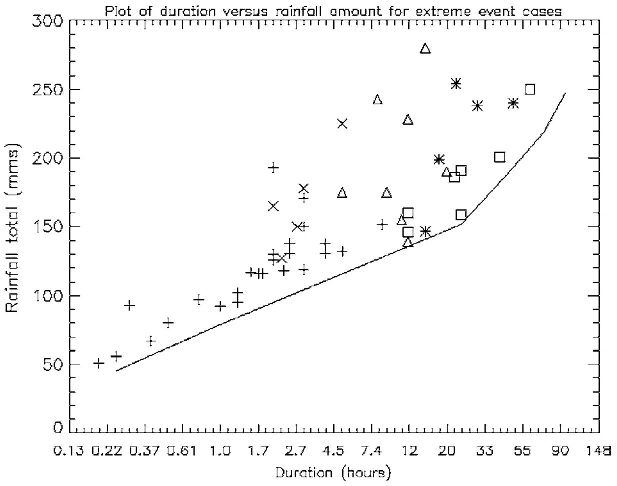

Figure 1. *Plot of point rainfall amount (mm) versus duration (h) (on a logarithmic scale) for each of the five event categories listed in Table 3. '+' = convective, '×' = convective*** (frontal forcing), * = orographic, △ = frontal*** (with embedded instability) and □ = frontal. The solid line plot indicates the lowest threshold used for extreme event classification as in Table 1.*

Final event selection was done by searching through a database of 'notable rainfall events in the twentieth century' held in the Met Office and picking out those that exceeded a curve of values derived from the criteria shown in bold type in Table 1 (see Figure 1). Other sources of information such as the *FSR* and the *British Rainfall* series of publications were also utilised to generate the list of extreme events in Table 3.

2.2. Data sources used for analysis of events

The selected events were investigated in detail using several different sources. Up to 1960 the *British Rainfall* series of annual publications was invaluable for providing detailed rainfall information for each event and also, on most occasions, a brief description (sometimes with maps) of the meteorological conditions and associated flooding. Some events were also published in the *Meteorological Magazine* (*Meteorol. Mag.*) and referenced by *British Rainfall*. Descriptions of events were often from interested members of the public who gave valuable insights into the possible

Table 3. *List of extreme event dates showing date, location, point rainfall amount (mm) and duration (h), classification and published source of additional information. In the classifications, frontal*** *indicates a significant convective component and convective*** *indicates significant frontal forcing.* DWR *is the* Daily Weather Report.

Date	Location	Point rainfall total (mm)	Duration (hours)	Basic type	Reference
12/07/00	Ilkley	95	1.25	Convective	Wilson (1900)
12/07/01	Maidenhead	92	1	Convective	*British Rainfall* (1901)
21/10/08	Portland (Dorset)	175	5	Frontal***	*British Rainfall* (1908)
09/06/10	Reading	130	2	Convective	*British Rainfall* (1910)
26/08/12	Norwich	186	22	Frontal	*British Rainfall* (1912)
25–26/09/15	Inverness	201	40	Frontal	*British Rainfall* (1915)
16/06/17	Kensington	118	2.3	Convective	*Symons's Met. Mag.* (1917)
28/06/17	Bruton (Somerset)	243	8	Frontal***	*British Rainfall* (1917)
29/05/20	Louth (Lincolnshire)	119	3	Convective	*British Rainfall* (1920)
19/08/24	Brymore (Somerset)	225	5	Convective***	Glasspoole (1924)
19–22/07/30	North Yorkshire	250	60	Frontal	*British Rainfall* (1930)
08/08/31	Boston (Lincolnshire)	155	11	Frontal***	*British Rainfall* (1931a)
2–3/11/31	SW England, Wales and the Lakes	240	48	Orographic	*British Rainfall* (1931b)
11/07/32	Cranwell (Lincolnshire)	126	2	Convective	*British Rainfall* (1932)
26/09/33	Fleet (Hampshire)	131	4	Convective	*British Rainfall* (1933)
22/07/34	West Wickham (Kent)	116	1.66	Convective	*British Rainfall* (1934)
25/06/35	Swainswick (Bath)	150	2.75	Convective***	*British Rainfall* (1935)
15/07/37	Boston (Lincolnshire)	139	12	Frontal***	*British Rainfall* (1937)
04/08/38	Torquay	127	2.25	Convective***	*British Rainfall* (1938)
16/07/47	Wisley (Surrey)	102	1.25	Convective	*British Rainfall* (1947)
12/08/48	SE Scotland, Tweed	160	12	Frontal	Glasspoole & Douglas (1949)
15/08/52	Lynmouth	228	12	Frontal***	Bleasdale & Douglas (1952)
26/06/53	Eskdalemuir	80	0.5	Convective	
17–18/12/54	Loch Quoich	254	22.5	Orographic	
18/07/55	Martinstown (Dorset)	280	15	Frontal***	*British Rainfall* (1955)
11/06/56	Bradford	165	2	Convective***	*British Rainfall* (1956)
08/06/57	Camelford (Cornwall)	138	2.5	Convective	Bleasdale (1957)
05/08/57	Rodsley (Derbyshire)	152	8.5	Convective	*British Rainfall* (1957)
05/09/58	Knockholt (Kent)	131	2.5	Convective	Ludlam & Macklin (1960)
11/07/59	Hindolveston (Norfolk)	93	0.3	Convective	
07/10/60	Horncastle (Lincolnshire)	178	3	Convective***	
06/06/63	Southery (Norfolk)	150	3	Convective	
18/07/64	Bolton	56	0.25	Convective	
17/12/66	Glen Etive	199	18	Orographic	Reynolds (1967)
08/08/67	Dunsop Valley (Lancashire)	117	1.5	Convective	
10/07/68	Chew Stoke (Bristol)	175	9	Frontal***	Salter (1968)
15/09/68	Whitstable (Kent)	190	20	Frontal***	Salter & Richards (1974a,b)
31/10/68	Tollymore Park (County Down)	159	24	Frontal	
11/06/70	Pershore	67	0.4	Convective	
27/06/70	Wisbech	51	0.2	Convective	
01/08/73	Norwich	138	4	Convective	
20/09/73	West Stourmouth (Kent)	191	24	Frontal	
09/11/73	Blaneau Ffestiniog (Wales)	147	15	Orographic	
17/01/74	Loch Sloy	238	30	Orographic	
14/08/75	Hampstead	171	3	Convective	Bailey et al. (1981)
25/06/80	Sevenoaks	116	1.75	Convective	Dixon (1980)
01/08/80	Orra Beg (Antrim)	97	0.75	Convective	
05/08/81	Tarporley (Cheshire)	132	5	Convective	Bader et al. (1983)
19/05/89	Walshaw Dean (Halifax)	193	2	Convective	Collinge et al. (1991)
31/08/94	Bungay (East Anglia)	146	12	Frontal	

nature of the system responsible for the event. Two examples follow. The first is part of a description of the Ilkley storm in 1900 from Wilson (1900):

> Sir, – On Thursday afternoon, July 12th, a terrific thunderstorm raged over a part of the West Riding of Yorkshire, beginning in the west about noon, and extending or propagating itself gradually eastwards. The direction of the thunder clouds was from S to N, although as is usual in such cases, the surface winds were very variable under the storm area, and in the district to the eastward the sky was very clear and blue, and a strong easterly wind blew into towards the storm centre…

The second example is part of an account of the storm of 4 August 1938 in *British Rainfall* (1938):

> . . . at Hedgebarton, 15 miles to the northwest of Torquay, Mr W. K. Kitson noted that the rain did not begin until 4 h 15 m and by 8 h as much as 5.86 inches was recorded. Very large hailstones occurred but the hail was of short duration. For four hours the lightning appeared to be continuous. It appeared to be a purely local storm confined to an area a mile in diameter and other localities appear to have had purely local storms.

After 1960 the *British Rainfall* series changed style and was much less useful for this study and additional information had to be gleaned from the Met Office *Daily Weather Report* (*DWR*) series and published articles. It is perhaps ironic that the details of events were better recorded in the earlier reports, but that the provision of underlying meteorological information was better in later years. Articles in *Weather* regarding many events provide information about atmospheric conditions and 'less official' (i.e. amateur) rainfall observations.

Upper air data were only available from the 1920s (routinely later) and radar and satellite data from the 1960s. Moreover, it was only in the 1930s that fronts were routinely analysed on charts published in the *DWR*, so for the early events these had to be inferred professionally from available data. Flooding information was also well documented and easy to determine in *British Rainfall* prior to 1960 but less so after that date.

2.3. Basic analysis of events

Out of the 50 cases (coincidentally a round number), 30 were found to be predominantly convective, 15 predominantly frontal and five of the orographic type. Although in many cases orography was a contributing factor due to forced ascent of moist air, the cases deemed to be orographic were those in which general orographic uplift was the dominant mechanism for the very high rainfall. The decadal and seasonal distributions of events throughout the twentieth century are shown in Figures 2 and 3.

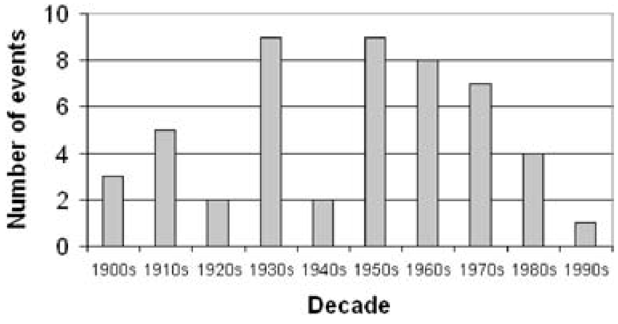

Figure 2. *Number of extreme events per decade.*

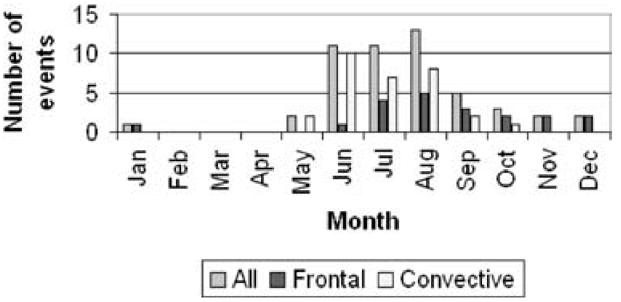

Figure 3. *Number of extreme events per month and type (frontal type includes orographic).*

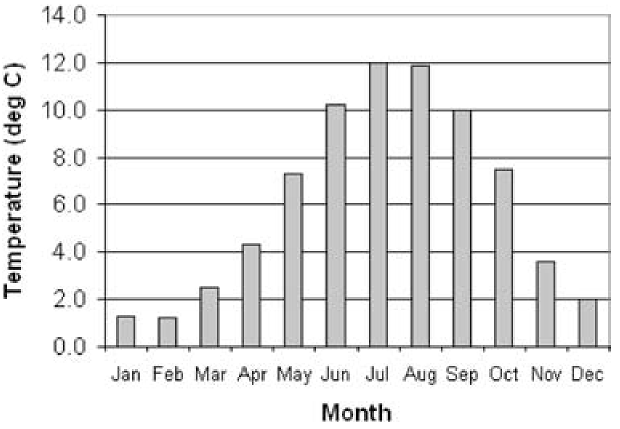

Figure 4. *Distribution of average monthly minimum temperature at Manchester (1961–1990).*

The distribution per decade (Figure 2) indicates no significant variation during the century with the 1930s and 1950s having most cases, and there being more cases in the second half of the twentieth century than in the first. However, no conclusions should be drawn from this since the first half included two world wars and there seems to be a loose correlation with the density of professionally maintained raingauges.

The monthly distribution (Figure 3) is more interesting. There were no events in February, March or April. Most events occurred during the summer months with a rapid increase in number in June with a gradual tailing off during the autumn. Naturally, convective events tail off more quickly than frontal ones, with no convective events in November, December or January since insolation is an important forcing factor for convection. An explanation for this highly skewed distribution of extreme events is that relatively low sea temperatures and colder air during the spring would mean less available moisture for rain-producing systems. Even though atmospheric instability can be high in April, these results would suggest that although shower events can give short bursts of very heavy rain at that time of year, they are not capable *by themselves* of providing extreme rainfalls. It is also interesting to compare the monthly minimum temperature distribution of a typical inland site (see Figure 5b for location) like Manchester Airport (Figure 4) with the monthly extreme rainfall event distribution (Figure 3). The 1961–1990 average monthly minimum temperature distribution shows a similar pattern with higher values in the autumn compared to the spring months as a consequence of higher soil and sea temperatures.

It was clear from the data that a number of the frontal cases had a significant convective element. This was usually characterised by embedded thunderstorms shown plotted within a general band of otherwise frontal dynamical precipitation (for example, Lynmouth in 1952). Similarly, some convective events arose due to instability being released due to the presence of an otherwise inactive front (for example, Bradford in 1956). These cases are labelled with *** in Table 3. The basic classifications in Table 3 are shown in graphical form as a function of rainfall amount and duration in Figure 1.

This graph is interesting in that the convective cases seem to be closely scattered about a well-defined line. The scatter increases for durations greater than about 2 hours when convective cases with dynamical forcing become included. The frontal events are also grouped so as to increase linearly but with more scatter than the convective cases with some notable outliers. The largest rainfall amounts for specific durations occurred in cases where there was significant embedded instability (for example, the rainfall events in Bruton in 1917, Lynmouth in 1952 and Martinstown in 1955).

As well as meteorological features some hydrological aspects were examined using the comprehensive and detailed information in the *British Rainfall* series up to 1960 and in the 1968 edition. Out of the 34 cases up to and including 7 October 1960 and the 1968 cases, 94% of the rainfalls caused flooding. A lot of the flooding was serious and damaging, and in some cases tragic, as at Louth in 1920 and Lynmouth in 1952. In the two non-flooding cases (11 July 1932 and 26 September 1933) there was no mention of widespread flooding though it would be surprising if local flooding did not occur given the intensity of the rainfall on those occasions. Deluges of water cascading quickly down hillsides, for example at Ilkley in 1900, caused several serious events. A major factor in the Lynmouth flood was the build-up of water behind debris, which subsequently burst to give catastrophic results. Looking at the rainfall events in the two months prior to each extreme case, an estimate was made of the wetness of the ground: 34% of the cases in the sample were estimated to have very wet ground (likely surface water) beforehand, undoubtedly contributing to flooding. (In the two non-flooding cases, the ground was not wet prior to the event.) All in all, the analysis implies that all extreme rainfall events are highly likely to cause flooding. It supports the findings by Collier & Fox (2003) that flooding will be exacerbated if the rain falls in sensitive catchments, over steep orography or over already very wet ground.

There are a number of interesting features revealed by the locations in which extreme rainfalls have been observed. However, some conclusions must be tempered by the proviso that a number of events may not have been recorded because of their remote locations. The maps in Figures 5a and 5b show the distribution of the events by type excluding the two events that took place in Northern Ireland and the spatially extended event of 2–3 November 1931. Extreme rainfalls appear to be relatively rare in Wales and Scotland and no isolated convective events were observed there. Of course, these are also the least populated areas of the UK and such rains may have gone unobserved and not officially measured, especially if they were isolated storms. On the other hand, the cluster of events in the London area suggests that very little goes unrecorded in such a well-populated region.

Although it can be deceptive to use a map such as that in Figure 5a with a small number of events, the concentrations of extreme rainfalls in certain areas does reveal something of the roles played by small-scale features. Topographic effects are seen to be important contributors for the events in SW England and around the Pennines. Even the events in SE England may, in part, be the result of orographic forcing along the Downs; indeed, Bailey et al. (1981) suggest that the Hampstead storm of 15 August 1975 was influenced by terrain. All the frontal events occur close to coasts and this could suggest the importance of the local moisture source, from which locations further inland may be cut off. This possibility was raised by Wheeler (1997) in discussing the influence on rainfall in eastern Britain of moist onshore winds on the north side of depressions.

The groups of storms in SE England and East Anglia/Lincolnshire may underline the importance of insolation in convective storm generation. Excess surface heating may serve to initiate the storms or provide an area of additional forcing in the synoptic forcing environment of convective storms (see section 3.3). Fifteen events are diagnosed as purely convective in these two areas. All but two of these took place in June, July or August, the earliest event in the year being Louth on 29 May 1920 and the latest was at Fleet, Hampshire on 26 September 1933. This temporal distribution supports the theory that these storms are forced to some extent by high surface temperatures and, as is shown later, high values of convectively available potential energy (CAPE). These areas of the country experience high insolation in summer, supported at times by flows of hot continental air from the south and east.

3. Analysis of cases

3.1. Orographic events

The criterion for an orographic event was that rainfall was not directly associated with a frontal system or deep convection. A warm front may have passed through

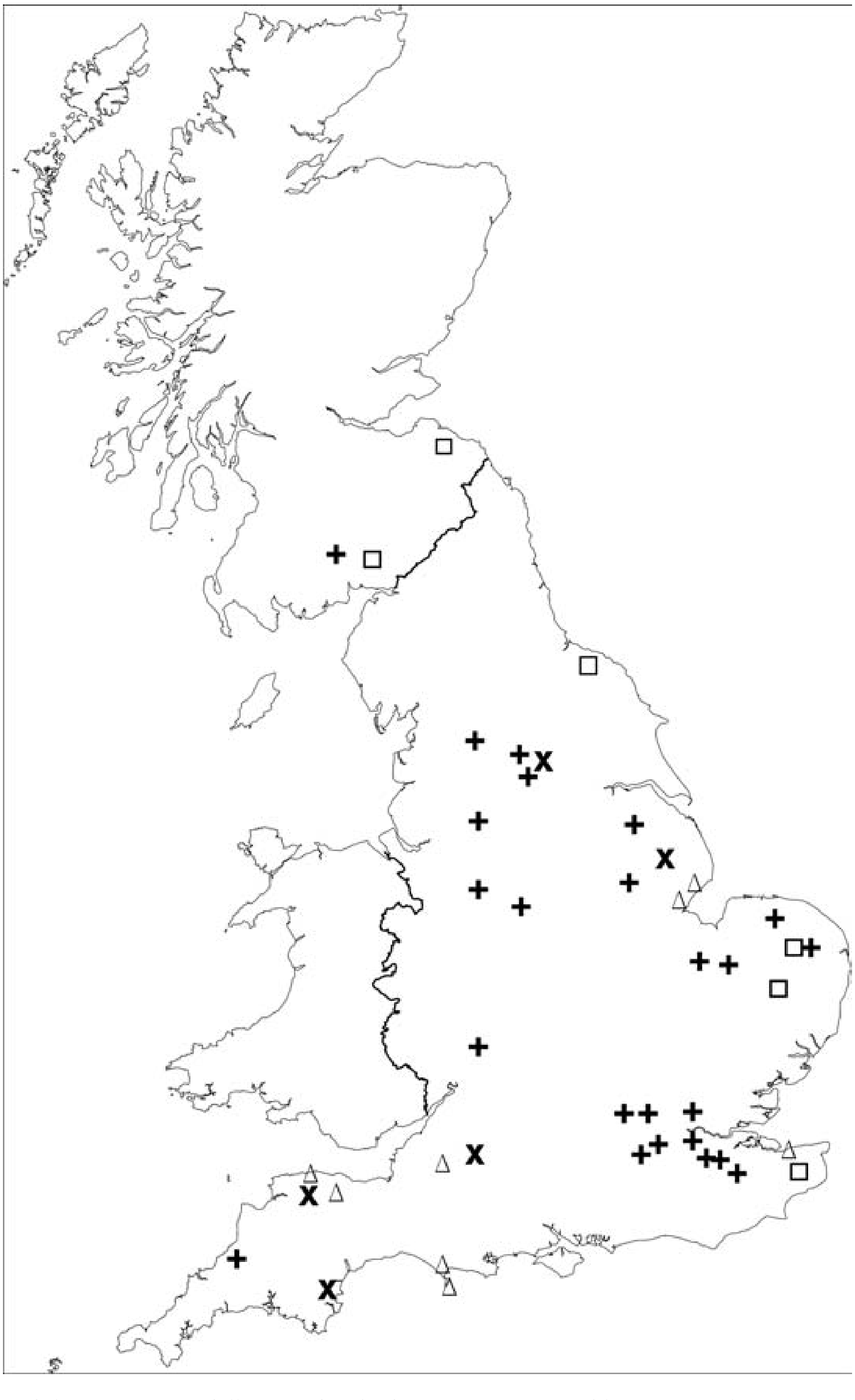

Figure 5a. *Locations of the extreme rainfall events for the four categories in Table 3 (orographic events and those in Northern Ireland are not shown).* '+' = *convective,* '×' = *convective*** (frontal forcing),* △ = *frontal*** (with embedded instability) and* □ = *frontal.*

the region but the main rainfall production mechanism would be the prolonged ascent of moist cloudy air over high ground. Such a situation would characteristically give continuous drizzle near sea level, but orographic enhancement would lead to many hours or even days of steady rain in the hills.

There were five cases in the sample: 2–3 Nov. 1931, 17–18 Dec. 1954, 17 Dec. 1966, 9 Nov. 1973 and 17 Jan. 1974. Note that all of these events were in the months November, December and January, which is consistent with orographic enhancement being a mainly wintertime phenomenon (e.g. Harrison 1997). The locations of these events are shown in Figure 5b, which shows that they were situated in the hilly west and north of Britain. It is these areas where moist southwesterly winds first encounter significant up-slopes. All cases involved a long sea fetch (greater than 2000 km) in a strong west to southwest straight airflow in a broad warm sector with a high pressure region centred either over the Bay of Biscay (Dec. 1954, Dec. 1966, Nov. 1973, Jan. 1974) or Greece with a ridge to Spain (Nov. 1931)

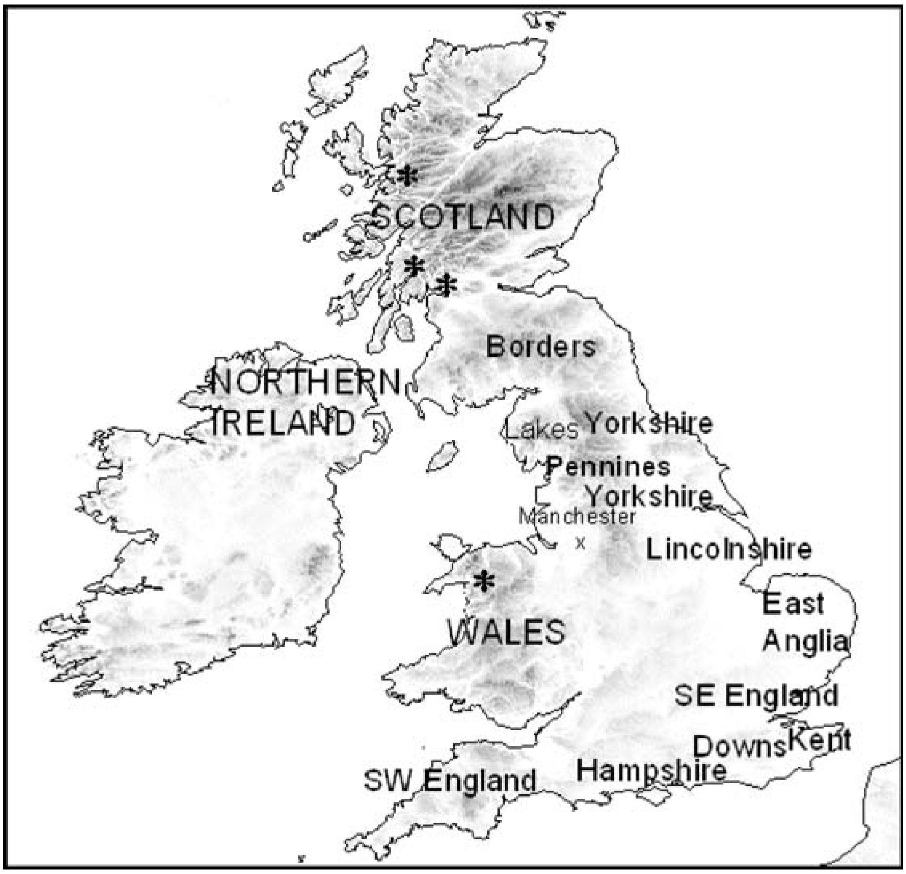

Figure 5b. *Map showing orography over the British Isles and locations of non-widespread orographic events (marked as a '*'). The spatially extensive orographic event of 2–3 Nov. 1931 occurred over Wales, SW England and the Lakes, which are shown in the figure together with other places in the UK referred to in the text.*

as summarised in Table 4. In these orographic cases, the speed of the parent low was variable, and there was no evidence of convective activity aloft in the stable surface flows. The common important factors from the sample were found to be fetch (direction and distance), wind speed and a moist and warm tropical maritime airmass. All of the fetches were greater than 2000 km in length from a direction between west and southwest persisting for 15 hours or more. The dewpoints of the air in the source regions were estimated to be greater than 14 °C and the average geostrophic (600 m) wind along each fetch was estimated from the isobaric patterns to be greater than 15 ms^{-1}.

An example of a typical synoptic situation that could lead to extreme orographic rainfall is shown in Figure 6 for 17 December 1966. The high rainfall occurred over western Scotland in the strong to gale force warm sector west-southwesterlies behind the warm front. Note the long fetch of warm and moist air which has air temperatures in the source region around 21 °C.

3.2. Frontal events

An extreme event was classed as frontal if the rainfall was widespread and continuous over a large area and was clearly associated with a synoptic scale frontal system. If there was significant embedded convection characterised by pulses of very heavy rain or thunderstorms, the event was classified as Frontal*** (as denoted in Table 3).

Table 4. *List of orographic events giving point rainfall amount and duration, the fetch of the airmass specifying direction and distance, estimated mean wind speed along fetch at 600 m (from surface isobars) and the estimated airmass source dewpoint.*

Event	Point rainfall total (mm)	Duration (h)	Fetch direction	Fetch distance (km)	600 m wind speed (m/s)	Source dewpoint (°C)
2–3 Nov. 1931	240	48	SW	2500	25	17
17–18 Dec. 1954	254	23	WSW	3000	25	14
17 Dec. 1966	199	18	WSW	3500	25	18
9 Nov. 1973	147	15	WSW	2000	15	16
17 Jan. 1974	238	30	WSW	4000	25	15

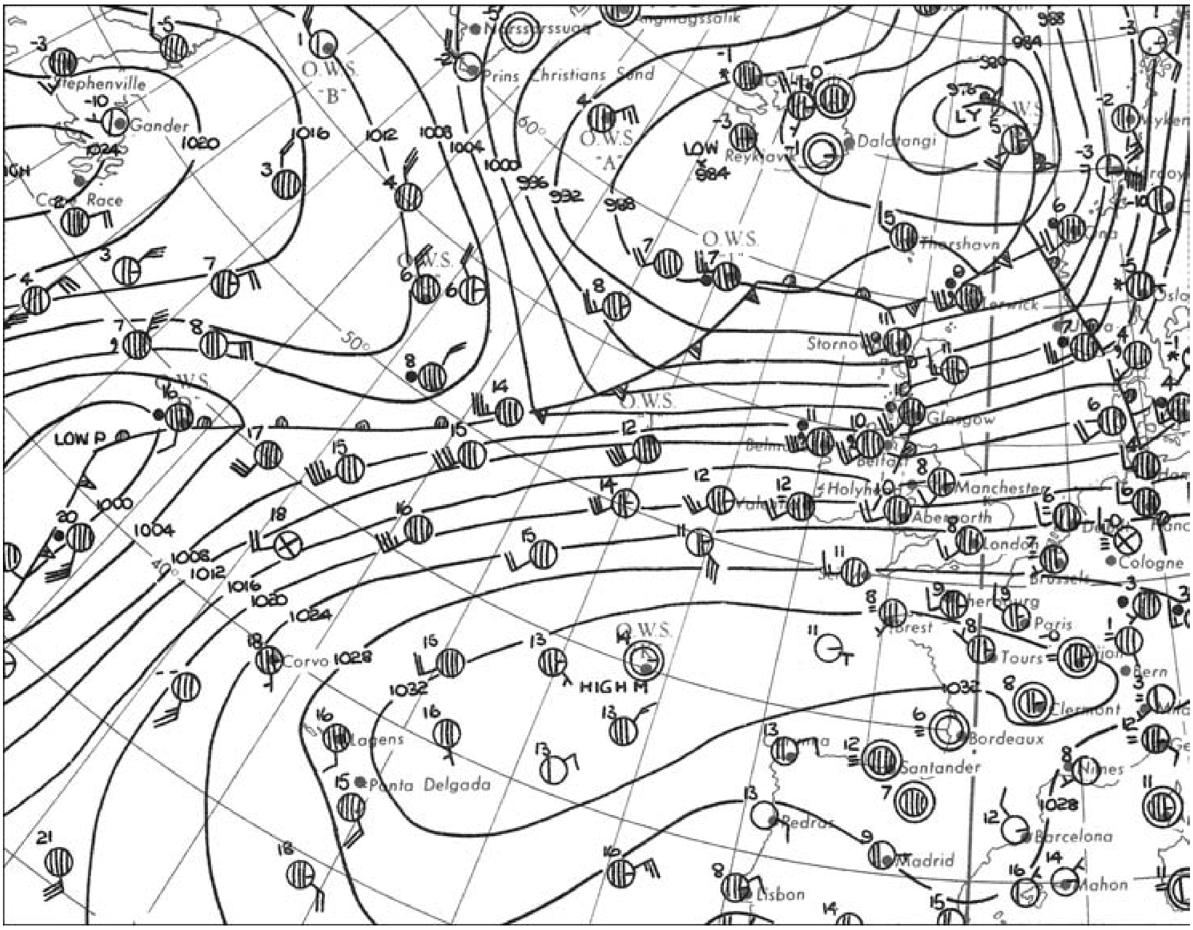

Figure 6. *Surface chart for 1200 GMT 17 Dec. 1966 (from DWR).*

Looking at the surface synoptic charts for all of the 15 frontal cases it is clear that all of the events were either associated with a slow-moving frontal system or a depression that was close by, and in 10 cases a combination of both.

Figure 7 shows the aspect of the rainfall centre of each frontal event in relation to the depression centre. For example a square on the arm labelled 'W' at '−200' would mean that the event occurred 200 km to the west of the depression.

None of the 15 frontal events was more than 450 km at its closest point from a depression and 80% (12 events) were within 200 km. Eight frontal events had significant embedded instability (Frontal*** category). In terms of aspect, all events occurred north of a depression and 73% either northwest (NW) or north (N). Nine of them (60%) were both NW or N and within 200 km at their closest distance from the low pressure centre. Of those, six had significant embedded instability and three had little evidence of instability. In 12 out of the 15 cases the speed of the low was less than or equal to 10 ms^{-1} and in 7 out of the 15 cases it was less than or equal to 5 ms^{-1}.

It is interesting to note that the frontal event (Martinstown in 1955) that gave the most rainfall (280 mm in 15 hours) was an almost stationary front extending almost west to east across southern England with embedded instability.

Since most of the fronts were either to the east or south of the event centre the rain-producing system naturally involved the northward or westward advection and ascent of very moist and relatively warm air. A very good example of this is illustrated in a diagram from Glasspoole and Douglas (1949) of the 'Tweed floods' of 12 August 1948 reproduced in Figure 8. The low pressure centre is clearly seen tracking to the south of the Tweed across England, with a slow-moving warm occlusion to the north providing the prolonged and heavy rainfall. Another example on 21 July 1930 is shown in Figure 9 from *British Rainfall* (1930). The rainfall event in north Yorkshire was to the west of the low, which moved very slowly east during 21 and 22 July. The dashed line indicating a front curving round the north and west of the low was probably a slow-moving warm occlusion similar to the 1948 case.

The chart for the Lynmouth flood event reproduced from Bleasdale and Douglas (1952) is shown in Figure 10. This again shows a slow moving depression running close to and southeast of the extreme event. A key feature is the advection of very moist air (indicated by the warm front) northwestwards into the potentially unstable region over Exmoor lying just to the east of

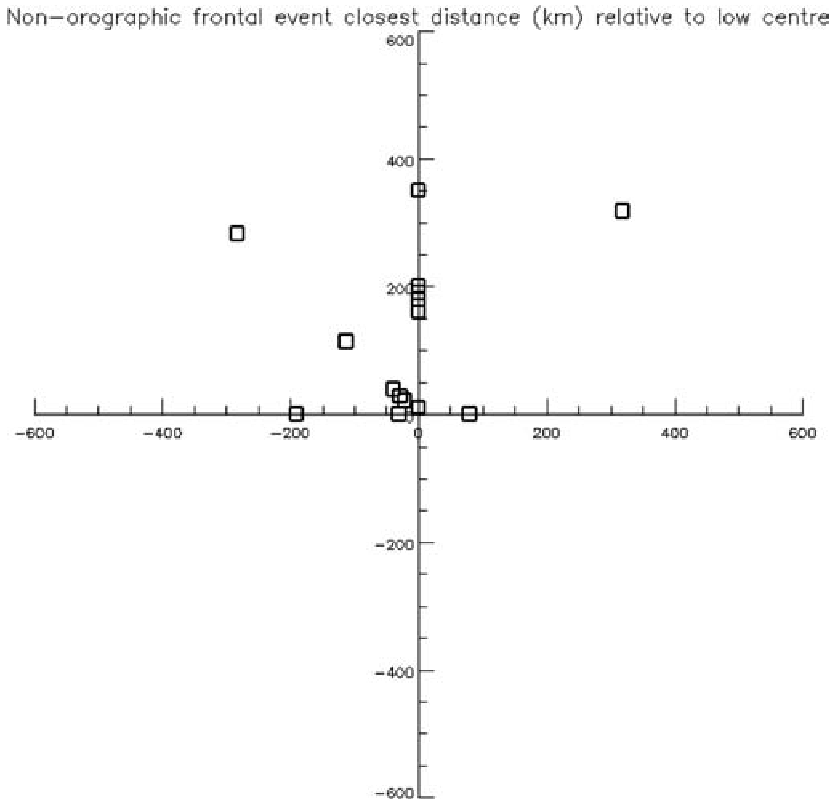

Figure 7. *Direction and closest distance of each frontal event from closest approach of depression centre (0 on the compass cross). (See text for more details).*

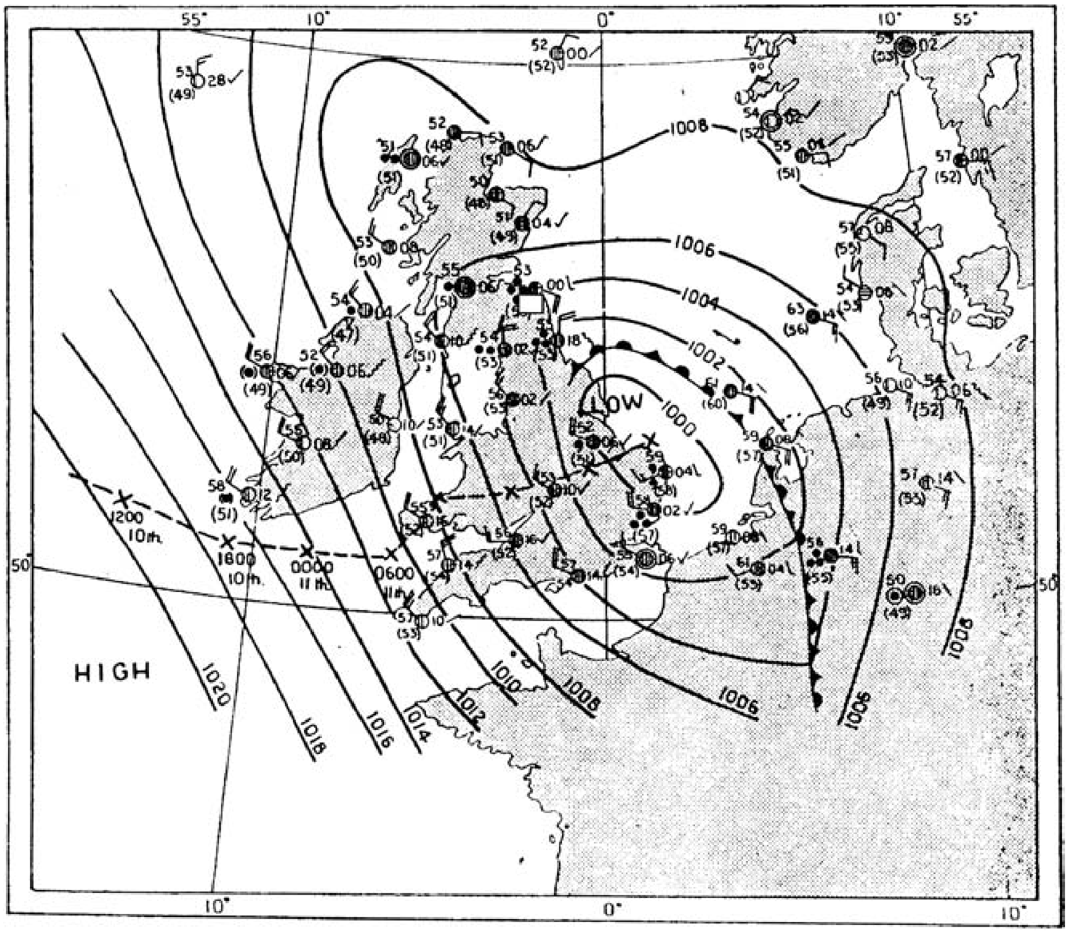

Figure 8. *Surface chart showing movement of depression and associated frontal system and position of low centre at 0600 UTC 12 Aug. 1948. (Reproduced from Glasspoole & Douglas1949). The approximate centre of the rainfall event is marked with a □.*

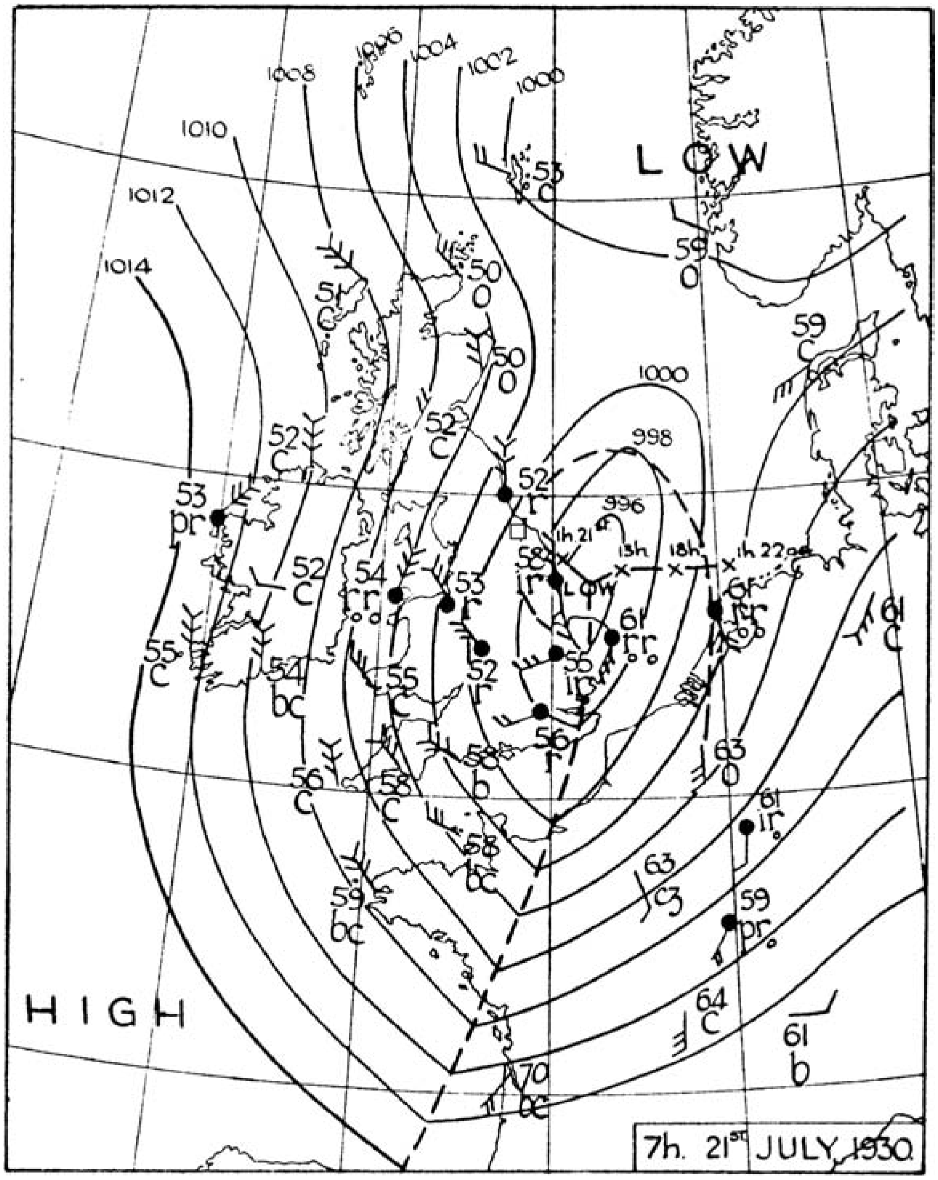

Figure 9. *Surface chart for 0700 UTC 21 July 1930. The movement and position of the low at other times is indicated by crosses and the position of fronts by dashed lines. The number of wind feathers indicate Beaufort force. (Reproduced from British Rainfall 1930). The approximate centre of the rainfall event is marked with a □.*

an upper trough. The final example is for Whitstable in Kent on 15 September 1968 from Salter & Richards (1974a) and is reproduced in Figure 11. Again it is noticeable that heavy rainfall to the north and west of a small low pressure centre is in association with a well-marked warm occlusion with much embedded instability.

The schematic in Figure 12 illustrates the main features that occurred in 10 out of 15 of the frontal cases: 21 Oct. 1908, 26 Aug. 1912, 22 July 1930, 15 July 1937, 12 Aug. 1948, 15 Aug. 1952, 10 July 1968, 15 Sept. 1968, 20 Sept. 1973 and 31 Aug. 1994. Although details and orientations were different, the key similarities were a slow-moving low within 200 km of the rainfall event centre; a warm, moist ascending airflow marked by a slow-moving warm front or occlusion; the possibility of instability release leading to thunderstorms either close to the low centre or within the ascending warm airmass; and the extreme rainfall either along the warm front (occlusion) or in the northwest quadrant relative to the low centre.

3.3. Convective events

Convective events were distinguished from frontal events by the much more localised and less continuous nature of the rainfall, even if the convection was triggered by an old frontal system. The convective cases broadly fell into two categories:

(a) Forcing was from a synoptic scale feature such as a front, or up-draughts and down-draughts in the system were very strong, with a high value of convectively available potential energy (CAPE);

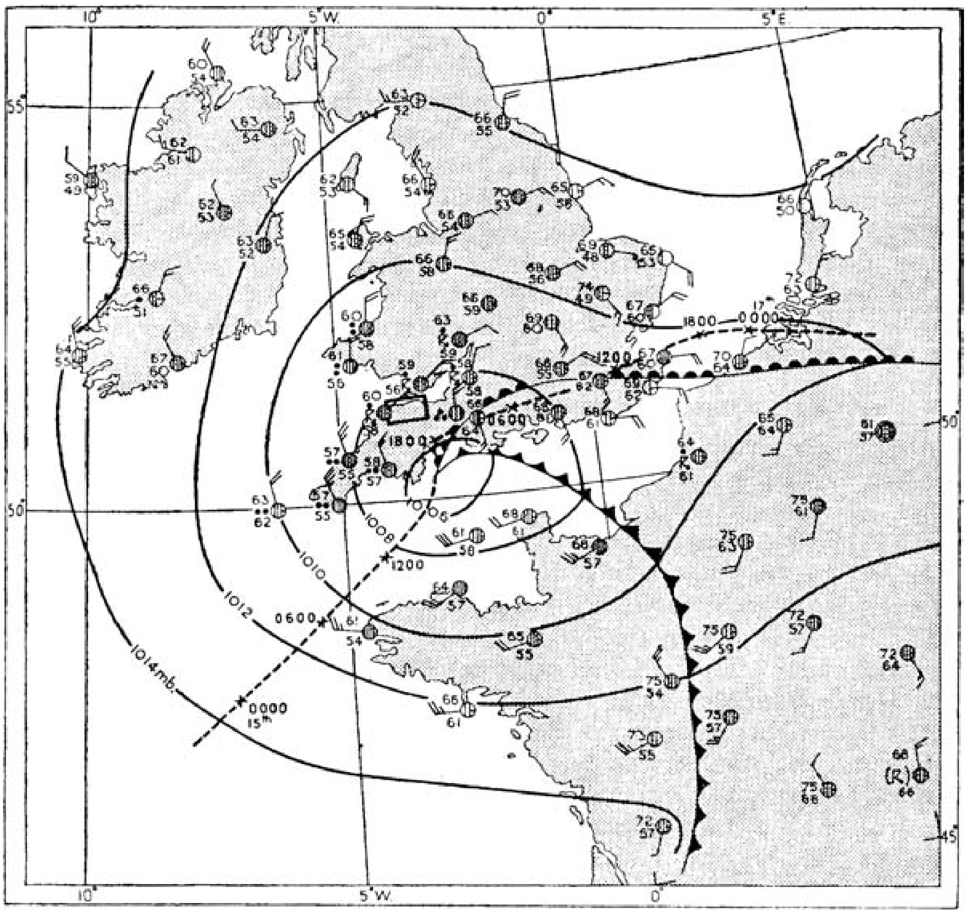

Figure 10. *Synoptic chart for 1500 UTC 15 Aug. 1952. (Reproduced from Bleasdale & Douglas 1952). The approximate centre of the rainfall event is marked with a □.*

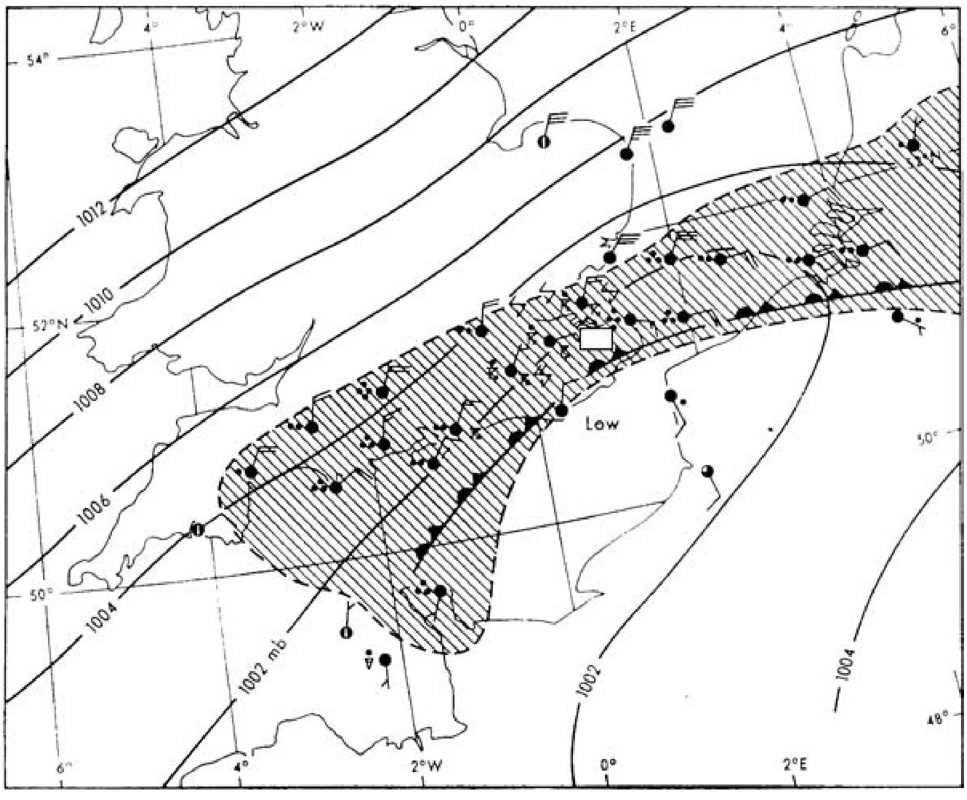

Figure 11. *Synoptic chart for 0900 UTC 15 Sept. 1968. (Reproduced from Salter & Richards 1974a.) The approximate centre of the rainfall event is marked with a □.*

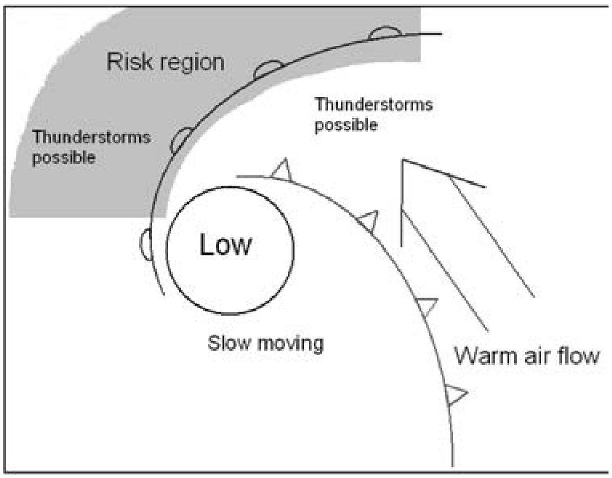

Figure 12. *Schematic diagram showing archetypal situation that occurred in several of the extreme frontal events. The main region at risk of extreme rainfall is shaded. The direction of the main warm and moist airflow is shown by the broad arrow.*

(b) Forcing was either from insolation or a meso-scale feature such as a convergence line or sea breeze with smaller values of CAPE.

Identification of cases where frontal forcing was dominant was straightforward and was achieved by looking at sequences of plotted surface observations on synoptic weather maps and reading published accounts. Assessment of CAPE was either very laborious or impossible, with limited or no upper air information. Therefore, in most cases, accounts and observations of large hail were used as a proxy. Hail was reported in many cases, as would be expected in extreme convective events, but special mention tended to be made in publications when the hail was large enough to damage crops, greenhouses and other property. These cases were put into category (a). However, in a few cases, available data and information were insufficient in order to determine the cause of the convective event. These cases were put into category (b). The categorisation of convective events is shown in Table 5. Events that contained large hail and events that did not are plotted in Figure 13. This analysis shows a tight group of cases with large hail with durations in the range of 2–3 hours. The non-hail cases in that range are all type (a) cases: 11 June 1956, 7 Oct. 1960, 14 Aug. 1975 (multicell) and 19 May 1989 (multicell). There are two outlier large hail events – 11 July 1959 and 19 Aug. 1924.

Figure 13 is very encouraging as it implies that, if we can identify storms that are likely to have large and damaging hail, then we will have some idea of the possible nature of the storm in terms of rainfall duration and amount. Moreover, if storms that have strong frontal forcing or large amounts of CAPE are included, then there is a good separation on the diagram.

Unlike the frontal and orographic cases it was not possible to identify common synoptic causes. Each case was different in some aspect of detail and an extreme event would not necessarily occur given a similar-looking synoptic pattern on another occasion. However, looking in broad terms it was found that out of the 30 convective events, 16 were 'weakly forced' – i.e. there was no discernible triggering mechanism on the synoptic scale. Potential instability could be released by meso-scale features such as troughs, convergence lines, sea breezes, temperature hot-spots, local orography, etc. It was also encouraging that only 33% of type (a) cases were weakly forced (those that were, produced multicells or large hail) whereas 73% of type (b) cases were weakly forced.

Table 5. *Categorisation of convective events into type (a) and (b). (See text for details.) An indication of the likely cause of the event and other evidence is shown.*

Type (a) events	Evidence/cause
09/06/10	Large clusters of rainfall. Large hail.
16/06/17	Strong vertical wind shear. Large hail.
19/08/24	Trough/cold front? Substantial fall of hail.
11/07/32	Sea breeze convergence? Large hail.
25/06/35	Occlusion. Wind shear (horizontal and vertical). Large hail.
04/08/38	Occlusion. Wind shear (vertical). Large hail.
11/06/56	Slow moving frontal zone.
08/06/57	'Unusually heavy hail'
05/09/58	Large CAPE. 'Tennis ball'-sized hail. Tornado.
11/07/59	Trough/small low. Large hail.
07/10/60	General thundery rain.
06/06/63	Thundery rain. Large hail.
14/08/75	Local insolation. Multicell. Large CAPE.
25/06/80	Trough? Prolonged fall of hail.
19/05/89	Old front in region. Multicell.
Type (b) events	
12/07/00	Convergence? Possible multicell?
12/07/01	Convergence?
29/05/20	Trough. Convergence lines.
26/09/33	General release of instability in a warm and damp easterly airflow.
22/07/34	Trough? Squall-like.
16/07/47	Upper part of split cold front?
26/06/53	Convergence. Unstable northerly flow.
05/08/57	Clusters of thunderstorms.
18/07/64	Convergence line. Low pressure over Wales.
08/08/67	Orography?
11/06/70	Insolation?
27/06/70	Convergence line. Front.
01/08/73	Sea breeze?
01/08/80	Upper trough.
05/08/81	Old fronts.

A good example of a weakly forced situation is provided by the Hampstead storm of 1975 for which the general synoptic situation is shown in Figure 14. The situation was fairly static with a stationary front over Wales

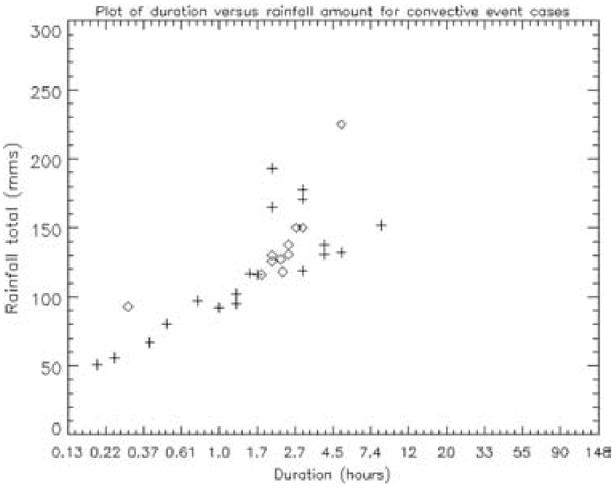

Figure 13. *Plot of rainfall amount (mm) versus duration (h) for the convective event cases. Crosses indicate events where there was no evidence of large hail, and diamonds indicate cases where large hail was reported.*

and SW England with very warm air to the east of it. Thunderstorms were thought to be triggered by a combination of the London heat island and the topographic effect of Hampstead Hill (Bailey et al. 1981). Once triggered, the storm maintained itself for 3 hours due to the development of new convective cells very close to previously active ones.

A surface chart for a case that was not weakly forced is shown in Figure 15. It was very clear that on this occasion the thunderstorms in the Torquay area were triggered by the cold occlusion which had lost most of its frontal precipitation, but still remained active as an airmass discontinuity with associated upward air motion.

All of the fronts in the convective cases where the primary triggering mechanism was frontal were of the cold type, i.e. either a cold front, cold occlusion or trough.

3.4. Combined analysis of all events

To bring together all the findings, a diagram (Figure 16) was constructed showing the four types of extreme rainfall event. The types of event in the diagram are

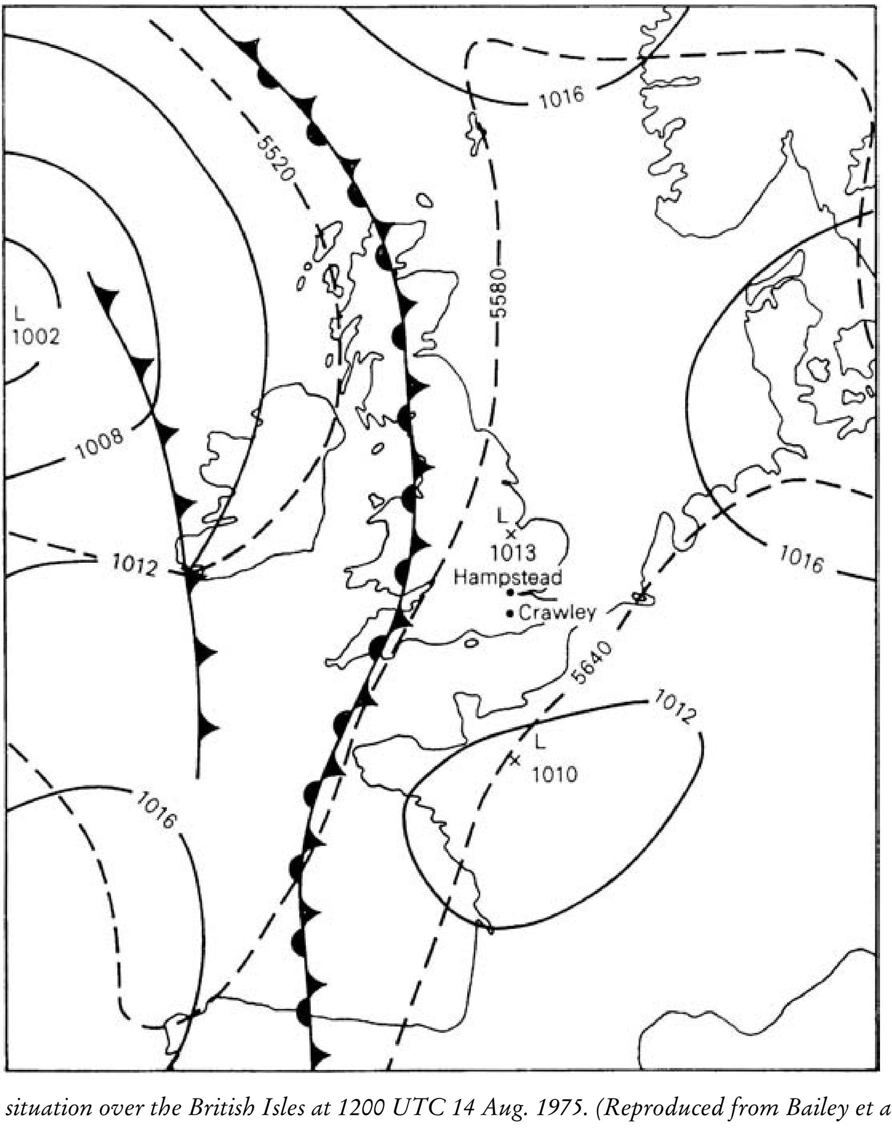

Figure 14. *Synoptic situation over the British Isles at 1200 UTC 14 Aug. 1975. (Reproduced from Bailey et al. 1981).*

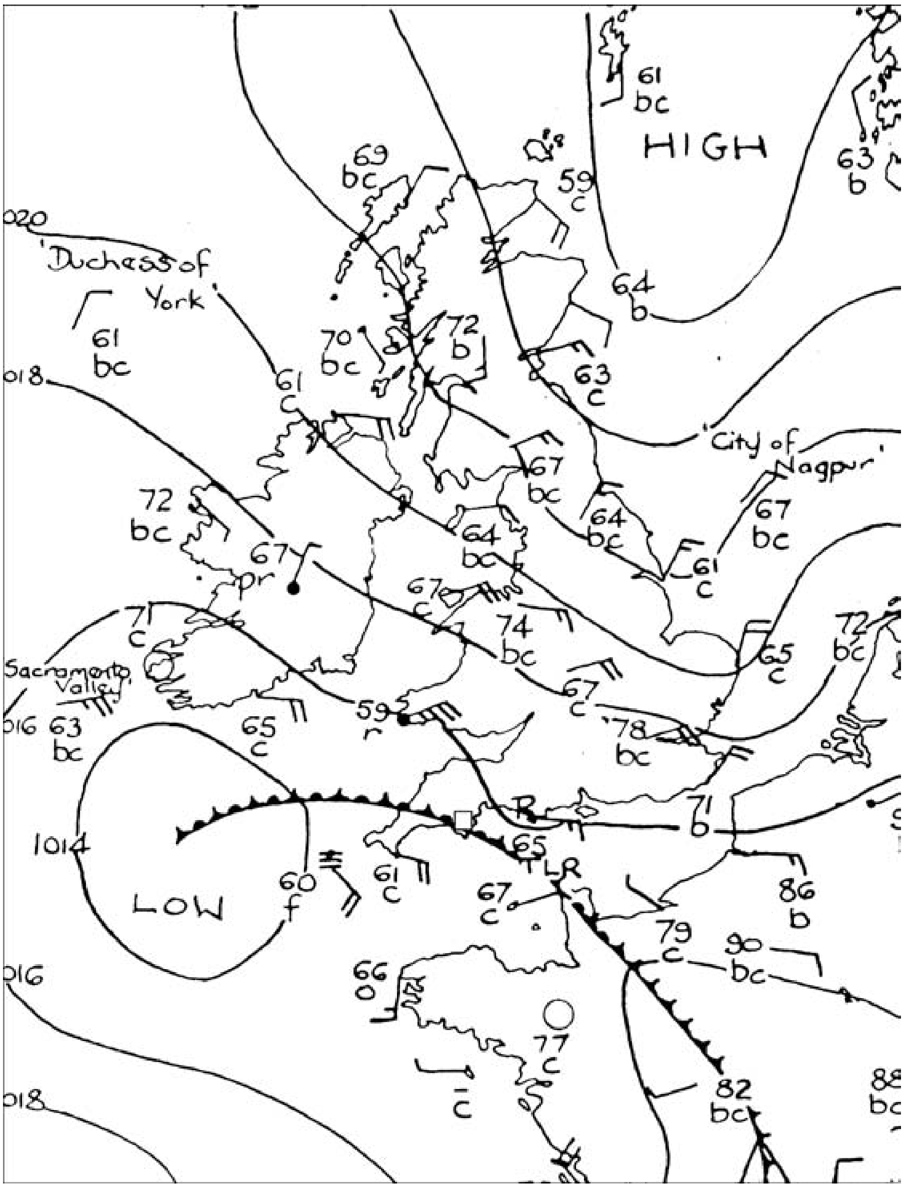

Figure 15. *Surface synoptic chart for 1300 UTC 4 Aug. 1938. (Reproduced from Douglas 1938.) The approximate centre of the rainfall event is marked with a □.*

as follows:

(a) Severe convective events that are triggered by synoptic-scale cold frontal forcing or have large hail. This class also includes isolated, near stationary rainfall clusters and large multicells in a strongly sheared environment.
(b) Convective events triggered by mesoscale features (e.g. convergence, sea breezes, troughs, upper cold pools, orography or local heating). These events may also have hail, but the hail should not be large and damaging or be very prolonged. Some multicellular organisation may also be possible but should not be too self-organizing or long lasting.
(c) Prolonged frontal or orographic events that have little or no convective element.
(d) Frontal (widespread rainfall) events that have a significant convective element (embedded instability).

There appears to be a clear differentiation in terms of the separation of rainfall depth and duration between the different types of event, and one type of event of a particular profile may not be of the same concern as another in the same location (Collier & Fox 2003). Therefore, not only is the possibility of extreme rainfall of importance, but also the character and return period of the depth-duration of that rainfall. Figure 16 provides the information that would be critical for a flood forecaster.

3.5. Upper air analysis of events

In the case of storms for which upper air data were available, a range of indices commonly used in the forecasting of severe weather were tested. These indices

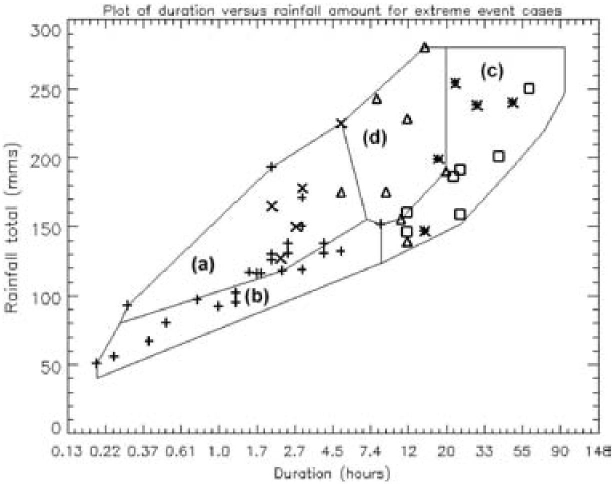

Figure 16. *Diagram showing different regions labelled (a), (b), (c) and (d), which correspond to different types of extreme rainfall event. See text for details. Individual events are marked with '+' = convective, '×' = convective*** (frontal forcing), * = orographic, △ = frontal*** (with embedded instability) and □ = frontal.*

are generally employed in the prediction of convective storms and, as the forcing for these events can vary, no distinction was made in the selection of indices to test between those aimed at different types of event. The indices examined are summarised in Table 6. They include the Boyden and Rackliff indices which have commonly been used in Britain as indicators of thunderstorm probability; they have been shown to be the most reliable for these types of event in NW Europe by Collier & Lilley (1994). Other indices used around the world were also tested. Table 7 shows the results for each index for each event studied.

Many of the events on the overall list occurred prior to the regular use of sondes and therefore have no upper air data. Later events often have only a limited data record due to the nature of the data collection at that time. Because of this, certain indices cannot be accurately calculated for some of the events. Despite these restrictions there are a number of conclusions that can be drawn. It is seen that there is no consistency in the values of the indices as a measure of extreme rainfall potential. The single exception to this is CAPE which in all cases shows moderate to high values. One reason for this is that the number of events with sounding data is simply too small for general trends to be observed. One could break the events into the categories used elsewhere in this paper, but that would simply lead to very small numbers in each section. Other reasons why

Table 6. *Definitions of severe weather indices.*

Index	Definition	Value indicating thunderstorms	Source
Rackliff	$\theta_{w900} - T_{500}$	≥ 30	Rackliff (1962)
K	$(T_{850} - T_{500}) + T_{d850} - (T_{700} - T_{d700})$	≥ 20	George (1960)
Boyden	$(Z_{1000\text{-}700} - T_{700}) - 200$	≥ 94	Boyden (1963)
Showalter	$T_{parcel} - T_{500(\text{from 850 mb})}$	< -2	Showalter (1953)
Lifted index (LI)	$T_{parcel} - T_{500\,\text{from surf}-25\,\text{mb}}$	< -2	Galway (1956)
Total totals	$TT = T_{850} + T_{d850} - 2T_{500}$	> 48	Miller (1967)
SWEAT (Severe weather threat index)	$SW = 12^*D + 20^*(TT - 49) + 2^*F850 + F500 + 125^*(S + 0.2)$	> 500	Miller et al. (1971)
CAPE (Convective available potential energy)	Energy of adiabatic ascent of free convection	≥ 1500	Bluestein (1993)
CIN (Convective inhibition)	Energy required to initiate convection	Variable	Bluestein (1993)
Wind shear	6 km shear (kt)	15 ms^{-1}	Bluestein (1993)
Precipitable water	Integrated column (mm)	Climatological norm *1.25	Peppler (1988)

Table 7. *Values of indices for case study events.*

Event	Date	Type	Sonde	Rackliff	K	Boyden	Showalter	LI	TT	SWEAT	CAPE	CIN	Shear	PW
Lynmouth	15/08/52	F***	Camborne	30	26	93		3	45	85		−591	37	26.4
			Larkhill	31	28	96		0	48	137	3050	−245	14	25.7
Martinstown	18/07/55	F***	Camborne	30.2	30	100		0	46	115	564	−249	6	34.0
Bradford	11/06/56	C***	Liverpool	25.5	22	95.2		−1	38	103	2533	−309	5	29.0
Camelford	08/06/57	C	Camborne	34.9	27	98.5		5	56	230	3083	−300	6	19.6
Hindolveston	11/07/59	C	Hemsby	31.2	16	94.1		−1	46	191		−602	6	22.6
Chew Stoke	10/07/68	F***	Camborne		25		4	3	45		88			27
Whitstable	15/09/68	F***	Crawley		20		2	1	50		125			22
Hampstead	14/08/75	C	Crawley		23		5	−1	44		814			26
Tarporley	05/08/81	C	Aughton		28		4	5	44					27
Halifax	19/05/89	C	Aughton		20		4	−4	47		959			19

the indices reveal little are:

- The events are caused by different convective forcing mechanisms and their potential will be indicated by a different measure of atmospheric instability in each case.
- The forcing mechanisms that produce extreme rainfall totals over small areas are themselves so localised that they cannot be represented by profiles from either sonde ascents or models. This is considered the most likely cause of the failures of the standard indices. For example, the Hampstead storm was located approximately 50 km from the sounding taken at Crawley, but the storm was believed to result in such extreme rainfall on account of the combination of urban heating and small-scale orographic features (Hampstead Hill). These are not represented in the sounding data.
- The timing of sonde ascents did not adequately sample the vertical structure of the atmosphere as it evolves over the course of the day.

3.6. Conclusions

This work has been conducted in such a fashion that the conclusions and recommendations have been driven by evidence from the case studies without any preconceptions. The aim of this work was not to describe a set of case studies but to draw together all the case-study evidence into something useful and applicable overall. However, the event references should be useful as a framework for future study and the development of training material for practitioners. The following conclusions are drawn:

- Extreme rainfall events are very unlikely to occur in February, March or April.
- Convective events are most likely in June, July and August and are very unlikely in November, December, January, February, March or April.
- An extreme rainfall event is highly likely to produce serious flooding situations, particularly if it occurs over a sensitive catchment or steep orography or when the ground is already very wet from previous rainfalls.
- All frontal cases involved prolonged ascent of very moist air with 80% of cases having a depression pass slowly within 200 km at closest approach to the south or east of the event.
- 80% of frontal cases also involved a slow-moving front, usually a warm occlusion, in the situation.
- Frontal cases with embedded instability (53%) generally produced larger totals for a given duration and were close to a depression centre.
- An archetypal situation that occurred in several frontal cases is shown in Figure 12.
- All orographic events occurred in December, January or February and were associated with a high pressure region over the Bay of Biscay or Spain, with a very strong west to southwest flow with a fetch greater than 2000 km persisting for 15 hours or more. The dewpoint of the air in the source region was estimated to be greater than 14 °C and the average geostrophic (600 m) wind along the fetch was greater than 15 ms^{-1}.
- Convective events were either weakly forced (potentially unstable) or associated with large synoptic features such as a cold front or occlusion. The presence of large hail was very useful for discriminating the more severe events.

All events can be categorised into four basic types, (five if orographic events are considered separately), which could form the basis of future work in devising methods for formulating early warnings of extreme rainfall, perhaps for periods of 24 hours or more ahead. The four basic types are:

(a) severe convective events that are triggered by synoptic scale cold frontal forcing or have large hail associated with high values of CAPE;
(b) convective events triggered by mesoscale features – these events may also have hail, but the hail should not be large and damaging or be very prolonged;
(c) prolonged frontal or orographically forced events that have little or no convective element; and
(d) frontal (widespread rainfall) events that have a significant convective element (embedded instability).

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