The Boscastle flood: Meteorological analysis of the conditions leading to flooding on 16 August 2004

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On the afternoon of 16 August 2004, 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 the 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, using operational observations and analyses, with additional insight from experimental high-resolution model simulations of 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 focused extreme conditions in the Boscastle area.

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 drier 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 Fig. 1, derived from all available daily rain gauges. Most of north Cornwall was wet during this period, with Boscastle receiving about 25% more than normal. There was considerable spatial variability, so the resulting pattern is constrained by the distribution of available raingauges.

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 100 mm. 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 80–220 mm SMD to 40–180 mm SMD in this period.

Synoptic environment

Synoptic-scale flow over south-west England was dominated by a complex, slow-moving low-pressure area to the west of the UK, with a moist south-westerly gradient over Cornwall (Fig. 1 of Burt, this issue). Figure 2 shows the radiosonde sounding from Camborne at 1200 UTC (1300 local time (British Summer Time)). The atmosphere was primed for storm development, with very moist lower layers readily forming convective cloud from a base at about 900 m. Above, strong instability in the lowest layers would produce a rapidly growing cloud. However, the equilibrium level where most clouds would stop was at only 450 hPa (6.5 km). The highest cloud tops would be at the tropopause at 250 hPa (9.7 km). The Convective Available Potential Energy (CAPE) was about 170 J kg^{-1}. Undilute convection with this CAPE would have a maximum vertical velocity of about 18 m s^{-1}, so after allowing for entrainment and averaging over the depth of the cloud, the mean vertical velocity was probably about 5 m s^{-1}, a value supported by the absence of observed hail in the storm. At this speed it would have taken about 15 minutes for air from the boundary layer to reach the equilibrium level, and another 15 minutes to reach the tropopause.

If the total column of air were lifted until there was no water left in it, the average rain

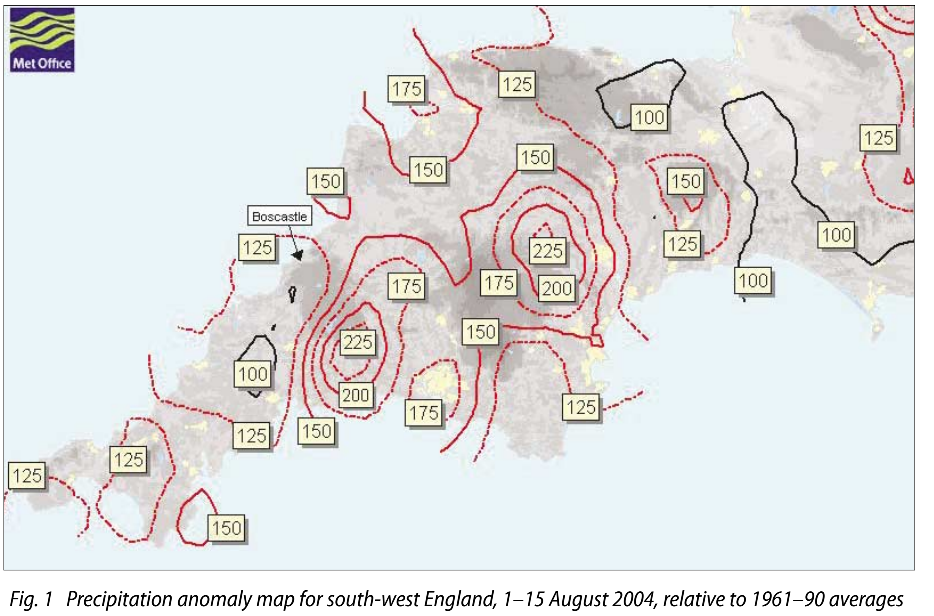

Fig. 1 Precipitation anomaly map for south-west England, 1–15 August 2004, relative to 1961–90 averages

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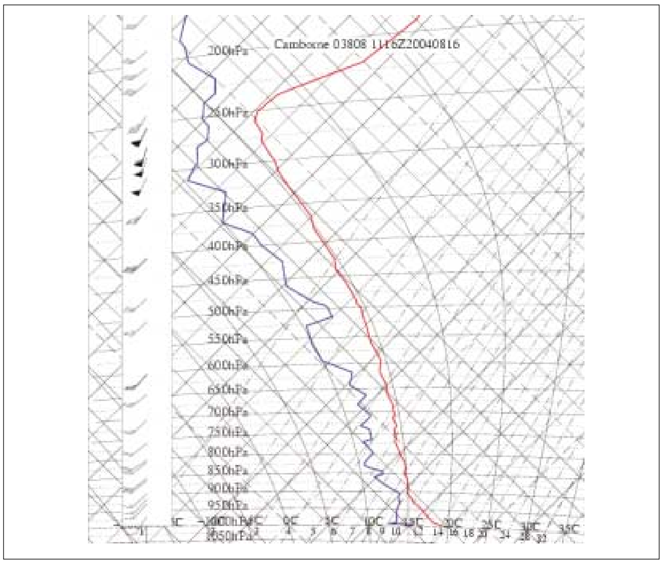

Fig. 2 Tephigram showing 1200 UTC radiosonde from Camborne (actually released 1116 UTC)

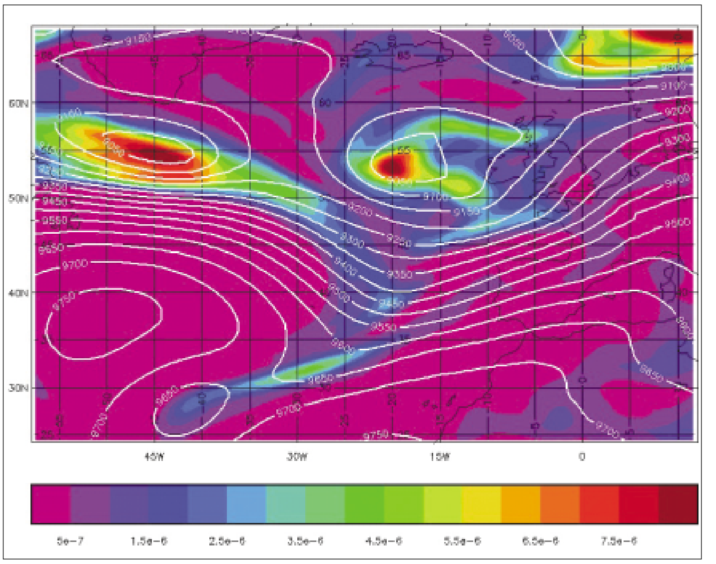

Fig. 3 300 hPa height (contours in gpm) and Potential Vorticity (colours in s^{-1}) at 1200 UTC 16 August 2004

rate would be given by the precipitable water divided by the lifting time. In this case, 26 mm of precipitable water lifted to dryness in 15 minutes corresponds to about 100 mm hr^{-1} rain rate. In real clouds, much of the rainfall usually evaporates into the surrounding air giving a rainfall 'efficiency' of less than 50%. Maximum 15-minute rain rates observed by raingauges and the radar in this case were 80–100 mm hr^{-1}, indicating an unusually high efficiency, while hourly accumulations of up to 60 mm indicate that this high efficiency was maintained over multiple cloud lifecycles without a break. The high tropospheric relative humidity (80% or more below 700 mbar) contributed to this high efficiency.

The near-surface wind in the Camborne ascent (Fig. 2) was south-south-westerly, veering to south-westerly 7.5 m s^{-1} (15 kn) at the top of the boundary layer. There was weak, unidirectional shear from there up to cloud top – the wind remaining south-westerly, increasing to 17.5 m s^{-1} (35 kn) at 400 mbar. This structure ensured that any downdraught would be down-wind of the initiation point. It did not favour development of either multi-cell or supercell storms, which require directional shear of at least 20 degrees between cloud base and the height of origin of the downdraught (Pierce and Cooper 2000). The wind at the middle of the storm layer (~500 mbar), was south-west 12.5 m s^{-1} (25 kn) consistent with the observed movement of the storms (see below).

The efficiency of rainfall production from the convective storms was enhanced by large scale uplift induced by synoptic-scale forcing in the eastern Atlantic. At 1200 UTC on 16 August 2004, south-west England was under the left exit region of a jet stream maximum on the south-east flank of the eastern Atlantic upper vortex (Fig. 3). The resulting potential vorticity maxima in Fig. 3 can be traced in the dark, dry bands of the Meteosat-8 upper tropospheric water vapour image in Fig. 4 and were associated with the surface troughs approaching south-west England. The first of these troughs, between Devon and Brittany (Fig. 1 of Burt, this issue) with its apex over southern Cornwall shown in Fig. 4, exhibited rotation in the satellite imagery, indicating upper tropospheric vortex development. This is consistent with the backing of the jet stream winds at tropopause level shown in the Camborne ascent (Fig. 2) and may have been the source of observed surface pressure falls of over 1 mbar recorded in Cornwall. The effect of these larger-scale processes on storm development was to create an environment of weak uplift, maintaining high humidity and hence supporting the retention of cloud water in the atmosphere, which contributed to the unusually high rainfall efficiency.

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 5 shows the initiation

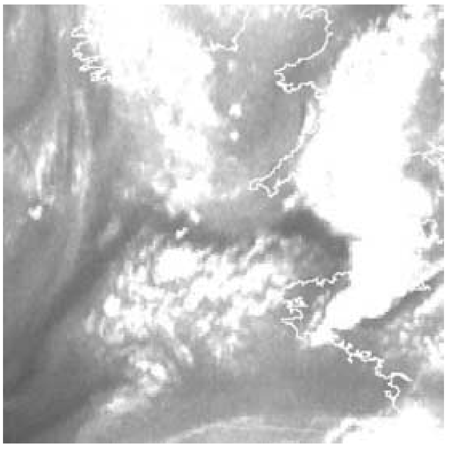

Fig. 4 Meteosat-8 image in the upper tropospheric water vapour band at 1230 UTC 16 August 2004

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 5 km, 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 6 shows the line of storms originating near Wadebridge at the head of the Camel estuary.

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 –

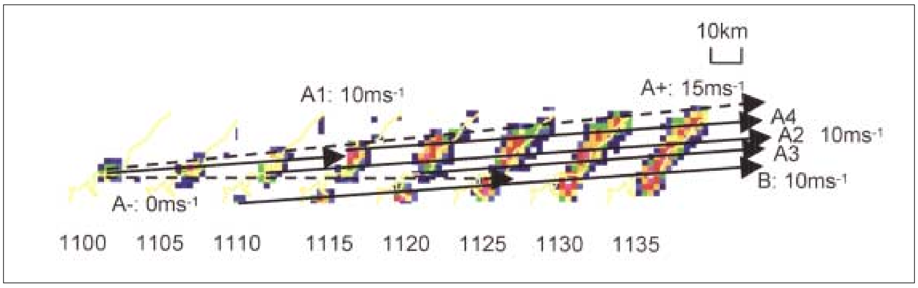

Fig. 5 Initial evolution of the 1st and 2nd storm cells, 1100–1135 UTC 16 August 2004. Each time is shifted right by an additional 25 km for clarity. See Fig. 7 for rain rate key.

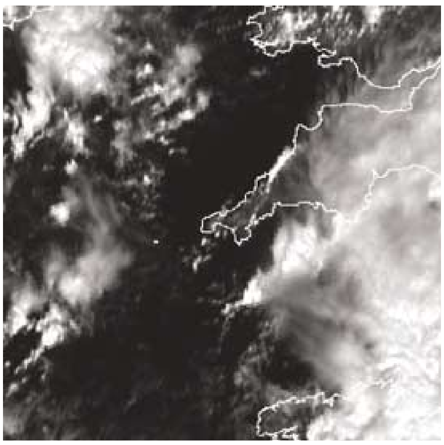

Fig. 6 Meteosat-8 high resolution visible satellite image for 1130 UTC

'snapshots' of the radar rainfall distribution taken two hours apart (Fig. 7) look remarkably similar in the vicinity of Boscastle, though close inspection shows that the axis of maximum rain has moved about 2 km 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 450 mbar (6.5 km). This implies a cloud top temperature of around −15 °C to −20 °C, which would have been only just cold enough to initiate ice processes. However, satellite images indicate that the clouds were being seeded with ice from the outflow anvils of earlier storms initiated over Brittany. These seed crystals would have grown rapidly by contact freezing. Whatever its microphysical origin, 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 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 north-east near Bude, a few storms were sufficiently energetic to reach the tropopause at around 250 mbar (9.7 km) 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 (Fig. 8). The greater vigour of these storms was reflected in their precipitation intensity at the ground, to the north of the main precipitation line (Fig. 7(b)). This precipitation was accompanied by a strengthened downdraught, resulting in a gust front 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 (Fig. 8) and radar imagery (Fig. 7(b)), 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 raingauge measurements and the daily observations have all been accepted by the Met Office quality control

Fig. 8 Meteosat-8 high resolution visible image for 1530 UTC 16 August 2004

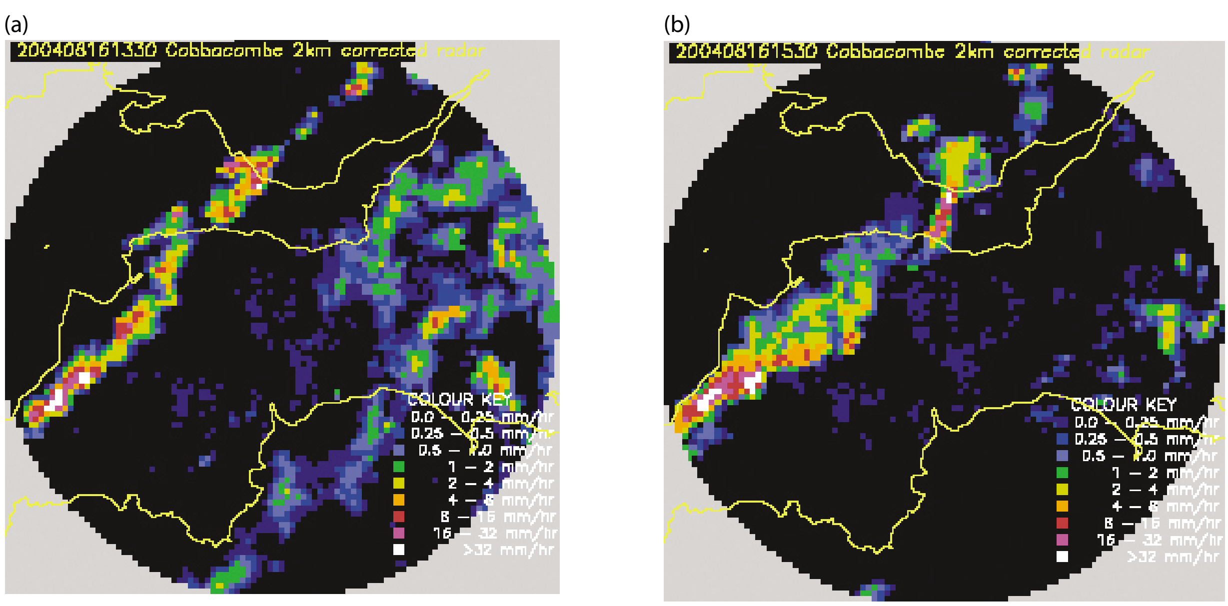

Fig. 7 Estimates of rainfall rate at 2 km resolution from the Cobbacombe radar at 1330 UTC (a) and 1530 UTC (b), 16 August 2004

(p. 233 follows Weather Log)

Fig. 9 Distribution of accumulated rainfall on 16 August 2004 : 5-hour totals (1200–1700 UTC) from 2 km corrected Cobbacombe radar data (colours) and 24-hour (0900–0900 UTC) raingauge totals (spot values)

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. Burt (this issue) discusses the issue of rain gauge accuracy further. 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 100 km. 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 2 km resolution, both radars recorded nine pixels (36 sq km) with accumulations exceeding 96 mm.

Twenty-four hour raingauge totals from all available raingauges are shown as point values in Fig. 9, 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 (76.5 mm), Lesnewth (184.9 mm), Otterham (200.4 mm), Credacott (123 mm) and Crowford Bridge (75.5 mm). Of these, only Otterham and Lesnewth are confirmed daily gauges. After correction to match the daily check gauge, the Lesnewth TBR recorded maximum short period accumulations of 82 mm in 1 hour, 148 mm in 3 hours, and 183 mm in 5 hours. Burt (this issue) discusses return periods for these accumulations. 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 south-west of Otterham near the A39.

The Lesnewth TBR record is shown in Fig. 10, computed from the time taken for each millimetre to fall. This produced a smoothed profile compared to the raw 0.2 mm counts, which were recorded only to 10-second precision. There was considerable variability, both at short timescales of 5 to 10 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 (Fig. 10). (See Burt, this issue, for more detail on the timing and location of the heavy rain bursts.) During the last period, at about 1535 UTC, the gauge recorded an uncorrected peak rain rate of nearly 300 mm/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 400 mm/hr.

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

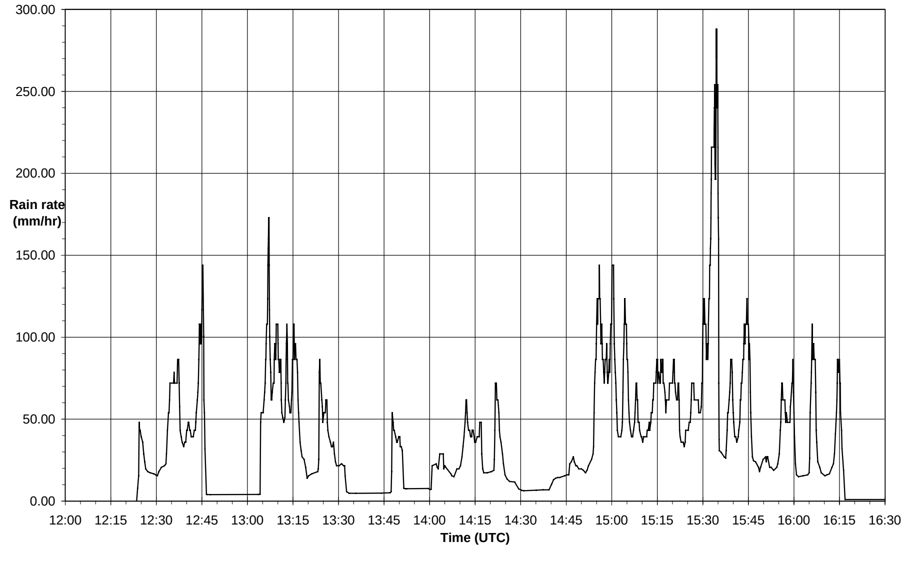

Fig. 10 Smoothed, uncorrected, rain rate profile 1200–1630 UTC from the Lesnewth Tipping Bucket rain gauge on 16 August 2004

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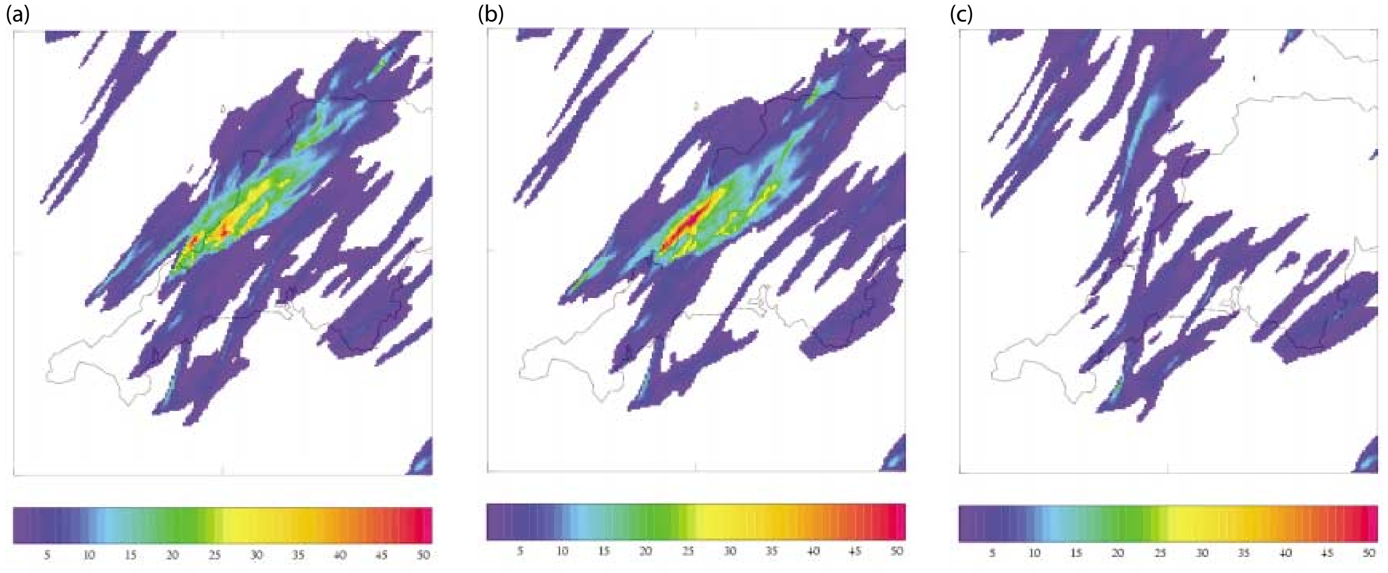

Fig. 11 Accumulated precipitation in mm from 1200–1700 UTC 16 August 2004 from 1km grid length integrations of the Unified Model. Full simulation (a), flat orography (b), flat orography with surface fluxes and land temperature fixed to sea values (c).

area covering only 300 × 300 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 11(a) 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 5 km, the minimum scale realistically represented by a 1 km 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.

Figure 12(a) shows the corresponding distribution of 10 m wind and its convergence at 1100 UTC. Strong convergence (~0.001 s^{-1}), shown as bands of orange shading close to the north coast, was highly persistent in the forecast and strong enough to generate substantial vertical motion (a few m s^{-1}) at cloud base. There are two mechanisms that could generate such convergence lines. One is the sea-breeze, which results from an onshore pressure gradient generated by differential heating of the land and sea. Interaction between an offshore wind and a sea-breeze can produce a quasi-stationary sea-breeze front along the coast (Simpson 1994). On this occasion, such interaction would have been complicated by the ambient wind being along the coast, and only offshore over the land due to frictional backing. The second mechanism arises when the wind over the sea is parallel to the coast, and is caused by acceleration and turning of air flowing from a rough land surface on to the smooth sea. The result is a coastal jet that may be significantly stronger than the ambient flow over the sea (Hunt *et al.* 2004) with a resulting boundary between the backed flow over land and the coastal jet, which is marked by convergence and uplift.

In order to clarify the processes involved in generating the convergence line, re-runs

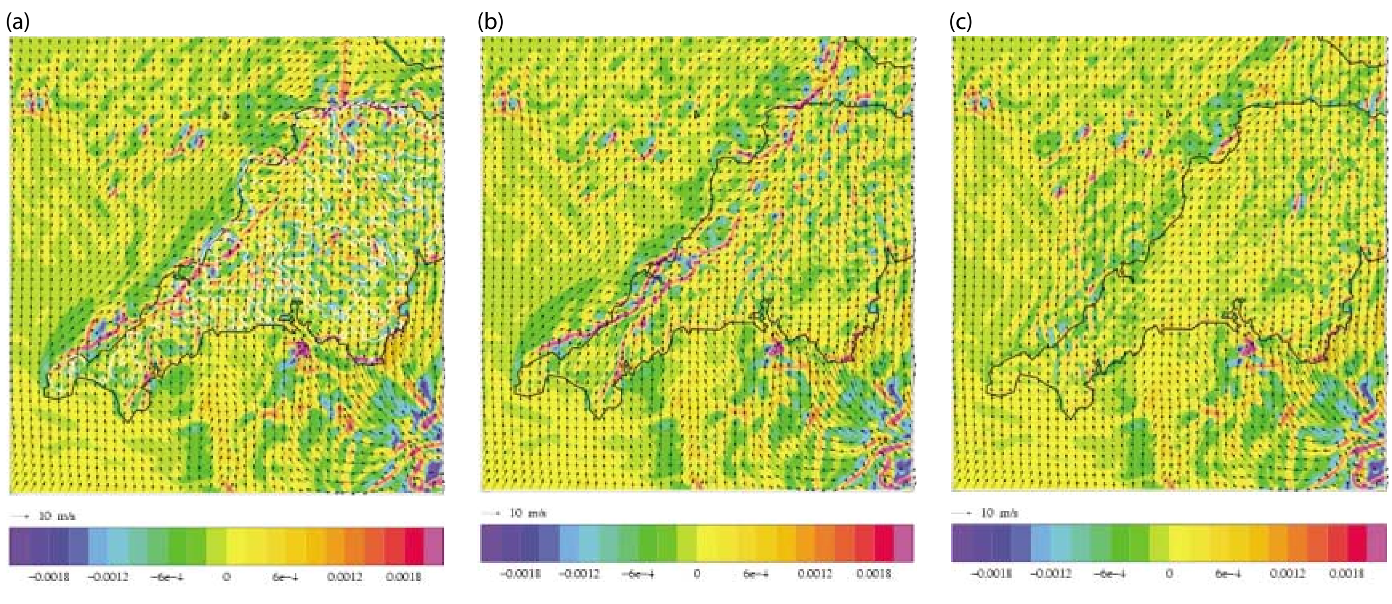

Fig. 12 Surface wind (variable length arrows) and convergence (colour scale in s^{-1}) at 1100 UTC, 16 August 2004 from 1km grid length integrations of the Unified Model. Full simulation (a), flat orography (b), flat orography with surface fluxes and land temperature fixed to sea values (c). Wind arrows are plotted every 4 km.

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. Figure 12(b) shows that the influence on precipitation of just changing the land height is small. The rainfall pattern is simpler and shifted to the north-west so that the heaviest rain falls in the sea, consistent with the loss of drag from the hills allowing a strengthened off-shore wind. Figure 12 shows that the convergence line is also more organised and closer to the coast in this case. Removing the enhanced surface fluxes (right panels) removes the Boscastle precipitation peak almost completely. This is expected, as surface heating is required to initiate convection. However, Fig. 12 shows that the coastal convergence has also disappeared. Thus, it appears that the convergence line was a sea-breeze front whose position was determined by a subtle balance between the gradient wind direction, retardation and backing of the wind over land, and differential heating.

Summary

Synoptic-scale developments over the eastern Atlantic on 16 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 about 6.5 km 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 200 mm of rain was recorded at the head of the Valency river catchment above Boscastle, and peak rates may briefly have reached 400 mm hr^{-1}.

Acknowledgements

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"View from the bridge": The dark waters sweep into lower Boscastle, smashing cars into buildings (courtesy Truran Books) © Wayne Grundy