Cloudburst upon Hendraburnick Down:
The Boscastle storm of 16 August 2004

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On 16 August 2004 the coastal village of Boscastle in north Cornwall was devastated by flooding as a result of a series of torrential thunderstorms depositing over 200 mm of rainfall within four hours into the small rocky catchment. This article describes the meteorological circumstances of this exceptional storm, in particular the rainfall observations made in the locality during and immediately after the event, and compares it to other intense rainstorms observed in the British Isles.

The Boscastle storm

In an unstable cyclonic situation, heavy, thundery showers developed in parts of south-west England by late morning on 16 August 2004. The synoptic situation at 1200 UTC is shown in Fig. 1; the upper-air ascent made at 1200 UTC from Camborne, Cornwall – about 70 km south-west/upwind of Boscastle - is shown in Golding (this issue, Fig. 2, page 231). In west and north Cornwall convergence effects between onshore winds and local topography resulted in the repeated development of intense storm cells over high ground just inland from the coast of north Cornwall between Padstow and Bude (see Fig. 2 for locations referred to in the text). The repeated generation and propagation of these cells in much the same area over several hours during the afternoon resulted in enormous quantities of rain falling in a narrow strip parallel to and a few kilometres inland from the coastline. The area of heaviest rainfall lay close to the headwaters of several coastal streams, which rose very rapidly during the afternoon resulting in the destruction of bridges and property particularly in the coastal settlements of Boscastle and Crackington Haven. Less severe flood damage was reported across north-west Cornwall and into north Devon.

In Boscastle itself, over 70 properties were flooded and several destroyed (at least one of which was over 400 years old) while 70–80 cars were swept through the village by the force of the flood, damaging bridges and property during their passage. Many of these cars were subsequently washed out to sea. All the boats in the harbour were destroyed. Several bridges were severely damaged or destroyed and in places road surfaces were scoured completely away. The immediate danger to local residents and tourists alike was sufficiently serious that about 130 adults and children had to be rescued (winched from roofs and trees) by seven coastguard and Royal Navy helicopters. Local lifeboats were scrambled when it was feared that people had been trapped in cars and washed out to sea. It is clear that without the prompt response of the coastguard, local emergency services and the military, many lives might have been lost and it is indeed fortunate that no-one was killed in this major rainstorm in a popular tourist area at the peak of the holiday season. More details and photographs of the storm damage in and around Boscastle are given in Doe (2004) and eyewitness accounts given in a Radio 4 documentary broadcast exactly four months later (Kirby 2004).

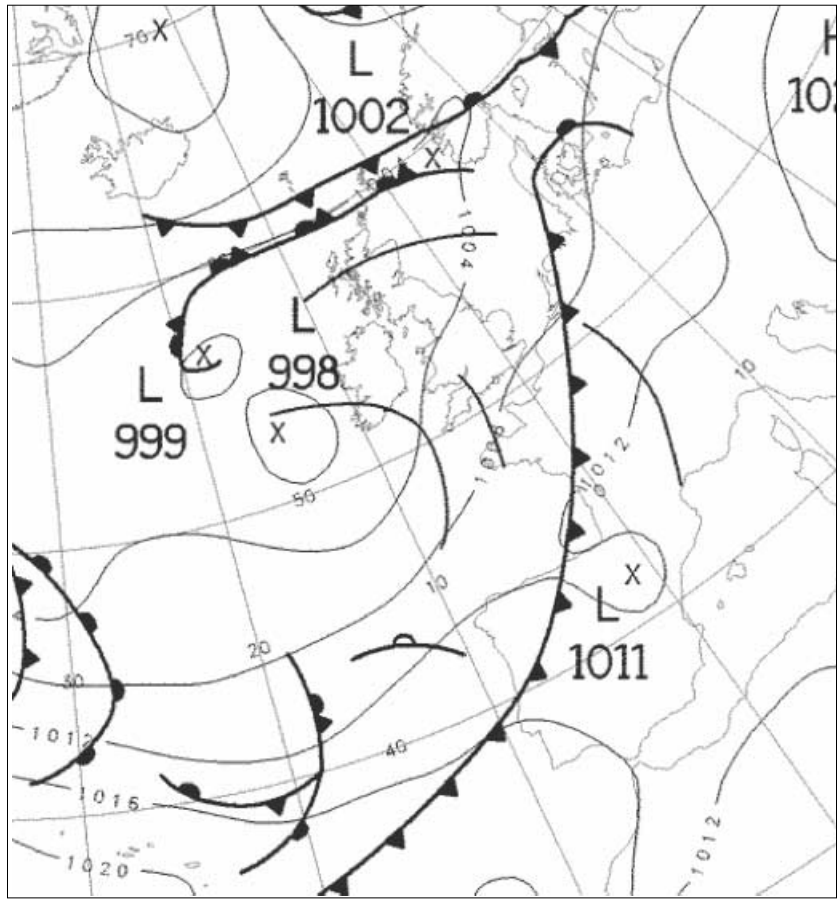

Fig. 1 Synoptic situation at 1200 UTC on 16 August 2004. UK Met Office analysis – Crown Copyright.

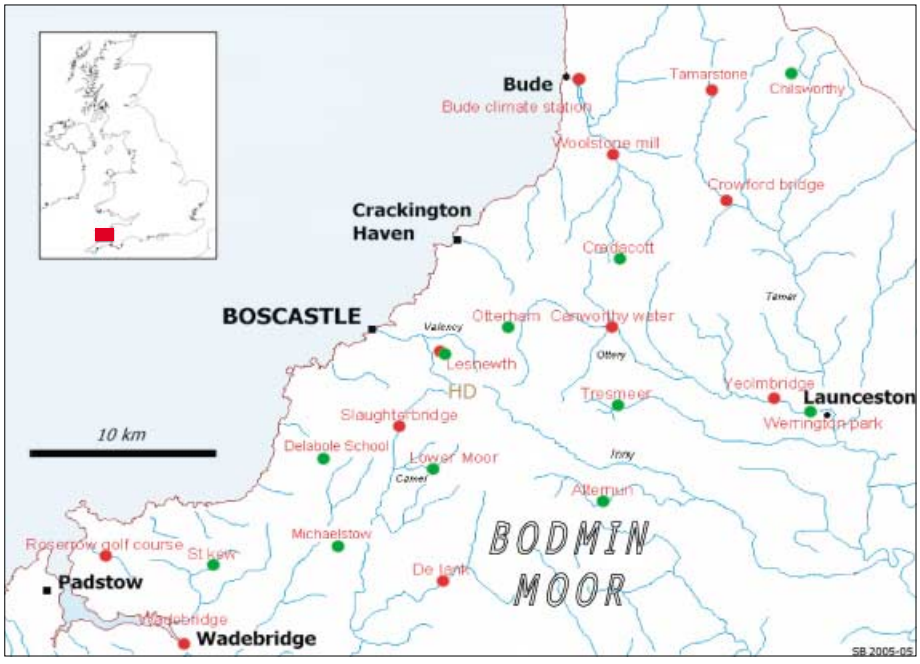

Fig. 2 Locations of places referred to in the text; inset shows location of detailed map. Standard daily-read raingauges are shown by green circles, recording gauges by red circles. HD marks the location of Hendraburnick Down. Base map courtesy of Environment Agency.

Rainfall records

Rainfall observations are available for this date from 21 locations in the area shown by Fig. 2. Eleven of these are recording gauges, the majority being telemetered tipping bucket raingauges (TBR) operated by the Environment Agency, providing 0.2 mm or 0.5 mm rainfall resolution at fixed 15 minute telemetering intervals. At the time of writing none of the raingauge data presented in this paper had yet been subjected to Met Office Quality Control procedures.

At five sites, the rainfall for the rainday 16 August 2004 (i.e. the 24 hours commencing at 0900 UTC on 16 August) exceeded 75 mm, the highest daily fall being at Otterham (National Grid Reference (NGR) SX 169 916), about 7 km east of Boscastle, where 200.4 mm was recorded. The highest fall at a site with an autographic rainfall record was at Lesnewth (NGR SX 131 902), about 4 km west-south-west of Otterham, where 184.9 mm was recorded in a standard raingauge and 155.2 mm in the adjacent logged tipping-bucket gauge.

Figure 3 shows the approximate distribution of rainfall for the rainfall day of 16 August 2004. This is based upon the 21 daily raingauge totals (including 'as read' totals from the tipping-bucket gauges where no checkgauge value was available, although these are likely to be significantly lower than the true precipitation particularly in areas affected by intense rainfall), together with the composite 2 km × 2 km Cobbacombe Cross radar rainfall accumulations for the period 1100–1800 UTC shown in Fig. 4. Although the radar-derived totals are low by a factor of about 2 in the central area of the storm*, the radar rainfall evidence suggests that the highest totals were probably recorded over or close to the moorland of Hendraburnick Down (rising to a little over 300 m above mean sea level) about 3 km south-west of Otterham; the fall in this area probably exceeded 250 mm and may have surpassed 300 mm over perhaps 1 km^2. Just as remarkable as the very large rainfall totals are the exceptional gradients on the south and east flanks of the storm system. At Lower Moor on the outskirts of Camelford – and only 5.5 km south-south-west of Hendraburnick Down – just 2.0 mm fell during the day (a rainfall gradient of almost 50 mm/km), while just 6 km east of Otterham only 15.0 mm fell at Canworthy Water (a gradient of over 30 mm/km). There are no raingauges in Boscastle itself, but radar rainfall evidence would suggest that perhaps only 30–50 mm fell there.

Figure 5 shows 15 minute totals from eight recording raingauges across north Cornwall on 16 August 2004. Totals from these and other gauges shown in Fig. 2 are given in Table 1. Based upon both radar and raingauge evidence, the main sequence of events appears to have been as follows:

- The first shower cell originated to the south-west of Padstow about 1115 UTC, giving a short burst of intense rainfall at Roserrow shortly before 1130 UTC: 1.4 mm fell in 2 minutes (42 mm/hr). As the cell developed and moved north-east on the mid-level winds (see the Camborne ascent in Golding, this issue, Fig. 2, page 231), it produced 5.5 mm in the 30 minutes commencing 1200 UTC at Slaughterbridge and 18 mm in 30 minutes commencing 1215 UTC at Lesnewth.
- A second major cell formed on its south flank in the Delabole/Camelford area at about 1215 UTC. This cell was responsible for the majority of the observed rainfall

* The Boscastle area is on the edge of the radar coverage – Otterham is 70 km west-south-west of the Cobbacombe Cross radar. At this distance the radar beam (at 0.5° elevation) is approximately 800 m above mean sea level.

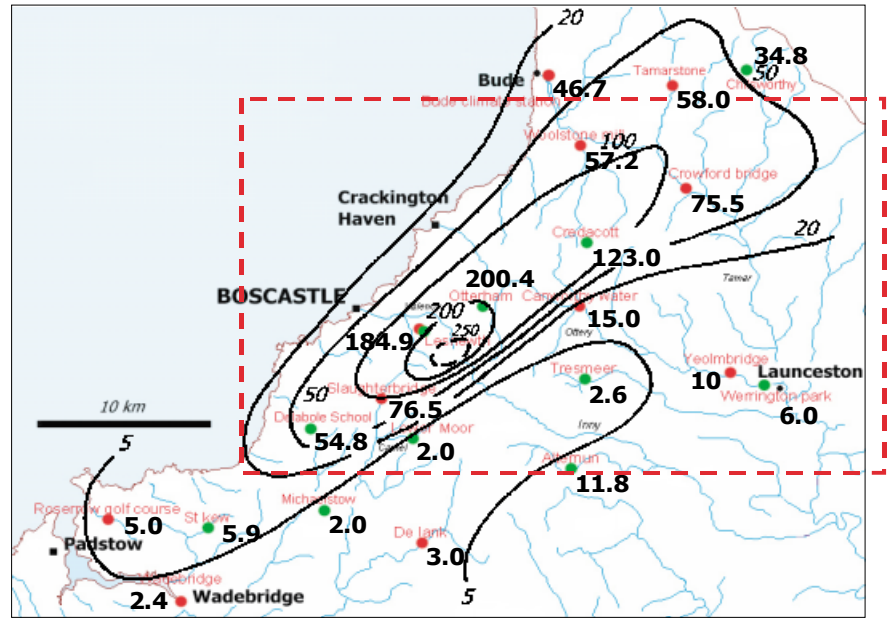

Fig. 3 Approximate distribution of rainfall for the rainfall day of 16 August 2004. Units are millimetres: isohyets are at 5, 20, 50, 100 and 200 mm. The approximate area covered by the radar rainfall accumulation map (Fig. 4) is shown by the dashed rectangle.

Table 1

Rainfall data from recording gauges in north-west Cornwall on 16 August 2004
All times are in UTC and are taken directly from original records

		TBR details				Total rainfall (mm)		Wettest hour		Wettest 15 min		
Site	NGR	Capacity	Resolution	Source	Adjusted*	09-09h	12-18h	mm	Commencing	mm	mm/hr	Commencing
Wadebridge	SW 988 727	0.2 mm	15 min	Telemetered	No	2.4	nil	0.4	1815	0.4	2	2300
Roserrow Golf Course	SW 945 780	0.2 mm	10 sec	Logged	No	5.0	0.8	2.6	1804	2.4	10	1804
De Lank	SX 132 765	0.2 mm	15 min	Telemetered	No	3.0	1.6	1.8	1745	1.4	6	1745
Slaughterbridge	SX 109 857	0.5 mm	15 min	Telemetered	No	76.5	74.5	46.0	1300	21.5	86	1300
Lesnewth, Trevalec	SX 131 902	0.2 mm	10 sec	Logged	Yes	184.9	183.2	85.7	1450	32.6	130	1530
Canworthy Water	SX 227 916	0.5 mm	15 min	Telemetered	No	15.0	14.5	12.5	1330	9.5	38	1330
Yeolmbridge	SX 317 873	1 mm	15 min	Telemetered	No	10	nil	7	1830	5	20	1845
Crowford Bridge	SX 290 991	0.5 mm	15 min	Telemetered	No	75.5	74.5	34.0	1300	22.0	88	1315
Woolstone Mill	SS 227 018	0.2 mm	15 min	Telemetered	No	57.2	57.0	39.6	1545	14.0	56	1615
Tamarstone	SS 282 056	0.5 mm	15 min	Telemetered	No	58.0	57.0	34.5	1600	20.0	80	1630

* Adjusted to adjacent checkgauge total where available.

Data courtesy of Environment Agency

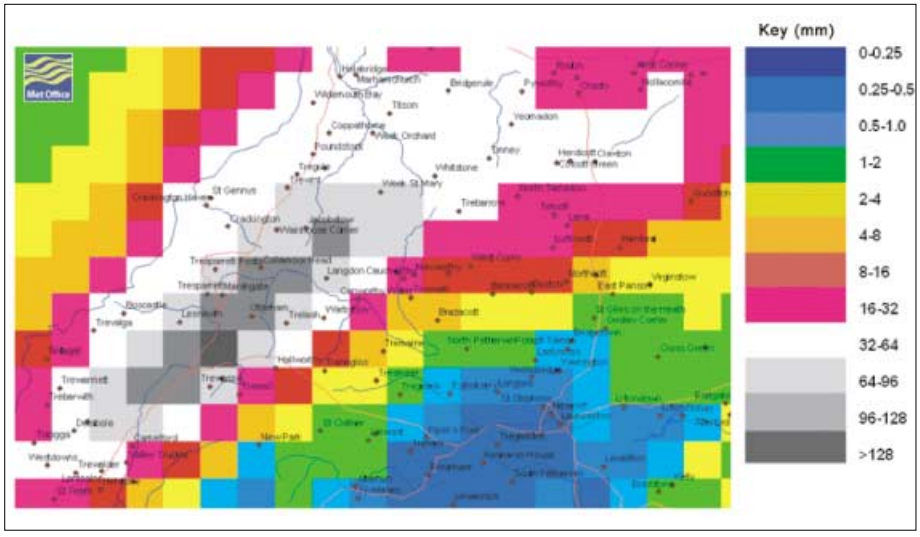

Fig. 4 Composite 2 km × 2 km radar rainfall accumulations for the period 1100–1800 UTC. The area covered by the plot is shown in Fig. 3. Courtesy Met Office – © Crown Copyright

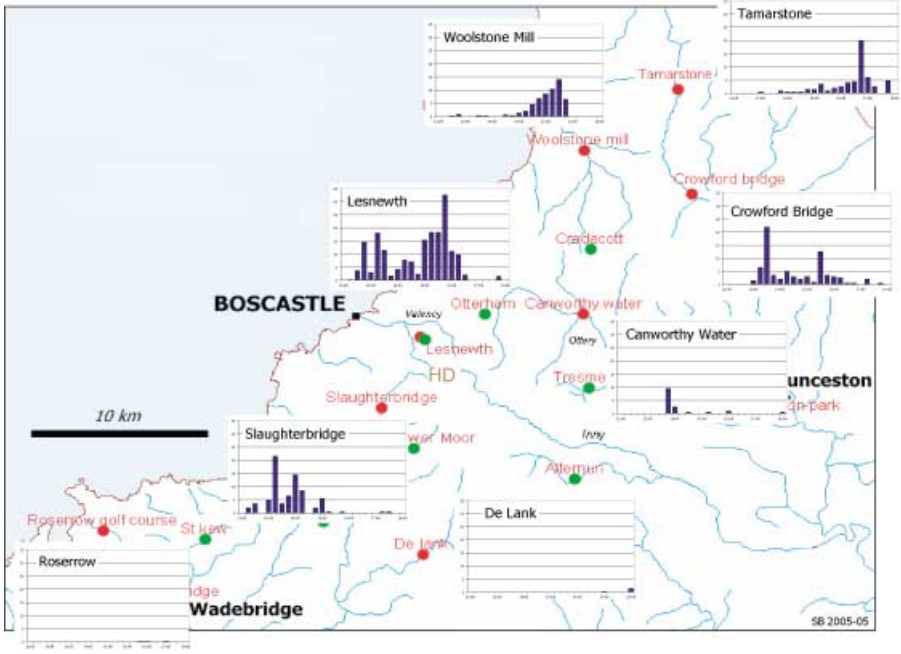

Fig. 5 Rainfall totals over 15 minute periods from eight recording raingauges in north-west Cornwall on 16 August 2004, period 1200 to 1800 UTC. The axes are the same for all plots – 0–35 mm (line rules every 5 mm) on value axis, 1200 to 1800 UTC on time axis.

at Slaughterbridge: here 80% of the afternoon's rainfall (59.5 mm of the 1200–1800 UTC total of 74.5 mm) fell between 1245 and 1415 UTC, including 21.5 mm in the 15 minutes commencing 1300 UTC (86 mm/h). From about 1300 a series of extremely narrow convective cells (approximately 10 km wide) developed close to Delabole, just 5 km or so inland from the Atlantic coast. A line of similar narrow, intense storms extended quickly north-east in an almost unbroken chain of echoes across north Devon, the Bristol Channel and into South Wales (see hourly rainfall radar images, Fig. 6).

- At Lesnewth the commencement of this highly organised, narrow linear convective storm regime was marked by a prolonged spell of intense rainfall (30 mm in 30 minutes commencing 1300 UTC) while the cells developing to the north-east produced intense rainfall at Crowford Bridge (22 mm in 15 minutes commencing 1315 UTC, 88 mm/hr) and at Canworthy Water (9.5 mm in 15 minutes commencing 1330 UTC, two-thirds of the afternoon's rainfall at this site).
- Another very intense storm cell developed about 1430 UTC, again in the Delabole area. The storm grew in intensity very rapidly as it moved north-east, such that Slaughterbridge received only 8 mm in the 45 minutes commencing 1430 UTC from this cell whereas at Lesnewth, only 5 km away, about 96 mm fell in 75 minutes commencing 1445 UTC. A further developing storm cell intensified the rainfall at Lesnewth around 1530 UTC (see below).
- At about 1615 UTC the character of the storm system changed, from a line of very intense, narrow cells to a much wider, less intense decaying multi-cell storm system (compare the images for 1500, 1600 and 1700 UTC in Fig. 6). A large area of intense rainfall affected the Bude area and eastwards into north Devon from 1530–1600 UTC onwards,

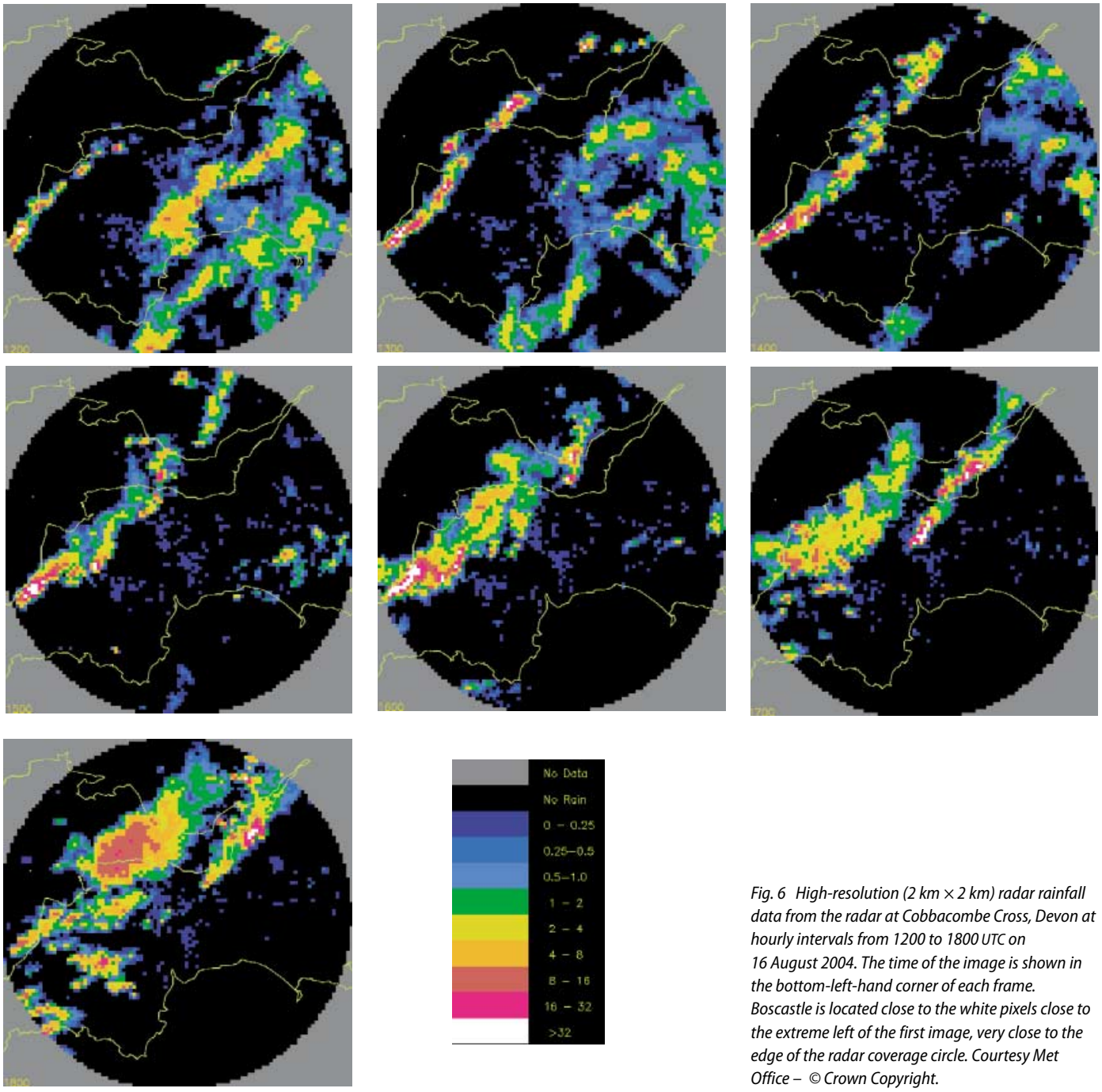

Fig. 6 High-resolution (2 km × 2 km) radar rainfall data from the radar at Cobbacombe Cross, Devon at hourly intervals from 1200 to 1800 UTC on 16 August 2004. The time of the image is shown in the bottom-left-hand corner of each frame. Boscastle is located close to the white pixels close to the extreme left of the first image, very close to the edge of the radar coverage circle. Courtesy Met Office – © Crown Copyright.

eventually extending to cover the western Bristol Channel and reaching South Wales. At Woolstone Mill, south-east of Bude, 39.6 mm fell in the hour commencing 1545 UTC while at Tamarstone, east of Bude, 20 mm fell in 15 minutes from 1630 UTC. By this time, heavy rainfall had ceased in the Boscastle area and although further showers continued during the evening and overnight, they were much less intense in nature. At the same time, another very narrow band of intense storm cells developed quickly a little north-east of Okehampton (about 50–60 km eastwards of the 'Boscastle storms cell line' a couple of hours earlier, and with an origin close to the Cobbacombe Cross radar site), generating a line of showers and thunderstorms stretching as far as the upper Severn estuary. This system persisted for about 2½ hours, a little more than half as long as the Boscastle event, but as these cells did not develop repeatedly above a single area, point rainfall totals were not exceptional although intensities probably reached 100–150 mm/hr at times.

The extraordinary rainfall distribution shown in Fig. 3 thus resulted mainly from the repeated generation of storm cells a little to the south of Boscastle followed by a longer declining tail of very heavy rainfall for many kilometres north-east. Throughout the afternoon sequence of radar rainfall images it is striking how very narrow the band of intense rainfall was, and how for 3–4 hours the trigger point for individual cells remained anchored in the Delabole area. Significant flooding occurred on all the major rivers in the locality, particularly the Valency in Boscastle. That the flooding southwards on the Camel through Camelford and Wadebridge was not worse can be attributed to the heaviest of the rain after about 1430 UTC affecting only the top-most headwaters. In fact, the heaviest of the rainfall fell upon the watershed separating the Valency, Ottery, Inny and Camel rivers and this fortuitously dispersed the enormous volume of runoff across several catchments. Had the storm been centred more squarely within one of the smaller catchments the effects would have been truly catastrophic. Downstream flooding on the Ottery and Inny (and eventually the

Tamar) was mostly minor, although the rapid rise in river levels during the evening was remarked upon as a 'wall of water' in places.

The Lesnewth rainfall record

The tipping-bucket gauge at Lesnewth was close to the centre of the highest rainfall area and fortunately remained in working order throughout the storm. The total fall from the 0.2 mm resolution tipping-bucket gauge over the rainfall day was 155.2 mm, a shortfall of almost 19% from the adjacent daily 'checkgauge' value of 184.9 mm. Of this 155.2 mm, 152.0 mm (98% of the 0900–0900 total) fell between 1215 and 1619 UTC – just over 4 hours.

Totals from this gauge at 15 minute resolution are shown in Fig. 5. Fortunately, the records from this gauge are available from the original logger records at a much finer temporal resolution (10 seconds) and using the original tip-time data and applying a correction to the observed totals to agree with the checkgauge total, we can examine the fine structure of the rainfall event at this location close to the centre of the storm in greater detail (Fig. 7). This is the highest resolution record yet obtained of any major rainfall event in the British Isles.

Recording raingauges normally read slightly lower than standard raingauges for a variety of reasons, and it is therefore standard practice wherever possible to adjust tabulated records from the recording gauge to agree with the manual measurement from a co-located standard raingauge (the 'checkgauge') where both records are available (Met Office 1981). It should be noted, however, that not all of the tipping-bucket raingauge records considered here have adjacent checkgauges and thus this correction cannot be undertaken for every site (see Table 1).

During periods of intense rainfall, a tipping-bucket gauge can under-read significantly compared to a standard raingauge owing both to losses in the tipping process and to a process of 'continuous tipping', whereby the inflow of water from the raingauge funnel is so large that the smooth mechanical operation of the mechanism slows down or even ceases*. At a rainfall rate of 500 mm/hr, for example, it takes only 1.4 seconds to fill a 0.2 mm capacity tipping bucket. An increasing proportion of the incoming rainfall will be lost as the rainfall intensity increases, and above about 50–100 mm/hr the loss of record becomes increasingly significant. It is therefore likely that more of the shortfall between the tipping-bucket gauge and the checkgauge occurred at the higher intensities at the peak of the storm, than at lower intensities. Applying a heuristic correction to the amount of every tip on the original record in linear proportion to the observed rainfall intensity such that the 24 hour rainfall total from the tipping-bucket gauge equals the total rainfall over the same period measured in the checkgauge, we can construct Fig. 7 which shows the rainfall intensity (in millimetres per hour) at Lesnewth over 5 minute periods from 1215 to 1630 UTC, comprising the main storm period. There was a break of a little over an hour in the rainfall after 1620, followed by further, much lighter, showers during the evening and overnight.

* Hailfall can also lead to considerable uncertainty in short-period estimates of precipitation intensity owing both to loss of hailstones (bouncing out of the collecting funnel) and to the build-up and subsequent slower release of a mass of frozen precipitation, but on the basis of eyewitness accounts of the Boscastle storm hail does not appear to have contributed significantly to observed precipitation amounts, if at all.

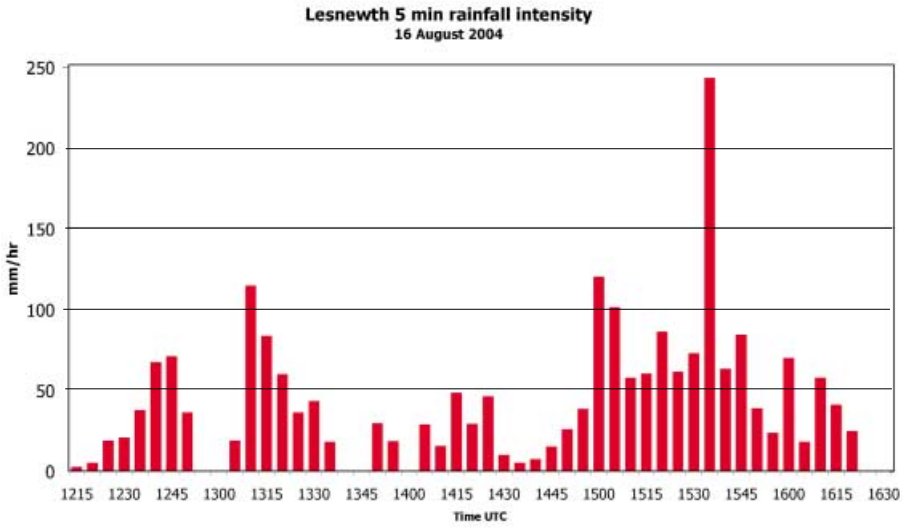

Fig. 7 Rainfall intensity (in millimetres per hour) at Lesnewth, Cornwall over 5 minute periods from 1215 to 1630 UTC on 16 August 2004

From Fig. 7 we can see there were four main periods of heavy rainfall observed at Lesnewth:

- The first, commencing about 1220 UTC, lasted about 30 minutes with a peak 5 minute rainfall rate of close to 75 mm/h; about 21 mm fell in this spell;
- The second spell commenced at 1303 UTC and built very rapidly in intensity to almost 120 mm/h in the 5 minutes ended 1310, attaining a peak intensity of 156 mm/h over 2 minutes from 1306 UTC; for a period of 10 seconds at 1307 UTC the rainfall intensity probably exceeded 400 mm/h. By the time the rain stopped briefly at 1335 UTC, a further 31 mm had fallen;
- The third spell lasted from 1350 to 1440 UTC and was less intense than the first two spells, reaching a peak 5 minute intensity just under 50 mm/h at 1415 UTC. This third spell added 19 mm to the day's total, such that by 1440 UTC, 72 mm had already been recorded; and
- The fourth and final spell was the longest and heaviest spell of rain recorded at Lesnewth during this event. Commencing about 1440 UTC, the rain built quickly to an intensity of 120 mm/hr in the 5 minutes ended 1500 UTC, then decreased somewhat in rate ('eased off' seems hardly the correct term to use here) to a sustained 60–70 mm/h before a single, short and remarkable peak just after 1530 UTC. In the 5 minutes ended 1535 UTC about 20.3 mm fell, an average rainfall intensity of just over 240 mm/hr. Over a 20 second period within this 5 minute spell, the rainfall rate approached and possibly exceeded 500 mm/hr at 1534 UTC. After this burst of very intense rainfall, rates declined to 40–80 mm/h and the storm tailed off, the last rainfall tip being recorded at 1619 UTC. In the 90 minutes from 1440 UTC, approximately 109 mm fell at Lesnewth.

Inferences on peak depth-duration storm data

Table 2 shows the depth-duration data for the Lesnewth record, corrected as described above. These are much higher than the peak rainfall rates of around 50 mm/hr quoted in other accounts of the Boscastle Storm (e.g. Doe 2004).

It is clear from the observed distribution that storm rainfall varied hugely both spatially and temporally, and it is therefore unsafe to attempt to draw detailed conclusions with regard to the depth-duration profile at any other site. However, in Table 2 an attempt is made to *extrapolate* the depth-duration data based upon the Lesnewth record to Otterham, some 4 km

Table 2

Peak rainfall depth-duration measurements and estimates for the storm of 16 August 2004. The Lesnewth observations have been taken from the tipping-bucket record, adjusted to agree with the daily checkgauge value as described in the text. The Otterham and Hendraburnick Down values have been extrapolated/estimated respectively from the adjusted Lesnewth record.

Duration	Lesnewth SX 131 902	Otterham SX 169 916	Hendraburnick Down SX 1588
Daily rainfall 0900–0900 UTC	184.9 mm *Measured*	200.4 mm *Measured*	250 mm ± 20% *Estimated from radar rainfall accumulations*
4 hour rainfall	181.4 mm 1220–1619 UTC	Extrapolated 197 mm	Estimated 250 mm ± 20%
3 hour rainfall	148.4 mm 1300–1600 UTC	Extrapolated 160–170 mm	Estimated 220 mm ± 20 mm
2 hour rainfall	115.4 mm 1410–1610 UTC	Extrapolated 125–130 mm	Estimated 170 mm ± 15 mm
1 hour rainfall	85.7 mm 1450–1550 UTC	Extrapolated 95–100 mm	Estimated 125 mm ± 10 mm
15 minute rainfall	32.6 mm (130 mm/hr) 1530–1545 UTC	Extrapolated 35–40 mm (140-160 mm/hr)	Estimated 50 mm ±10% (~ 200 mm/hr)
5 minute rainfall	20.3 mm (240 mm/hr) 1530–1535 UTC	> 250 mm/hr	> 250 mm/hr
1 minute rainfall	6.3 mm at 1534 UTC (380 mm/hr)	> 500 mm/hr	> 500 mm/hr

distant, and (with considerably less certainty) to *estimate* the peak values close to the centre of the rainfall distribution shown in Fig. 3. It must be emphasised that the Hendraburnick Down figures are only reasoned estimates of the rainfall towards the centre of the storm: they are *not* direct measurements and are therefore not directly comparable with existing depth-duration extremes. **They should not be quoted without this important caveat.**

The Boscastle storm in context

Since reasonably widespread reliable rainfall records began in the British Isles about 140 years ago, rainfall totals exceeding 200 mm in 24 hours have been reliably recorded on only 11 previous occasions (see for example, Bleasdale 1963 and Reynolds 1978). The 200.4 mm measured at Otterham on 16 August 2004 was the first '200' in the British Isles for just over 30 years, and the first in England since 1957. A brief account of all such events known to the author is given below, in date order.* Of these 11 occasions, five were long-duration orographic falls, three were cyclonic rainfall events with little significant thundery activity, and the remaining three were intense convective rainstorms. In only two of these were the duration and intensity of the rainfall comparable to the Otterham value.

12 November 1897: 204 mm at Seathwaite, Cumbria

The publication of *British Rainfall* commenced in 1860, but it was not until 1897 that the first reliable record of 200 mm in a day was obtained. On 12 November 1897, in a long-duration orographic fall, 204.0 mm was recorded at Seathwaite in the Lake District (*British Rainfall* 1897). This was noted as some 15 mm above the previous daily highest fall on a record at the site back to 1844. An estimate of 295 mm in 24 hours was made for one of the monthly gauge sites on The Stye (now known as Sty Head) at the head of Borrowdale.

25-26 August 1912: 205 mm at Brundall, Norwich

In one of the most notable British rainstorms of the twentieth century, a long-duration cyclonic rainfall event brought more than 100 mm in about 24 hours to many areas in Norfolk and Suffolk (*British Rainfall* 1912). Near the centre of the storm 205.5 mm fell at Brundall, near Norwich, in about 22 hours (split across two rainfall days). Peak hourly amounts were estimated at 40 mm; there was very little thundery activity. In terms of the extent of the area affected by over 100 mm of rainfall (2800 km^2) the storm remains without precedent to this day.

11 October 1916: 208 mm at Kinlochquoich, western Scotland

Another long-duration orographic fall in western Scotland on 11 October 1916 led to a daily fall of 208.3 mm at Kinlochquoich in the notoriously wet Glen Garry (*British Rainfall* 1916, Douglas and Glasspoole 1947). More than 100 mm fell over some 1800 km^2 but less than 10 mm fell in parts of eastern and southern Scotland.

28 June 1917: 243 mm at Bruton, Somerset

A prolonged overnight cyclonic rainfall gave over 200 mm in two locations in Somerset (Mill and Salter 1917). At Bruton (Sexey's School) 242.8 mm was recorded (confirmed by the measurements at nearby King's School of 215.4 mm and at Pitcombe Vicarage of 200.7 mm), while a few kilometres away at Aisholt (Timberscombe) 213.1 mm fell. Some thunder occurred during the long night rain, but it does not appear to have been a prominent feature; the highest 2 hour falls were estimated at no more than 50–60 mm. In all, about 2100 km^2 received over 100 mm, 35 km^2 over 200 mm.

* All falls are listed to 0.1 mm for consistency with previously published accounts (for all falls prior to about 1970 this is a conversion from the original rainfall measurement in inches) although for the intense convective storms the accuracy of the measurement is likely to be at least two orders of magnitude less than is implied by this precision. Some of the falls are part-estimates, including (for example) the effects of hail bouncing out of the raingauge in one storm.

18 August 1924 : 239 mm at Cannington, Somerset

A series of very intense but remarkably localised overnight thunderstorms with hail gave a 'daily' fall of 238.8 mm at Cannington (Brymore House) on 18 August 1924 (Glasspoole 1925). From eyewitness accounts, it is believed that a little more than 200 mm fell in 5 hours 0130–0630 h. The band of intense rainfall was very narrow: only 35 km^2 received a fall of 100 mm, just 8 km^2 over 200 mm.

11 November 1929: 211 mm in Rhondda Valley, South Wales

Secondary depressions and a very moist, mild warm sector gave heavy orographic rainfall over wide areas of western England and Wales on 11 November 1929, the highest daily fall being 211.1 mm at Lluest Wen Reservoir in the upper Rhondda Valley (*British Rainfall* 1929). All of this fell in about 18 hours steady rainfall which rarely exceeded 15 mm/hr. This remains the highest daily rainfall total yet measured in Wales (Woodley 1982). In the Rhondda Valley, more than 100 mm fell over approximately 55 km^2, and 200 mm over just 5 km^2.

15 August 1952: 229 mm at Longstone Barrow in north Devon – the 'Lynmouth Storm'

The famous 'Lynmouth Storm' of 15 August 1952 resulted in 34 flood-related fatalities in the north Devon villages of Lynton and Lynmouth (Delderfield 1953). Over the heights of Exmoor, a gauge at Longstone Barrow recorded 228.6 mm in the rainfall day (*British Rainfall* 1952, Bleasdale and Douglas 1952); of this, approximately 135 mm is believed to have fallen in 5 hours of intense thundery rainfall. Up to 275 mm was estimated to have fallen near the centre of this storm. More than 100 mm fell over approximately 400 km^2, and 200 mm over 45 km^2. Exmoor lies approximately 70 km north-east of the centre of the August 2004 storm *.

17–18 December 1954: 256 mm at Loch Quoich, western Scotland

A prolonged orographic fall brought 256.5 mm in 22½ hours at Loch Quoich (Cruadhach) on 17–18 December 1954. Had the fall not been split across two rainfall days (153 mm was recorded on 17 December and 110 mm on 18 December) this event would have ranked as the largest daily total on record to that time (*British Rainfall* 1954, p. 46).

18 July 1955: 279 mm at Martinstown, Dorset

During a prolonged cyclonic rainfall event, Martinstown in Dorset (about 5 km south-west of Dorchester) recorded a daily fall of 279.4 mm. This remains the highest 24 hour total yet reliably measured in the British Isles. The fall was confirmed by daily totals of 241.3 mm at Upwey (Friar Waddon), 228.6 mm at Upwey (Higher Well), 211.1 mm at Upwey (Elmwell) and 200.7 mm at Wynford House (*British Rainfall* 1955, pp. 46–48). At Martinstown, approximately 190 mm fell in about 4½ hours commencing 1430 GMT, with a peak hourly fall of perhaps 50 mm. There was some thundery activity during the storm, but this was not a significant feature of the event. In all, about 825 km^2 received more than 100 mm and 125 km^2 over 200 mm.

8 June 1957: 203 mm at Camelford, Cornwall

On 8 June 1957 a daily fall of 180.1 mm was recorded at Camelford in Cornwall, less than 10 km from the centre of the 16 August 2004 rainfall event. Of this total, 138 mm fell in 2½ hr 1230–1500 GMT; approximately 100 mm fell in the first hour (Bleasdale 1957). The daily total was judged to be low owing to a considerable amount of hail which fell during the storm being lost from the raingauge, and the true daily total was estimated at 203 mm. This remains the highest daily rainfall total on record for Cornwall. A careful site survey conducted shortly after the event led to the conclusion that at least 225 mm had fallen over an area approximately 4 km long by up to 1 km wide just east of Camelford. Severe flooding occurred on the Camel river, where four bridges were destroyed or badly damaged, and there is a photograph in *Meteorological Magazine* showing the enormous drifts of hail in Camelford itself. There was an intense rainfall gradient around this localised storm, amounting to over 100 mm in less than 2 km horizontal distance.

17 January 1974: 238 mm at Sloy, western Scotland

Another long-duration orographic rainfall event (approximately 24 hours) in western Scotland gave 238.4 mm at Sloy Main Adit in the upper headwaters of Loch Lomond during the 24 hours commencing 0900 UTC on 17 January 1974. This remains the highest daily rainfall total yet measured in Scotland (Woodley 1982).

16 August 2004: 200 mm at Otterham, Cornwall

The event described in this paper is thus the first 200 mm fall to be recorded in the British Isles for just over 30 years, and the first to be recorded in England for almost 50 years. More than 100 mm fell over about 83 km^2 in this storm, and 200 mm or more over perhaps 12 km^2.

Relevant short-duration intense rainfall events

After placing the 200 mm fall at Otterham in context as one of the highest 24 hour rainfalls yet observed within the British Isles, the next step was to assess the position of the event within previous short-duration rainfall events.

Although the falls in this storm up to 2 hour duration were remarkable, the hourly fall of 86 mm at Lesnewth has been exceeded on numerous previous occasions (the British Isles sub-hour records are summarised in Burt (2000) – 80 mm in 30 minutes at Eskdalemuir, Dumfries and Galloway on 26 June 1953 (Anon 1953); 97 mm in 45 minutes at Orra Beg, Co. Antrim on 1 August 1980 (Woodley 1981) and 110 mm in 58 minutes at Wheatley, Oxfordshire on 9 June 1910 (*British Rainfall* 1910)).

The most intense **2 hour** phase of the Boscastle Storm produced 115 mm rainfall at Lesnewth, probably 125–130 mm at Otterham, and an *estimated* 170 ± 15 mm towards the centre of the storm event. The latter figure is at least as high as the estimated maximum 2 hour rainfall to be expected in the area based upon the methodology used in the *Flood Studies Report* (NERC 1975 – Fig II 4.1). The maximum 'storm efficiency factor' as defined in the *Flood Studies Report* (*ibid*, Chapter 4) – viz. the ratio of rainfall to the amount of precipitable water in the representative air column during the storm – implied for this storm is between about 6 and 7 (155–185 mm rainfall compared with a precipitable water content of 26 mm from the 1200 UTC Camborne sounding): the 2 hour maximum rainfall projections in the *Flood Studies Report* were predicated on a maximum 'storm efficiency' factor of 3.86. This value is substantially exceeded by the observed Lesnewth value (4.46) and the extrapolated Otterham value (4.83) and implies that maximum 2 hour falls may have been considerably underestimated in the *Flood Studies Report*.

At least ten previous rainstorms within the British Isles have exceeded 115 mm in

* On 10 August 1959 more than 100 mm fell in very severe thunderstorms over Exmoor; the highest *observed* daily fall was 129 mm at Porlock, Nutscale Reservoir although there was some evidence that the fall elsewhere in Porlock may have reached 250 mm (*British Rainfall* 1959–60, pp. 77–79).

2 hours: the five most intense storms on record (where measurements based upon actual raingauge observations are available) are listed in Table 3*. All five storms were more intense than the estimated fall at Otterham, but it is likely that closer to the centre of the storm only the Calderdale storm of 19 May 1989 (193 mm in 2 hours at Walshaw Dean Reservoir) and the Hewenden Reservoir fall of 11 June 1956 (155 mm in 109 minutes) surpassed it in intensity†.

Over a **3 hour** period 148 mm fell at Lesnewth and probably 160–170 mm at Otterham. As much as 200 mm ± 10% may have fallen close to the centre of the storm event. At least five previous rainstorms within the British Isles are known to have reached or exceeded 165 mm in 3 hours: these are listed in Table 3. At the centre of the storm the fall may have exceeded the existing British Isles extreme value for this duration.

Over a **4 hour** period 181 mm fell at Lesnewth and probably 197 mm at Otterham. Close to the centre the fall has been estimated above as 250 mm ± 20% (i.e. possibly 300 mm). Almost all of this would have fallen in 4 hours. The observed Lesnewth value ranks as the fourth-highest 4 hour measured rainfall on record within the British Isles, exceeded only by the 2 hour Calderdale storm of 19 May 1989, the 18 August 1924 Cannington storm (just over 200 mm in 5 hours) and the 18 July 1955 Martinstown event (approximately 190 mm in about 4½ hours). The extrapolated 4 hour Otterham value of 197 mm has probably never been surpassed in the British Isles historical record.

How rare an event was this storm?

Media coverage of the 'Boscastle flood' tended to be sensationalised and carried little or no historical perspective. Contrary to media reports, serious flooding has occurred before at Boscastle: for instance, in late-October 1996 when ex-hurricane *Lili* delivered a combination of heavy rain and high tides which inundated the lower part of the village; in each of the Junes of 1963, 1958 and 1957 when sudden floods developed in circumstances similar to 16 August 2004; and in July 1847 when a much broader region was affected (Eden 2004). The short, steep valleys of north Cornwall and north Devon are particularly vulnerable to localised summer downpours. They collect water efficiently from the surrounding moors, channel it rapidly into swift-flowing streams which can rise and fall quickly, and take it all out to sea in a few hours. Because of their almost instantaneous response to a sudden cloudburst, these valleys are known as 'flashy catchments' and they produce true 'flash floods'. There have in all probability been many more major flash flood events in the village within the last few hundred years.

Twice within the past half-century or so and within 100 km distance there has been severe flooding as a result of violent convective storms, at Lynmouth in August 1952 and just a few kilometres away at Camelford in June 1957. Intense, damaging convective rainstorms are therefore a rare but hardly unknown feature of the local climate. It is impossible, and possibly meaningless, to

* Clark (2005) provides evidence for a very localised fall of approximately 200 mm in little more than an hour in the Cheviot Hills in northern England on 2 July 1893. This estimate is based largely upon streamflow evidence rather than raingauge observations and is therefore not included in the table.

† Both of these West Yorkshire records – the sites are only 10 km apart – have previously been subjected to considerable scrutiny. The Walshaw Dean value was not accepted at the time by the Met Office, although Collinge *et al.* (1990) suggested that "… the reading is likely to be in excess of the true value, as a consequence of insplash, though not by much": the Hewenden Reservoir value – with a storm efficiency of 5.3 – was deemed 'not acceptable' in the *Flood Studies Report* (NERC 1975, p. 33) although both events were listed in a recent Met Office study by Hand *et al.* (2004).

Table 3

The five largest rainstorms within the British Isles for 2 hour, 3 hour and 4 hour durations - approximately 1860 to date, excluding this event, and including only those storms for which documented raingauge observations exist. Figures in italic *indicate an estimated total for this duration from a longer-period fall. Based upon original sources together with Jackson (1974, 1979), updated by the author.*

Duration (hours)	Date	Location	Amount and duration	Reference(s)
2	19 May 1989	Walshaw Dean Reservoir near Halifax, West Yorkshire	193 mm	Acreman (1989), Collinge *et al.* (1990)
	11 June 1956	Hewenden Reservoir, West Yorkshire	155 mm *in 109 min*	*British Rainfall* 1956 pp. 30–31
	14 August 1975	Hampstead, north London	*140 mm*	Keers and Wescott (1976)
	6 June 1963	Southery, Norfolk	*132 mm*	Jackson (1979)
	5 September 1958	Knockholt, Kent	131 mm	Rowsell (1960), Ludlam and Macklin (1960)
3	19 May 1989	Walshaw Dean Reservoir near Halifax, West Yorkshire	193 mm *in 2 hr*	Acreman (1989)
	7 October 1960	Horncastle, Lincolnshire	*178 mm*	*British Rainfall* 1960, pp. 61–62
	14 August 1975	Hampstead, north London	169 mm in 2.6 hr 170 mm in 3 hr	Keers and Wescott (1976)
	18 July 1955	Martinstown, Dorset	*170 mm*	See 24 hour falls list
	18 August 1924	Cannington, Somerset	*165 mm*	See 24 hour falls list
4	19 May 1989	Walshaw Dean Reservoir near Halifax, West Yorkshire	193 mm *in 2 hr*	Acreman (1989)
	18 August 1924	Cannington, Somerset	*185 mm*	See 24 hour falls list
	18 July 1955	Martinstown, Dorset	*185 mm*	See 24 hour falls list
	7 October 1960	Horncastle, Lincolnshire	*180 mm*	*British Rainfall* 1960, pp. 61–62
	14 August 1975	Hampstead, north London	170 mm *in 3 hr*	Keers and Wescott (1976)

attempt to assign accurate return periods to the extreme events of 16 August 2004, but the preliminary report of the Environment Agency into the flooding in Boscastle (Environment Agency 2005) indicated that the heaviest hourly rainfall had a return period of approximately 400 years and the 3 hour fall approximately 1300 years. It should be noted, however, that the return period of the resultant flooding (also assessed as approximately 400 years) bears only a coincidental relation to the return periods of the rainfall which caused it.

Summary

The devastation by runoff flooding that occurred in Boscastle and Crackington Haven and, to a lesser extent, in other parts of Cornwall and Devon on 16 August 2004 was due to an exceptionally intense rainstorm, producing almost 200 mm of rainfall within 4 hours at the wettest gauged site and quite possibly 250 mm or more in the same period close to the centre of the storm. The storm that was centred upon Hendraburnick Down ranks as one of the most extreme British rainfall events on record, and the extrapolated fall of 197 mm at Otterham represents a new 4 hour British Isles rainfall extreme. Equally exceptional were the intense rainfall gradients on the south-east flanks of the storm, amounting to 50 mm/km or more.

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