METEOROLOGY OF THE BOSCASTLE FLOOD

Brian Golding,
Head of Forecasting Research,
Met Office, FitzRoy Road, Exeter,EX1 3PB, United Kingdom

INTRODUCTION

On the afternoon of 16th August 2002 the village of Boscastle on the north coast of Cornwall was severely damaged by flooding. A substantial number of people were helped to safety by emergency services, though thankfully and perhaps remarkably, given the severity and suddenness of the event, there was no loss of human life. This paper presents an analysis of the meteorological conditions leading to the event. Evidence will be presented on the soil conditions prior to the event, the meteorological conditions that generated the storms, the temporal and spatial characteristics of the rain and the small-scale mechanisms which focussed extreme conditions in the Boscastle area. The rarity of the event is then examined in the light of previous records.

CLIMATOLOGY OF RAINFALL IN NORTH-WEST CORNWALL

Rainfall in southwest England arises predominantly from Atlantic depressions in winter and from thunderstorms in summer. The moisture content of the air is an important factor determining rainfall, and the sea temperature, which reaches its maximum in late summer, largely controls this. The rainfall distribution is also enhanced where air is forced to ascend hills. Most coastal areas of Cornwall and Devon have annual rainfall totals of 900-1000 mm, but up to double this amount falls on the uplands of Dartmoor, Bodmin Moor and Exmoor. These figures can be compared to the driest parts of eastern England, which receive 500mm and over 4000 mm in the western Scottish mountains.

The southwest peninsula is prone to heavy summer thunderstorms. During the famous storm which devastated Lynmouth in north Devon on 15 August 1952, one place on Exmoor had 228 mm in 12 hours. Other extreme events have been the 203.2 mm in 24 hours at Camelford in Cornwall on 8 June 1957, 238.8mm in 24hrs at Cannington in Somerset in August 1924 and 242.8 mm in 13 hours at Bruton in Somerset in June 1917. The heaviest recorded daily rainfall total in the UK was at Martinstown in Dorset when 279.4 mm was recorded on 18 July 1955.

ANTECEDENT CONDITIONS

Following below average rain from March to June, July rainfall was generally above average in the region, though available observations indicate that the Boscastle area had about average rainfall, allowing the ground to remain dryer than normal.

Average August rainfall varies markedly across the north Cornwall region, with the driest areas in the vicinity of Padstow and Bude receiving less than half the rainfall observed on Bodmin moor. Boscastle is wetter than other parts of the coast, while the upper parts of the Valency catchment receive amounts approaching those of the open moor. The distribution of anomalies for the first half of August 2004 is shown in figure. 1, derived from all available daily rain gauges. Most of north Cornwall was wet during this period, with the Valency catchment receiving about 25% more than normal. There was considerable spatial variability, so the resulting pattern is constrained by the distribution of available rain gauges.

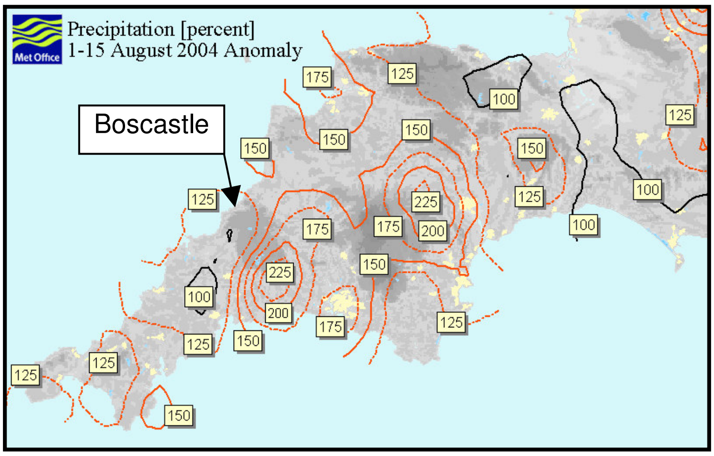

Figure 1 Precipitation anomaly map for southwest England, 1-15 August 2004, relative to 1961-90 averages.

The Met Office's MOSES-PDM land surface model (Met Office Surface Exchange Scheme incorporating the Probability Distributed Model) diagnoses the evolution of soil moisture using meteorological information, including radar rainfall and satellite cloud (Smith et al, 2005). The resulting soil moisture deficit (SMD) for Cornwall showed considerable spatial variability with values in the Valency catchment in excess of 100mm. The model diagnosed a reduction in SMD between 1st and 16th August consistent with the above average rainfall, the range of values around Boscastle dropping from 80-220mm SMD to 40-180mm SMD in this period.

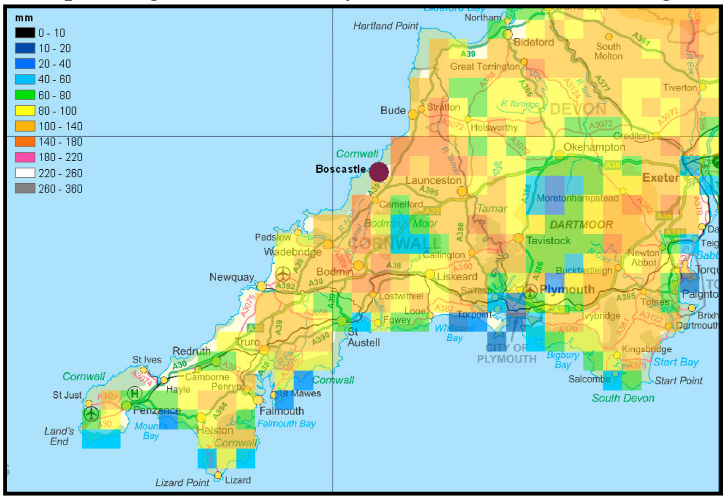

Figure 2 Diagnosed soil moisture deficit from MOSES-PDM for 0000UTC 16/8/2004

SYNOPTIC ENVIRONMENT

Synoptic scale flow over south-west England (figure 3) was dominated by a complex, slow-moving low-pressure area to the west of the UK, with a moist south-westerly gradient over Cornwall. Analysis of the radiosonde sounding from Camborne at 1200 UTC (1300 local time (British Summer Time)) shows an atmosphere primed for storm development, with very moist lower layers readily forming convective cloud from a base at about 900m. Above, strong instability in the lowest layers supported rapidly growing clouds. However, the equilibrium level where most clouds would stop was at only 6.5km. The highest cloud tops would be at the tropopause at 9.7km. The average upward speed of air parcels indicated by the sounding is about 5ms^{-1}, so boundary layer air would have reached the initial cloud top in about 15 minutes. Calculations of the expected intensity of precipitation (see Hand, 2002), given these air mass characteristics, indicate a high probability of heavy showers with rain rates up to 40mm.hr^{-1}. Maximum 15-minute rain rates observed by rain gauges and the radar in this case were 80-100 mm hr^{-1}, indicating an unusually high rainfall efficiency, while hourly accumulations of up to 60 mm indicate that his high efficiency was maintained over

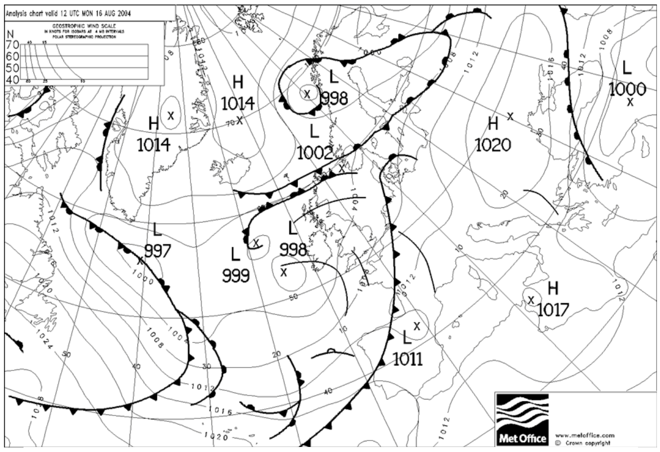

Figure 3 Surface Analysis Chart for 1200 UTC 16th August 2004

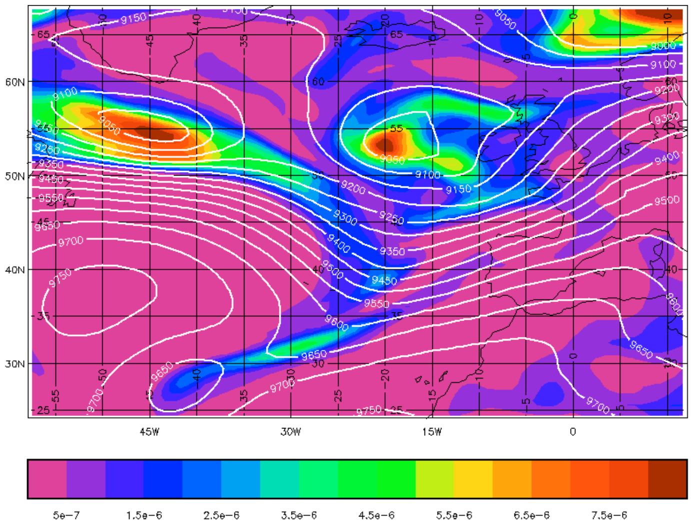

Figure 4 300hPa height (contours in gpm) and Potential Vorticity (colours in s^{-1}) at 1200 UTC 16th August 2004

multiple cloud lifecycles without a break. The wind at the middle of the storm layer was southwest 12.5 $m.s^{-1}$ consistent with the observed movement of the storms.

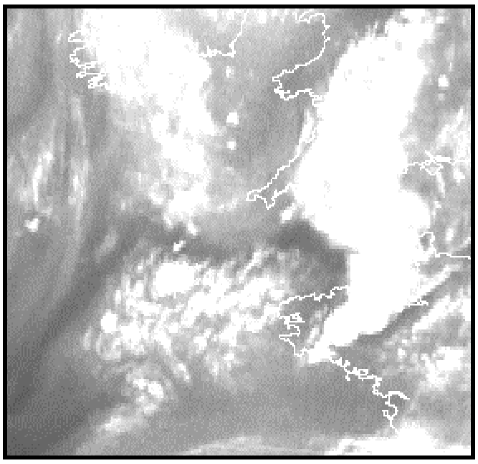

Figure 5 Meteosat-8 image in the upper tropospheric water vapour band at 1230 UTC 16th August 2004.

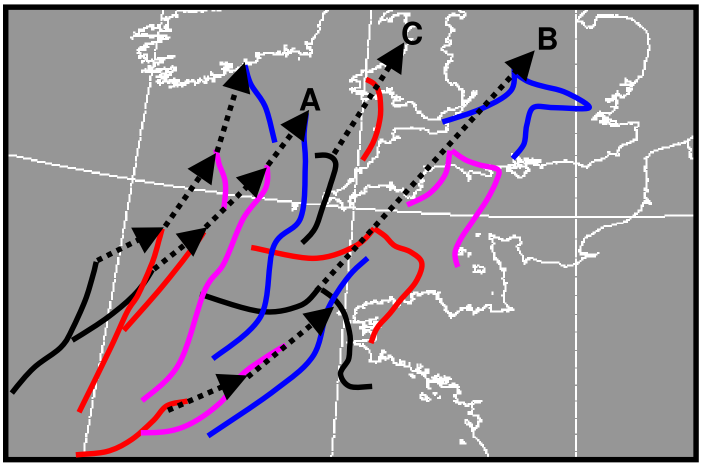

Figure 6 Tracks of dry features identified in the Meteosat-8 water vapour imagery. Colours show locations at 1030UTC (black), 1230UTC (red), 1430UTC (purple) & 1630UTC (blue).

The high efficiency of rainfall production from the convective storms was due to large scale uplift induced by synoptic scale forcing in the eastern Atlantic. At 1200 UTC on 16th August 2004, southwest England was under the left exit of a jet stream maximum to the southeast of an eastern Atlantic upper low (figure 4). The resulting potential vorticity maxima shown by the colours in figure 4 can be traced in the dark, dry bands of the Meteosat-8 upper tropospheric water vapour image in figure 5, which are tracked in figure 6, and were associated with the surface troughs shown approaching southwest England in figure 3. The first of these troughs, marked between Devon and Brittany in figure 3 and with its apex over southern Cornwall in figure 5, may have been the source of surface pressure falls observed in Cornwall.

INITIATION AND DEVELOPMENT OF PRECIPITATION

The extreme rainfall accumulations, observed in the Valency catchment above Boscastle, resulted from prolonged very heavy rain over the four hour period 1200-1600 UTC. The operational rainfall radar data showed that this was produced by a sequence of convective storms that developed along the north coast of Cornwall. Each storm element started as a non-precipitating cumulus either near the Fal Estuary or further north towards the Camel Estuary. Rapid cloud development started as each cell encountered convergence near the north coast, in the vicinity of Wadebridge. Figure 7 shows the initiation and subsequent development of precipitating cells along this convergence line between 1100 and 1135 UTC in radar imagery. The mean speed of movement of each cell was close to 10 $m\ s^{-1}$, consistent with the mid-level wind, while downstream cell development resulted in an apparent propagation speed closer to 15 $m\ s^{-1}$. New cells also formed upstream near the original location, so that each initial shower spread out into a line of storm cells, spaced at intervals of about 5km, appearing as a continuous line on radar imagery. The line was also evident on satellite imagery, especially in its early stage before anvils started to spread.

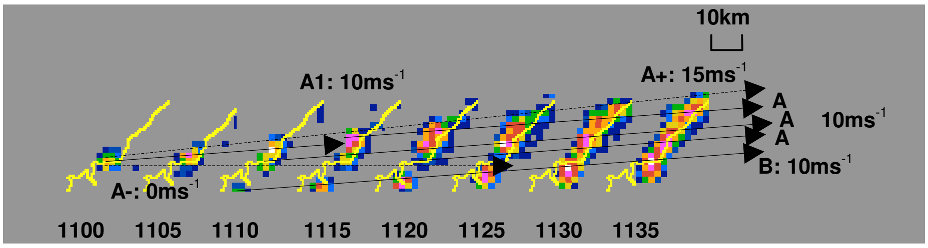

Figure 7 Initial evolution of the 1st & 2nd storm cells, 1100-1135 UTC 16th August 2004. Each time is shifted right by an additional 25km for clarity. See figure 8 for rain rate key.

Figure 8 shows the line of storms originating near Wadebridge at the head of the Camel estuary.

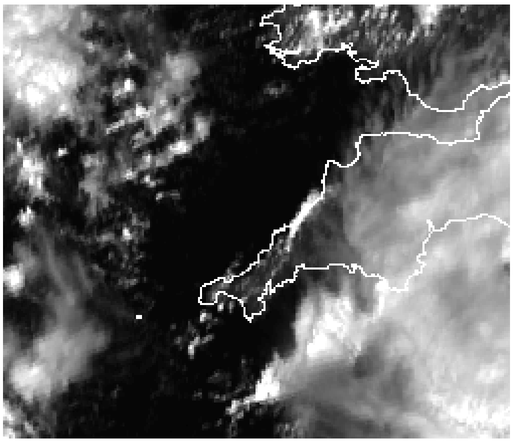

Figure 8 Meteosat-8 high resolution visible satellite image for 1130 UTC

The track of the rainfall cells varied slightly during the 1200-1600 UTC period, but between the Camel Estuary and Bude the variation was sufficiently small to ensure that the heaviest rain fell on the same coast-facing catchments throughout the period – 'snapshots' of the radar rainfall distribution taken two hours apart (figure 9) look remarkably similar in the vicinity of Boscastle, though close inspection shows that the axis of maximum rain has moved about 2km north west.

This phase of development produced rapid growth to mid-tropospheric depth with cloud tops (based on satellite imagery) in the vicinity of the equilibrium level in the Camborne ascent at 6.5km. This implies a cloud top temperature of around -15°C to -20°C which would have been only just cold enough to initiate ice precipitation processes. The extreme precipitation in the vicinity of Boscastle appears to have been related to the fact that while convection was strong enough to generate heavy precipitation, it was shallow enough

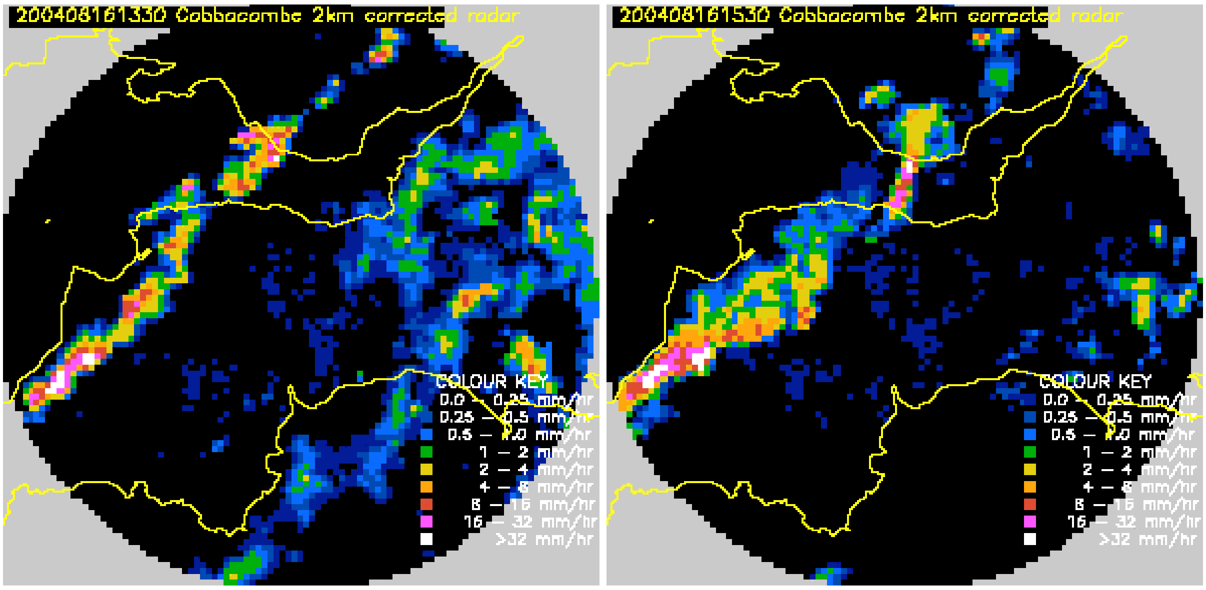

Figure 9 Estimates of rainfall rate at 2 km resolution from the Cobbacombe radar at 1330 UTC (left) and 1530 UTC (right), 16th August 2004.

to enable the development of closely packed storm cells with weak downdraughts that did not distort the coastal convergence line.

At a later stage, further northeast near Bude, a few storms were sufficiently energetic to reach the tropopause at around 9.7km where the temperature was -54°C. At these levels remaining cloud water rapidly turned to ice crystals, visible in the growth of a large cloud shield over the Hartland area (figure 10). The greater vigour of these storms was reflected in their precipitation intensity at the ground, to the north of the main precipitation line (figure 9, right panel). This precipitation was accompanied by a strengthened downdraught, which distorted the convergence line, causing it to bow in an eastward arc to the north of Bude. A succession of such arcs is visible in the satellite (figure 10) and radar imagery (figure 9, right panel),

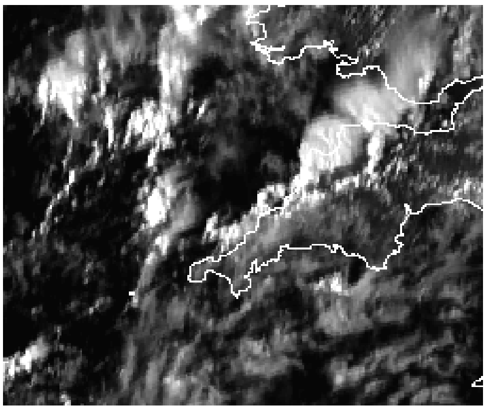

Figure 10 Meteosat-8 high resolution visible image for 1530 UTC 16th August 2004

generating new rows of storm cells which spread east into north Devon and across the Bristol Channel into south Wales.

RAINFALL DISTRIBUTION

With light surface winds, conditions favoured accurate rain gauge measurements and the daily observations have all been accepted by the Met Office quality control process. Tipping Bucket Rain gauges (TBRs) suffer from under-reading at high rain rates and this is reflected in the 24 hour Lesnewth TBR observation which was about 20% low. Conditions were also favourable for accurate radar rainfall observations with a high freezing level and no anomalous propagation. Two radars cover the Boscastle area at a range of less than 100km. Of these, Cobbacombe recorded a slightly higher maximum storm accumulation than Predannack, but there is very little overall bias evident between the two sets of data. In the areas of common coverage at 2km resolution, both radars recorded nine pixels (36 sq km) with accumulations exceeding 96mm.

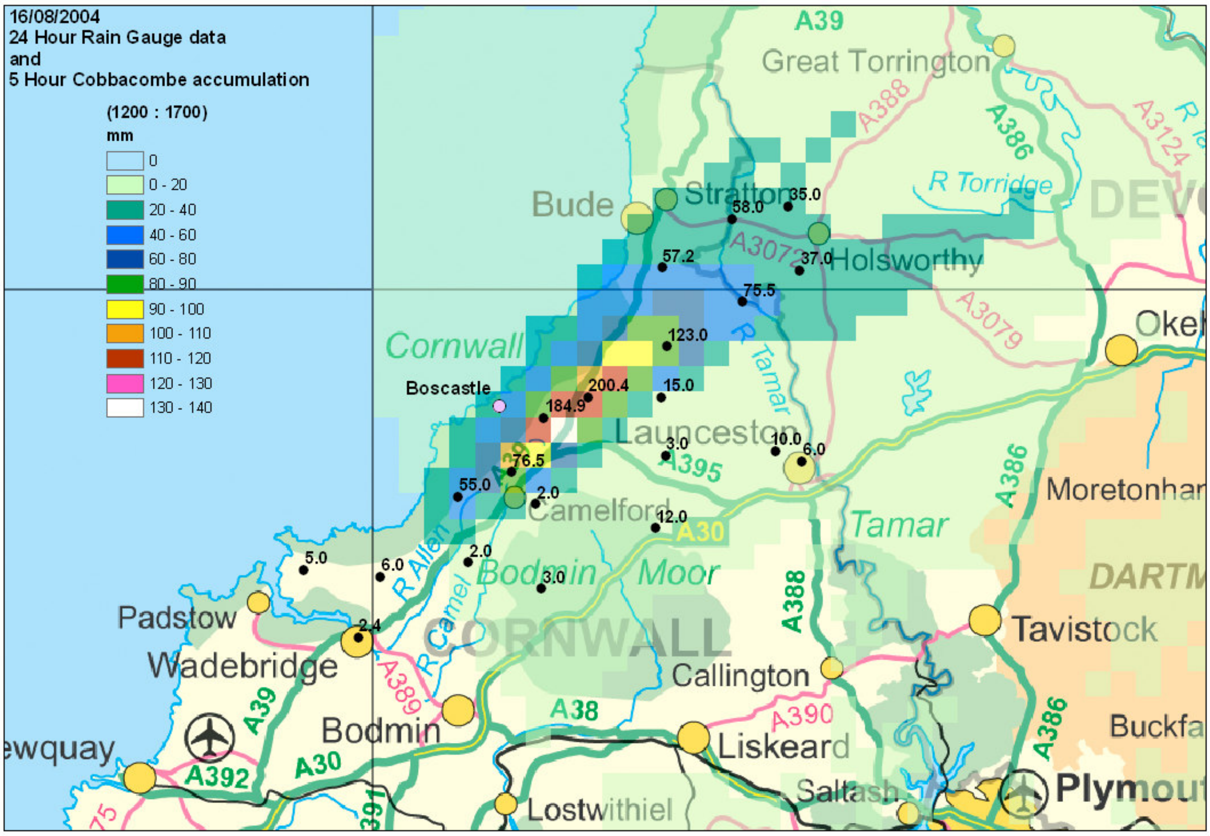

Figure. 11 Distribution of accumulated rainfall on 16th August 2004: 5-hour totals (1200-1700 UTC) from 2km corrected Cobbacombe radar data (colours) and 24-hour (0900-0900 UTC) rain gauge totals (spot values)

Twenty-four hour rain gauge totals from all available rain gauges are shown as point values in Fig. 11, superimposed on the distribution of five-hour accumulations derived from the Cobbacombe radar. The patterns are consistent, showing considerable spatial variability with an elongated strip of high accumulations through Slaughterbridge (76.5mm), Lesnewth (184.9mm), Otterham (200.4mm), Credacott (123mm) and Crowford Bridge (75.5 mm). After correction to match the daily check gauge, the Lesnewth TBR recorded maximum short period accumulations of 82mm in 1 hour, 148mm in 3 hours, and 183mm in 5 hours. Maximum values from the radar were somewhat lower, but due to the very high rainfall accumulation gradients, it is not possible to be sure that the differences in accumulations from those observed by gauges are not solely due to sampling differences. The radar spatial pattern indicates that the heaviest total rainfall accumulation probably occurred a few kilometres to the southwest of Otterham near the A39.

The Lesnewth TBR record is shown in figure 12, computed from the time taken for each millimetre to fall. This produced a smoothed profile compared to the raw 0.2mm counts, which were recorded only to 10sec precision. There was considerable variability, both at short timescales of five to ten minutes, associated with individual cells, and at longer timescales, with three half hour periods of heavier rain centred on about 1235, 1315 and 1415 UTC followed by a more continuous period from 1455-1615 UTC (figure 12). During the last period, at about 1535 UTC, the gauge recorded an uncorrected peak rain rate of nearly 300mm/hr. Given that the 20% shortfall of the TBR relative to the check gauge would have occurred predominantly in the heaviest periods of rain, the true maximum rain rate may have briefly reached 400mm/hr.

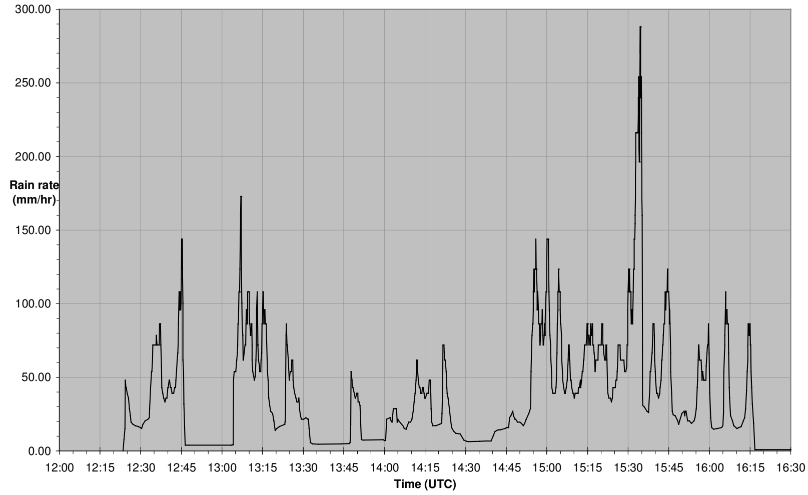

Figure 12 Smoothed, uncorrected, rain rate profile 1200-1630 UTC from the Lesnewth Tipping Bucket rain gauge on 16th August 2004

Figure 13 summarises the spatio-temporal radar information in a sequence of hourly rainfall accumulation maps obtained by summing 5-minute corrected radar rain rates at 2km resolution from the Cobbacombe Cross radar. The colour scheme emphasises the heavier rainfall amounts. The results have been displayed on a map background, with the Valency catchment boundary added, so that features can be geographically located. In the discussion below, the radar pattern is related to available TBR data, with TBR values given in brackets where available.

During the first hour, 1200-1300UTC, the axis of maximum rainfall was to the east of the Valency catchment, with three maxima of 15-20mm. Slaughterbridge (10mm) was between the 1st and 2nd of these and Lesnewth(17mm) was on the western edge of the 3rd, each having radar accumulations in the 10-15mm range. Otterham was on the axis of the maximum, with a radar estimate of 15-20mm.

During the period 1300-1400UTC, rainfall was much heavier, with the axis of maximum rainfall remaining along the east side of the Valency catchment and exceeding 30mm in a single 10km long, 4km wide plume from Slaughterbridge to Otterham. Maximum radar accumulations of 45-50mm occurred on the southeast edge of the Valency catchment, between Slaughterbridge (radar: 30-35mm; raingauge: 47mm) and Otterham (radar: 35-40mm). Again Lesnewth (29mm) was off the main axis of the rain with a radar pixel value of 20-25mm.

From 1400 to1500UTC, accumulations were lower than in the previous hour, with three local maxima, one of 25-30mm situated between Slaughterbridge and Boscastle, one of 35-40mm over the east part of the Valency catchment, and a more elongated one to the northeast reaching 30-35mm near Credacott. Slaughterbridge (8mm) was upwind of the first maximum, in a 15-20mm pixel; Otterham was downwind of the second maximum in a 25-30mm pixel; and Lesnewth (28mm) was on the western edge of the rain axis in a 15-20mm pixel.

Maximum rainfall was higher again in the hour from 1500-1600UTC, exceeding 35mm in a 12km long, 4km wide plume that runs right through the Valency catchment from near Slaughterbridge to beyond Otterham. The axis had shifted west by about 2km from the earlier position and Lesnewth (54mm) was in the heaviest pixel of >50mm. Slaughterbridge (2mm) was upwind of the main maximum in a 15-20mm pixel, while Otterham was on the eastern edge of the maximum in a 40-45mm pixel.

By 1600-1700UTC, the main rain area had moved away north and the remains of the plume had shifted west, putting Boscastle village under the maximum of 15-25mm, while the three local raingauges were all in pixels of less than 10mm. (Lesnewth TBR: 10mm, Slaughterbridge TBR: 0mm)

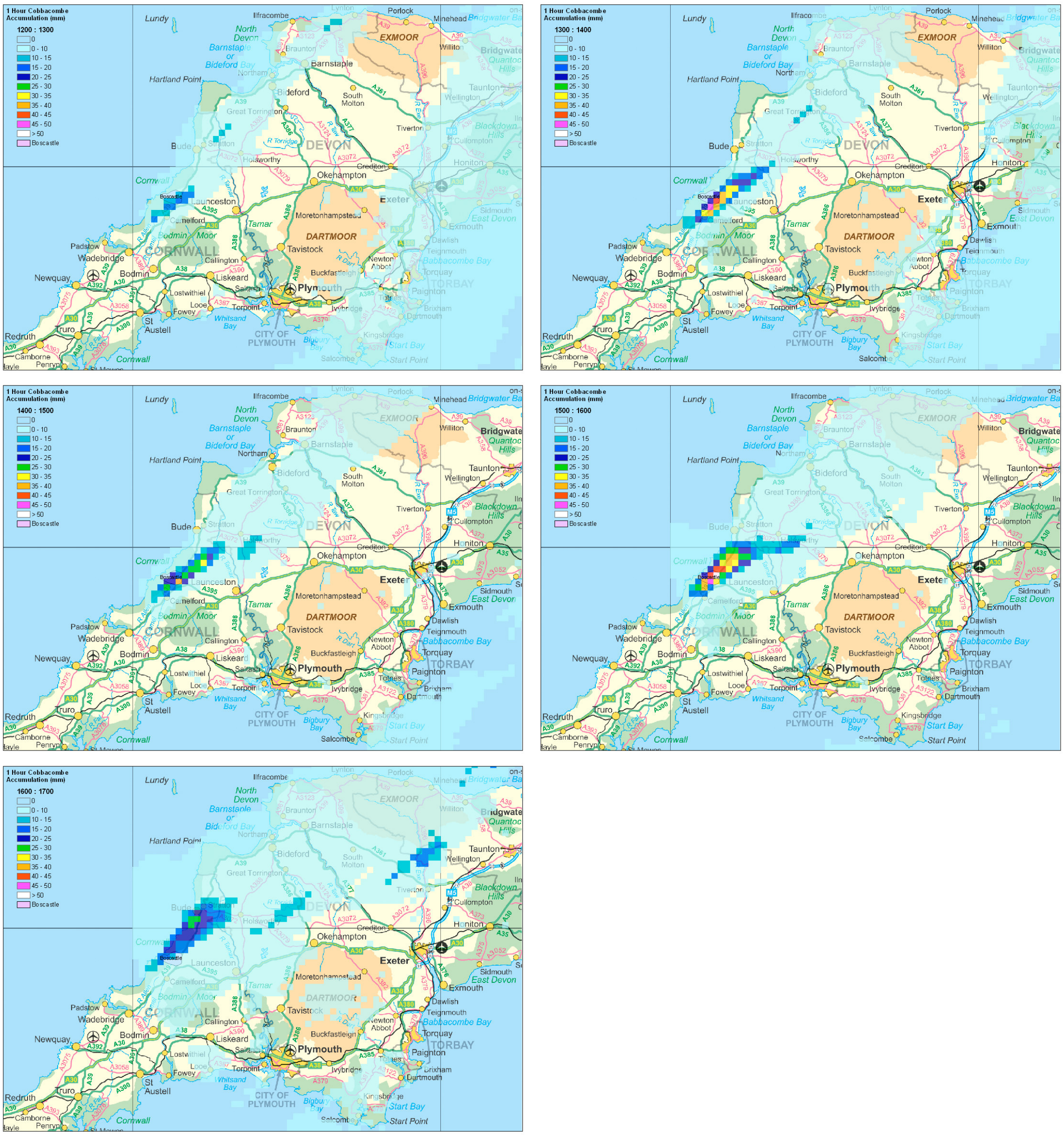

Figure 13 Sequence of hourly accumulations of 2km corrected Cobbacombe radar data, 1200UTC-1700UTC.

NUMERICAL MODEL SIMULATIONS

The highest resolution Met Office operational forecast model has a horizontal grid length of about 12 km and so accurately represents only features larger than about 60 km across. Convection has to be represented by an estimate of the change in the resolved flow resulting from a population of convective clouds in equilibrium with the larger scale forcing. Not surprisingly, this model produced a bland forecast, with heavy convective rain forecast to occur anywhere in Devon and Cornwall. In order to investigate the processes that led to extreme rainfall, the Unified Model (Cullen et al., 1997) was re-run at higher resolution (1 km nested in 4 km nested in the standard 12 km) in a form which allowed individual thunderstorms to form, albeit not well resolved. The 1 km configuration was run with double the vertical resolution (76 levels) compared with the 12 and 4 km versions, to resolve better the boundary layer processes. Such high resolution requires a great deal of computer time, so the 1 km resolution model was run over an area covering only 300x300 km, centred on Cornwall. The model was initialised from the 12 km analysis at 0000 UTC to give time for fine resolution features to develop.

Figure 14 (left panel) shows the predicted accumulation of precipitation from 1200-1700 UTC in (part of) the 1 km model domain. The model simulated intense precipitation, with maximum accumulations of about 50 mm, similar to radar observations averaged to 5km, the minimum scale realistically represented by a 1km model. The accuracy of the location is remarkable, especially considering the length of the forecast. This suggests that the location is determined by factors that are highly predictable.

Inspection of the model results shows a highly persistent line of convergent winds along the north Cornish coast. In order to clarify the processes involved in its generation, re-runs of the 1 km model were performed, first setting the land height to sea level over the south west peninsula and then also setting the surface heat and moisture fluxes and the surface temperature over land to values typical of the sea. The centre panel of figure 14 shows that the influence on precipitation of just changing the land height is small whereas removing the enhanced surface fluxes (right panel) removes both the Boscastle precipitation peak and the convergence line. This indicates that the convergence line was a quasi-stationary sea breeze front, which results when the on-shore pressure gradient generated by differential heating of the land and sea is opposed by an offshore wind (Simpson, 1994).

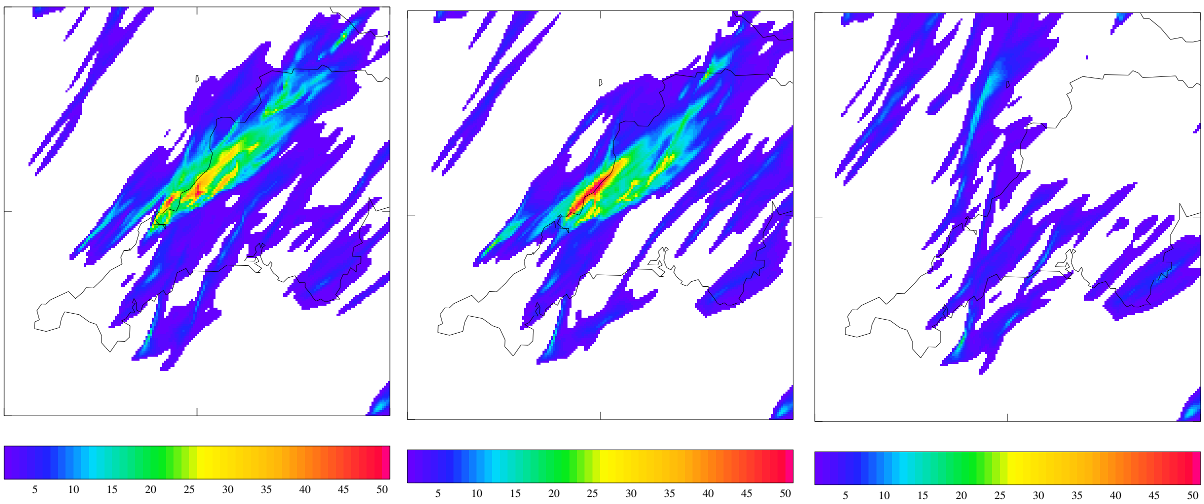

Figure 14: Accumulated precipitation in mm from 1200 to 1700 UTC 16th August 2004 from 1km grid length integrations of the Unified Model. Full simulation (left), flat orography (centre), flat orography with surface fluxes and land temperature fixed to sea values (right)

HYDROLOGICAL RESPONSE

The response of the Valency and Jordan rivers to this extreme rainfall event has been reported in Bettess (2005). Neither river is gauged, so the approach taken was to use the FEH rainfall-runoff method for ungauged catchments, applied to six sub-catchments and with rainfall input data derived from radar. Study of the wrack marks indicates a peak flow of $180m^3s^{-1}$ against a bankfull capacity of about $20m^3s^{-1}$. Eye-witnesses reported repeated surges of water, up to a metre deep, which have been associated with the collapse of walls and buildings, and with blocked bridges. Considerable difficulty was found in reproducing the observed peak flow. The best fit was obtained with rainfall inputs enhanced by up to 50% (justified by radar/raingauge differences) and with the time-to-peak parameter substantially reduced below that recommended (to about 1.5 hours for the catchment outflow). Even then, the modelled peak was lower and later than observed.

PROBABILITY OF RAINFALL EVENT

The probability of occurrence of the extreme rainfall observed in the vicinity of Boscastle has been studied in the context of climatology, meteorological phenomena, historical occurrence of storms, and historical occurrence of point rainfalls.

RETURN PERIOD USING THE FLOOD ESTIMATION HANDBOOK METHOD

The standard technique for assessing probability of occurrence of floods in the UK is the FORGEX method documented in the Flood Estimation Handbook (FEH: NERC, 1999). This is based on analysis of historical values of the highest rain gauge record in each year, and represents the probability as a return period at a point.

Table 1 is based on application of this method to values recorded during the Boscastle event. Note that the short periods are based on TBR records which are not quality controlled, and also that the FORGEX method is not designed for use with radar, which gives an area average rather than a point value.

The observed maximum one hour fall at the Lesnewth TBR (after correction to match the check gauge) has a return period of around 750 years. The three hour total, again at Lesnewth, was comparable with the Camelford flood in 1957, and with several events in other parts of the country, most of which were accompanied by large hail. The return period is about 2500 years. The overall storm has a return period in excess of 2000 years, but is not as high as the Lynmouth or Martinstown events. All covered very small areas, which contributes to their point rarity.

Table 1 Rolling peak rainfall accumulations and FEH point rainfall return periods

Duration (hrs)	1	2	3	4	5
Comp. QC 2km Radar (mm)	47	68	99	114	115
Return Period (yrs)	100	200	500	750	5-600
Cobb. QC 2 km Radar (mm)	48	83	117	132	133
Return Period (yrs)	~120	~400	~1000	~1300	~1100
Corrected Lesnewth (mm)	82	100	148	181	183
Return Period (yrs)	~750	~850	~2500	~4500	~4000
Slaughterbridge (mm)	46	63	73	74	74
Return Period (yrs)	100	150-200	150-200	100-150	100
Crowford Bridge (mm)	34	47	67	72	72
Return Period (yrs)	20-50	50	100-150	100-150	50-100
Woolstone Mill (mm)	48	70	72	73	74
Return Period (yrs)	100	200	150-200	100-150	100
Tamarstone (mm)	35	44	48	49	50
Return Period (yrs)	20-50	20-50	20-50	20-50	20

The method of pooling rainfall data in FORGEX allows data from gauges at distances up to 200km from a site to be used in order to make the most of all extreme data available, weighting the data closest to the site with the most importance. However, whereas there is rather good coverage of daily rainfall data, the density of hourly reporting gauges in the southwest of England is relatively low. For this reason the extreme short duration totals (1-6hr) depend on the pooling method more than in other parts of the UK. As a result, FEH estimates of rainfall rarity at Boscastle may be exaggerated, though they can safely be taken to indicate a return period of greater than 1000 years.

RARITY OF THE WEATHER SYSTEMS

Inspection of the mechanisms involved in generating the rainfall indicates that the key features were the efficiency of the rainfall production and length of time for which it remained over the same area.

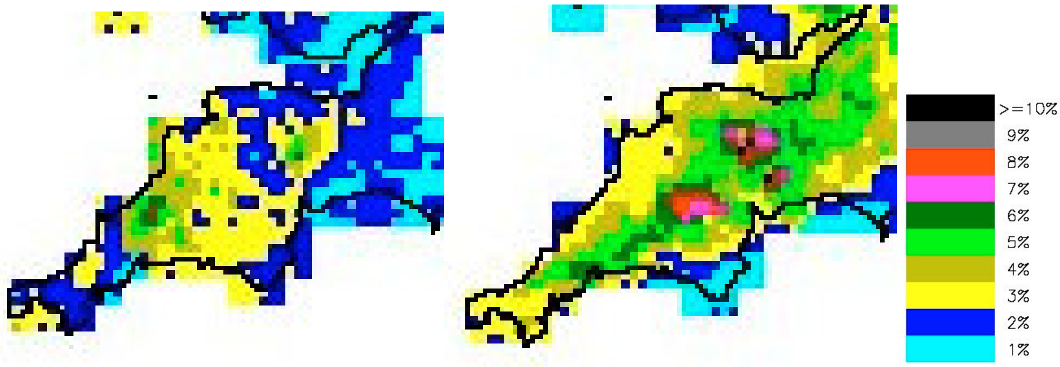

Figure 15 Probability of showers in a South or South-West wind during summer afternoons, determined from radar data in the period 2000-2003.

The summer climatology of showers in south-west England can be extracted from Hand (2003), who used a neural network applied to satellite imagery to distinguish areas of convective and stratiform cloud, and then accumulated the hours when convective precipitation was observed by radar on a 5-km grid. Figure 15 shows sections of the maps produced for south and southwest wind directions in summer. The results are expressed as the conditional probability of convective precipitation occurring, given the specified wind direction. This analysis shows that the maximum occurrence of showers tends towards the south side of the Cornish peninsula in southwesterly winds, but is focussed over Bodmin Moor in southerly winds. It should be noted that southerly winds are much less common than southwesterly winds.

The individual convective cells produced very heavy rain. Given the observed atmospheric sounding, the likelihood of hourly accumulations of 40mm or more was very high, and Figure 15 shows that Boscastle was more likely than other places to receive such convection in a southerly wind. The high efficiency of precipitation from the storms was certainly unusual, and resulted in maximum hourly rainfall with a return period of 750years as indicated by the FEH analysis, above. This was most likely related to the upper tropospheric forcing associated with the troughs identified earlier.

The repeated triggering of convection was not a rare event, and indeed is observed frequently in Cornwall in south-westerly winds. The occurrence of repeated triggering in a southerly wind with the subsequent storms moving up the coastal convergence is more unusual, but not considered rare. If it was critical for the storms to have sufficient vigour to create heavy precipitation, to be shallow enough to allow close packing of the storms, and to have weak enough downdraughts to avoid distorting the convergence line, then we may suppose that such conditions occur rarely. It is not possible to quantify how rarely, and neither is it possible to be sure that this combination was critical.

In summary, the individual conditions that caused the Boscastle storm are not considered to be individually extreme. Rather the extreme conditions resulted from their joint occurrence. It is not possible, given available data and resources, to judge the joint probability of these events coming together in the way observed at Boscastle. In any case, it is a characteristic of extreme convective events that they each have a unique combination of characteristics.

FREQUENCY OF OCCURRENCE OF THE LARGE SCALE METEOROLOGICAL CONDITIONS

The characteristics of extreme rainfall events in the 20th Century have been studied by Hand et al (2004). Of the fifty cases identified, thirty were predominantly convective, fifteen predominantly frontal and five orographic. The Boscastle event is convective in this classification, but it should be noted that the Lynmouth event of 1952 was predominantly frontal. Figure 16 shows rainfall amounts and durations for these storms, broken down into rainfall mechanisms, with values for the Boscastle storm superimposed, based on the measurement at Otterham.

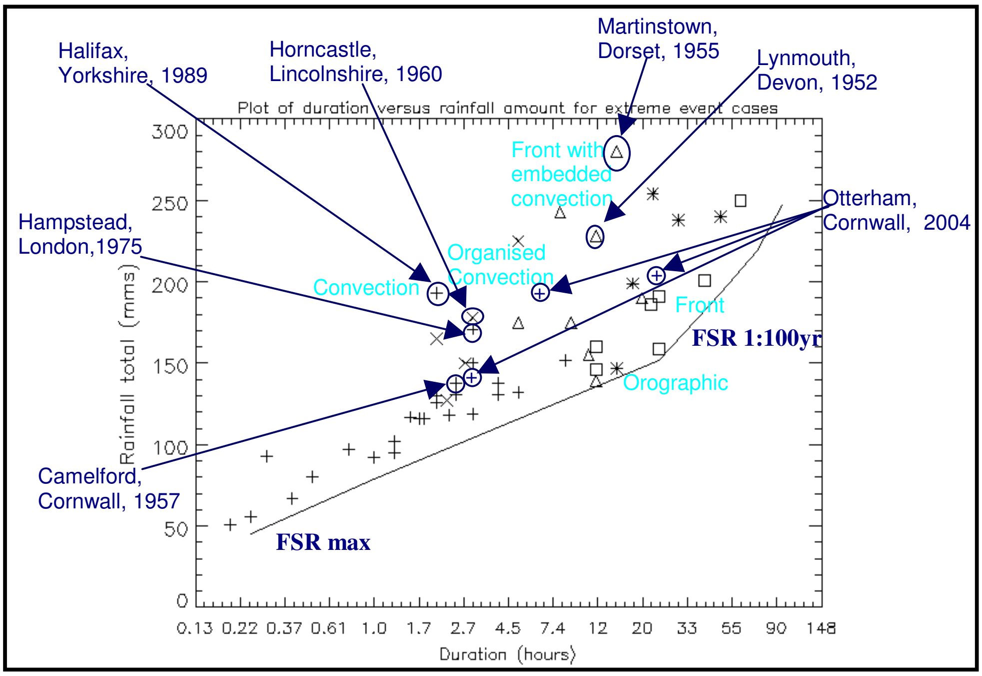

Figure 16 Extreme rainfall events of the 20th century with Boscastle superimposed. The dominant mechanism is convection (+), organised convection (x), frontal (□), frontal with embedded convection (ρ) or orographic (▯).

The distribution per decade (fig. 17a) indicates a high degree of natural variability with no discernible trend. The overall frequency is one event every second year. If we select only convective events, there is about a 30% chance of an extreme convective storm event occurring somewhere in the UK each year. Most of these events have occurred during the summer months (fig. 17b) with none between November and April. An explanation for this highly skewed distribution is that extreme events only occur when high sea temperatures generate high moisture content air in the vicinity of the UK.

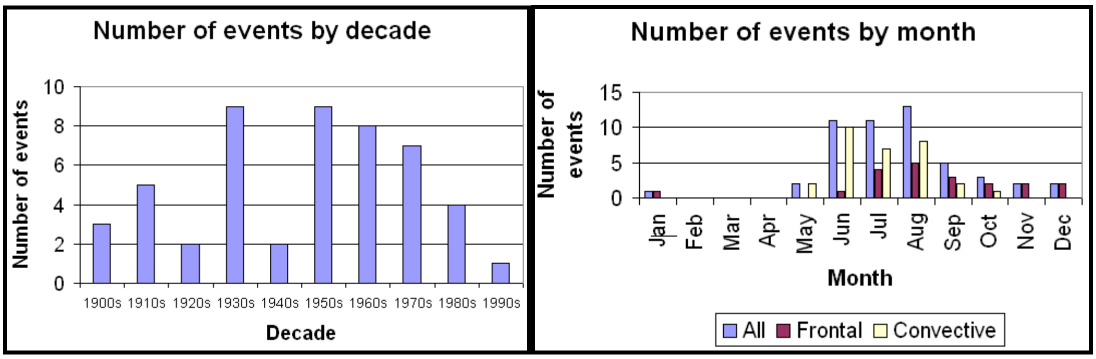

Figure 17 (a) Distribution of extreme rainfall events by decade (b) Distribution of extreme rainfall events by month

The southwest peninsula was subjected to six extreme rainfall events during this period, indicating that an extreme event will occur somewhere in this region about once every 20 years on average, but with considerable year-to-year variation. Assuming that the area affected by each is about 100 km^2 and relating this to the area of the southwest peninsula gives a return period of over 2,000 years for each $1km^2$. We note in passing that half of these six events occurred within just six years in the 1950s. This should emphasise the caution with which short periods and small numbers of events should be treated since had we calculated the probability from just these data we would have estimated just 240 years for the return period at any location. With hindsight, there is no reason to identify a climatic variation that justifies a higher probability estimate for the 1950s, so we conclude that it was a result of natural variability.

It is known that the climate cannot be considered stationary, for natural as well as possibly for human induced reasons, and there is no reason to suppose that the frequency of events such as this one has remained the same. Ultimately, the intensity of the precipitation in these events depends on the moisture content of the air, and this is the reason that late summer is the time when such storms occur most frequently. If any change in climate were to result in the sea temperature rising to the south west of the UK, it would be expected that the moisture content of air reaching the UK would be higher in suitable circumstances for storm development, and that the intensity of the storm would therefore be greater. This is consistent with the observation that severe rain storms in more southerly latitudes produce significantly heavier rain rates.

SUMMARY

Synoptic scale developments over the eastern Atlantic on 16th August 2004 created a moist, unstable environment with weak uplift over Cornwall. The interaction between frictionally backed winds over land and a developing sea breeze generated a stationary sea breeze front along the north coast. Cumulus clouds moving into it from the south, grew rapidly to a height of about 6.5km and spawned adjacent cells along the front, resulting in a continuous line of small but intense rain cells, which moved north-east with the mid-tropospheric wind. This line was most intense from 1230 to 1330 UTC and again from 1450 to 1615 UTC, moving slightly seawards between the two periods. Over 200mm of rain was recorded at the head of the Valency river catchment above Boscastle, and peak rates may briefly have reached 400mm hr^{-1}. The return period of the highest hourly fall was about 750 years, and the storm lasted five hours, over which period it had a return period of over 2000 years. This rarity arises from a combination of unusually high rainfall efficiency, relative to the moisture content of the inflowing air, and the unusually long period over which these intense storms affected the same small area.

ACKNOWLEDGEMENTS

The assistance of many colleagues from the Met Office, the Environment Agency, HR Wallingford and of eye-witnesses, is gratefully acknowledged, in particular: Ross Melville, Roderick Smith, Andrew Bennett, Andy Cooper, Malcolm Kitchen, Mark Beswick, Humphrey Lean, Nigel Roberts, Sarah Watkin, Michael Saunby, Joanne Crawford, Mark Smees, Tim Wood, Roger Quinn & Rod McInnes-Slegg, Roger Bettess, Murray Dale.

The work described in this paper was commissioned by the Environment Agency of England & Wales.

REFERENCES

Bettess, R., 2005, Flooding in Boscastle and North Cornwall, August 2004: Phase 2 Studies Report. HR Wallingford Report EX5160. Available from
http://www.hrwallingford.co.uk/downloads/publications/EX5160_Boscastle_floodings.pdf

Cullen, M.J.P., Davies, T., Mawson, M.H., James, J.A., Coulter, S.C. & Malcolm A., 1997 An overview of Numerical Methods for the Next Generation UK NWP and Climate Model Numerical Methods in Atmospheric and Ocean Modelling. In The Andre J.Robert memorial volume. Edited by Charles A Lin, Rene Laprise and Harold Ritchie, Canadian Meteorological and Oceanographic Society, Ottawa, Canada, 425-444

Golding, B.W. (Ed), 2005, Boscastle and north Cornwall post flood event study – meteorological analysis of the conditions leading to flooding on 16 August 2004. Forecasting Research Tech. Rep. No. 459, Met Office, UK available from http://www.metoffice.com/research/nwp/publications/papers/technical_reports/2005.html

Hand, W., 2002: The Met Office Convection Diagnosis Scheme. *Meteor. Appl.*, **9**, 69–83.

Hand, W.H., Fox, N.I., Collier C.G., 2004: A study of twentieth century extreme rainfall events in the United Kingdom with implications for forecasting. *Meteor. Appl.*, **11**, 15–31

Harrison,D.L., Driscoll,S.J. & Kitchen,M., 2000: Improving precipitation estimates from weather radar using quality control and correction techniques. Meteorol. Appl. 6, 135-144.

Hunt, J.C.R., Orr, A., Rottman, J.W. & Capon, R., 2004: Coriolis effects in mesoscale flows with sharp changes in surface conditions. Quart. J. Roy. Meteorol. S., 130, 2703-2731.

NERC, 1999: Flood Estimation Handbook

Pierce, C. E., and A. M. Cooper, 2000: Comparison of the performance of 2 km resolution object-oriented model and Nimrod advection precipitation nowcast schemes. Forecasting Research Tech. Rep. No. 350, Met Office, UK. Available from http://www.metoffice.com/research/nwp/publications/papers/technical_reports/2000.html

Robinson A.C. & J.C. Rodda, 1969: Rain, wind and the aerodynamic characteristics of rain gauges. Meteorol. Mag, 98, 113-120.

Simpson, J.E., 1994, Sea breeze and local wind. Cambridge University Press.

Smith, R.N.B., Blyth, E.M., Finch, J.W., Goodchild, S., Hall, R.L. & Madry, S., 2005, Soil state and surface hydrology diagnosis based on MOSES in the Met Office Nimrod nowcasting system. Submitted to Meteorol. Appl.