Meteorology Research and Development

Assessment of Radar Data Quality in Upland Catchments
Final Report – November 2006

Technical Report No. FRTR 534

Dr Huw Lewis

email: nwp_publications@metoffice.gov.uk

CONTENTS

14 Conclusions

15 Recommendations

Appendix I: Statistics

References

PART I

1 Background

Radar data is potentially of particular value for flood forecasting in small upland catchments where there may be little or no supporting gauge or river flow measurements. Most evaluations of radar data quality in the UK to date have been conducted in lowland areas because they rely on sub-daily gauge networks for ground truth.

The objective of this project is to assess the potential of radar data for flood forecasting and warning in upland catchments. This is to be achieved by comparing rainfall data from the UK weather radar network, processed using existing Met Office methods, with rainfall recorded by surface rain gauges over a year. Three catchments which offer contrasting quality of radar coverage have been selected for the assessment. The study aims to

- quantify the uncertainties in radar measurement over the selected areas,
- identify work required to address deficiencies identified in the results,
- make recommendations on the required radar coverage in upland areas.

Specific questions to be considered are:

- Is radar data quality at long range over hills better or worse than over lowland areas?
- What effect does quality of radar coverage over upland areas have on radar data quality?
- What are the benefits gained from the current Met Office orographic correction scheme?
- How variable is radar data quality between events characterised by orographic effects?

- Is radar data over upland areas of sufficient quality for flood forecasting?
- How representative are rain gauge measurements in upland areas?

- Would improvements to the UK weather radar network contribute significantly to improving flood forecasting in upland areas?
- Would improvements to the radar data processing contribute significantly to improving flood forecasting in upland areas?

1.1 Orographic enhancement

It is generally understood that upland areas are regions of relatively heavy rainfall (e.g. Douglas and Glasspole 1947). Numerous observations have reported examples of the strong influence of the surface topography on the local rainfall distribution in upland areas on a range of scales, from continental scale mountain ranges such as the Andes to hills only a few tens of metres high (e.g. Smith 1979). Several studies of the rainfall distribution in the UK have demonstrated a link between rainfall and topography. For example, Hill et al (1981) showed the average annual rainfall over the hills of South Wales to be up to 2.5 times greater than over nearby coastal regions. Analysis of eight case study periods during south-westerly flow conditions showed an average surface rainfall enhancement of 2.8 mmh^{-1} between coastal and hilltop rain gauges. Measurements conducted by Kitchen and Blackall (1992) showed that enhancements of up to 2 mmh^{-1} can occur over relatively small hills of just 150 m height in the North Downs and Chilterns. Analysis of data from over 700 rain gauges in Scotland by Weston and Roy (1994) showed rainfall totals to be over twice as large over the mountainous areas of western Scotland as over adjacent coastal areas.

Hills and mountains can influence the amount and distribution of rainfall in several ways. For example, changes to the airflow induced as it is forced to pass over a hill can displace raindrops formed upstream towards the lee slope if the hill is of significant along-stream extent (Bradley et al 1997). Hills are also known to trigger convection, which can lead to generation of rainfall (e.g. Gray and Seed 2000). This can be as a result of uplift of air over a hill in a potentially unstable layer or flow convergence caused by flow around the sides of orography. Alternatively, hill surfaces can act as elevated heat sources relative to the surrounding environment which can also trigger convection.

The dominant influence of hills and mountains on rainfall in the UK is in encouraging cloud formation at low levels. Air parcels may become saturated as they are lifted over a hill. Although this process typically takes place on too short a timescale for the development of rain, the presence of cloud droplets in saturated air at low levels can have a significant effect on the surface rainfall. This can be explained by the seeder-feeder mechanism, first proposed by Bergeron (1965). A schematic illustration of this process is shown in Figure 1.1.

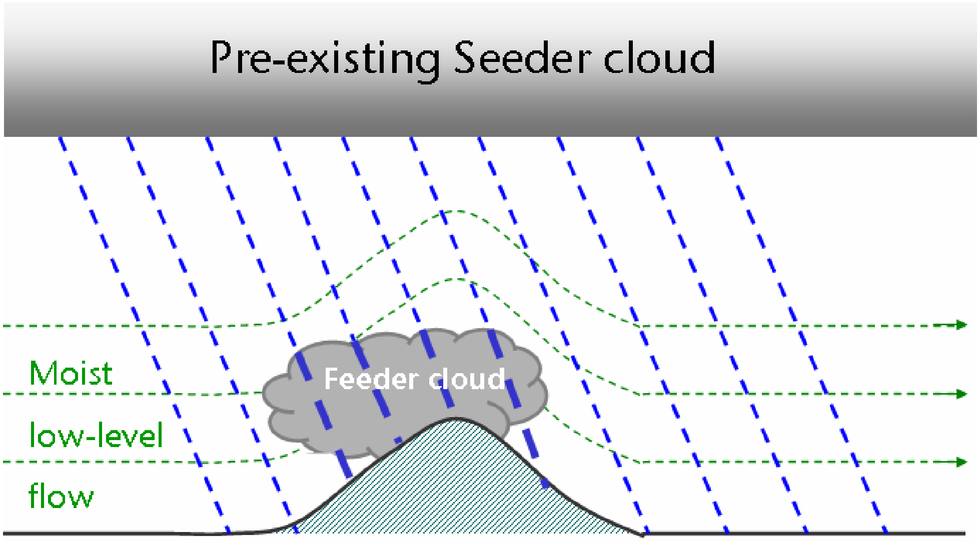


Figure 1.1: Schematic illustration of the seeder-feeder mechanism of orographic rainfall enhancement.

Low-level (feeder) cloud formed over a hill can act as a source of additional moisture for any rain formed further aloft in a pre-existing longer-lived (seeder) cloud. Rain falling out of the seeder cloud will therefore grow by coalescence with the feeder cloud droplets as it passes through the low level saturated region, producing a net increase of rainfall at the surface relative to that further aloft or over lowland regions. The observations of orographic enhancement over the hills of South Wales by Hill et al (1981) support this theory, with more than 80% of the enhancement shown to occur in the lowest 1500 m. The periods of enhanced rainfall over the hills were all associated with pre-existing (seeder) regions of precipitation. Hill et al. (1981) also demonstrated the mean enhancement between hill and coastal rainfall rates to increase as a function of wind speed measured at 600 m AOD.

Mechanisms of orographic rainfall enhancement have been simulated using a variety of analytical and numerical models which describe the effect of orography on airflow patterns and represent the efficiency of cloud droplet growth (e.g. Roe 2005). Bader and Roach (1977) provided one of the first analyses of a model of the seeder-feeder mechanism which demonstrated that the magnitude of orographic enhancement increases with background rainrate, low-level wind speed and relative humidity. The mean size and concentration of rain drops from the seeder cloud increases with background rainrate. This increases the efficiency of the coalescence process within the feeder cloud and the magnitude of rainfall enhancement at the surface. The dependence on wind speed arises because the saturated low-level air can be replenished more quickly in a faster flow. Condensation of this low-level air then takes place at a faster rate in a more humid layer. Bader and Roach (1977) found that no orographic enhancement occurred at all for upwind relative humidity below 82%. Further progress has been achieved by applying models with more realistic representation of the hill-induced flow patterns (e.g. Carruthers and Choularton 1983, Robichaud and Austin 1988, Dore and Choularton 1992) and inclusion of the effects of wind drift on the surface rainfall distribution (e.g. Carruthers and Choularton 1983, Alpert 1986). A number of modelling studies have also attributed the changes in pollution with altitude to the seeder-feeder mechanism. For example, Dore et al (2006) simulated observed increases of between 37 and 65% in wet deposition over upland areas across Snowdonia relative to lowland sites with a 1 km resolution orographic rainfall model.

1.2 Radar measurements of rainfall in upland areas

Surface rainfall rate estimates derived from radar data are prone to significant errors and uncertainty related to the radar measurement itself and the processing of radar data to compute a surface rainfall value (e.g. Joss and Waldvogel 1990). Generic problems associated with radar measurements include radar calibration, non-precipitation echoes due to clutter and anomalous propagation of the radar beam and attenuation of the radar beam by rain. The assumptions involved in the conversion of reflectivity measurements to rainfall and variations in the vertical profile of reflectivity (VPR) are most important in contributing to the uncertainty associated with the derived surface rainfall rate (Joss and Waldvogel 1990). The uncertainty tends to increase with range from the radar since the radar beam extends further above the surface and broadens with distance. This is likely to increase the possibility of signal attenuation and of the radar beam overshooting a region of shallow precipitation. In addition, the derivation of surface rainfall from the measured reflectivity is more prone to errors associated with the assumed variation of reflectivity with height.

Scarcity of rain gauges and high horizontal variability of rainfall in upland areas across the UK makes radar measurement particularly attractive for flood forecasting applications in upland catchments. Several contributing factors are likely to further restrict radar data quality in such areas however. The potential for beam blocking by hills and mountains is clearly increased, particularly where radars are required to be located within upland regions. This means that data at increased altitude from beams at higher elevation angles are required to derive the surface rainfall, which are prone to more significant errors at shorter range than might be achieved over lowland area. This is a particular problem for measurements in Alpine regions (e.g. Joss and Lee 1995). Further, the process of orographic enhancement tends to take place in the lowest 1500 m above ground (Hill et al. 1981) which is typically below the height of the radar beam at most ranges of interest. Additional assumptions and corrections are therefore required as part of the data processing method in order to obtain accurate rainfall estimates which account for the low-level enhancement. The scarcity of rain gauges in upland areas compared with lowland regions will limit their use for real-time calibration of the radar-derived surface rainfall. This is compounded by the uncertainty of how representative point rain gauge measurements are of the ground truth (Wood et al 2000).

1.3 Correction methods

The current operational processing of radar data conducted by the Met Office involves adding a correction to the derived background rain rate to account for the orographic enhancement process. The orographic correction therefore forms an integral part of the VPR correction process detailed by Kitchen et al. (1994). This diagnoses a background reflectivity factor at each radar pixel by fitting an idealised vertical reflectivity factor profile weighted by the radar beam power profile. A sketch of the idealised profile used when the freezing level, taken from the Met Office mesoscale model, is below cloud top height, as derived from satellite imagery, is shown in Figure 1.2. Alternative profiles are used for conditions when graupel or snow is suspected at the surface and when the freezing level height exceeds cloud top height.

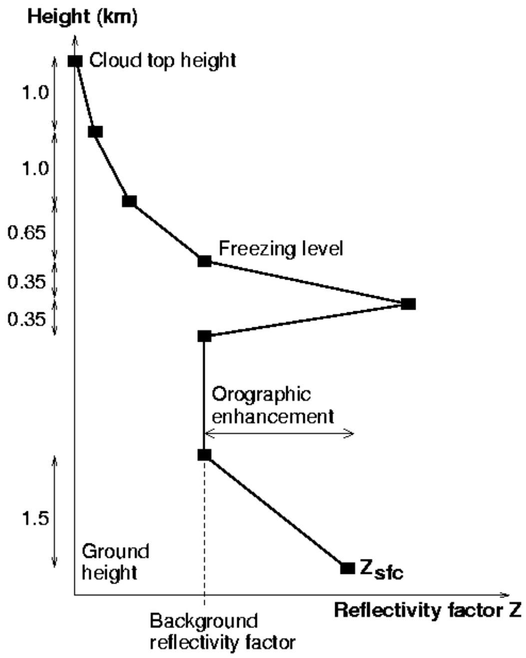


Figure 1.2: Idealised vertical reflectivity factor profile used in the Met Office VPR correction scheme to derive a background reflectivity factor from radar measurements.

The orographic correction added to the background reflectivity factor at each pixel is based on the climatology developed by Hill (1983) for measurements over England and Wales and the physical model developed by Alpert and Shafir (1989) for other regions. Example orographic correction fields applied across the UK radar network domain are shown in Figure 1.3. The magnitude and distribution of the correction field applied depends on the humidity, wind speed and wind direction at the 800 m level in the operational mesoscale model. Corrections are only applied if the model relative humidity is in excess of 85%. The correction applied at each pixel is then chosen from the relevant constant enhancement field for a given wind speed and direction, defined at a 5 km horizontal resolution. Different fields are defined for the 9 wind direction and 4 wind speed categories listed in Table 1.1. No correction is applied for wind speeds less than 8 ms^{-1}. The correction deduced from the appropriate constant correction field at each pixel is finally scaled by a relative humidity dependent factor to estimate the actual correction factor applied to the background data. This has the form,

$$OrographicCorrection = 0.1(RH - 85\%) \times CorrectionField$$

resulting in values ranging between 10% and 150% of those shown in Figure 1.3 for relative humidities of 86% and 100% respectively.

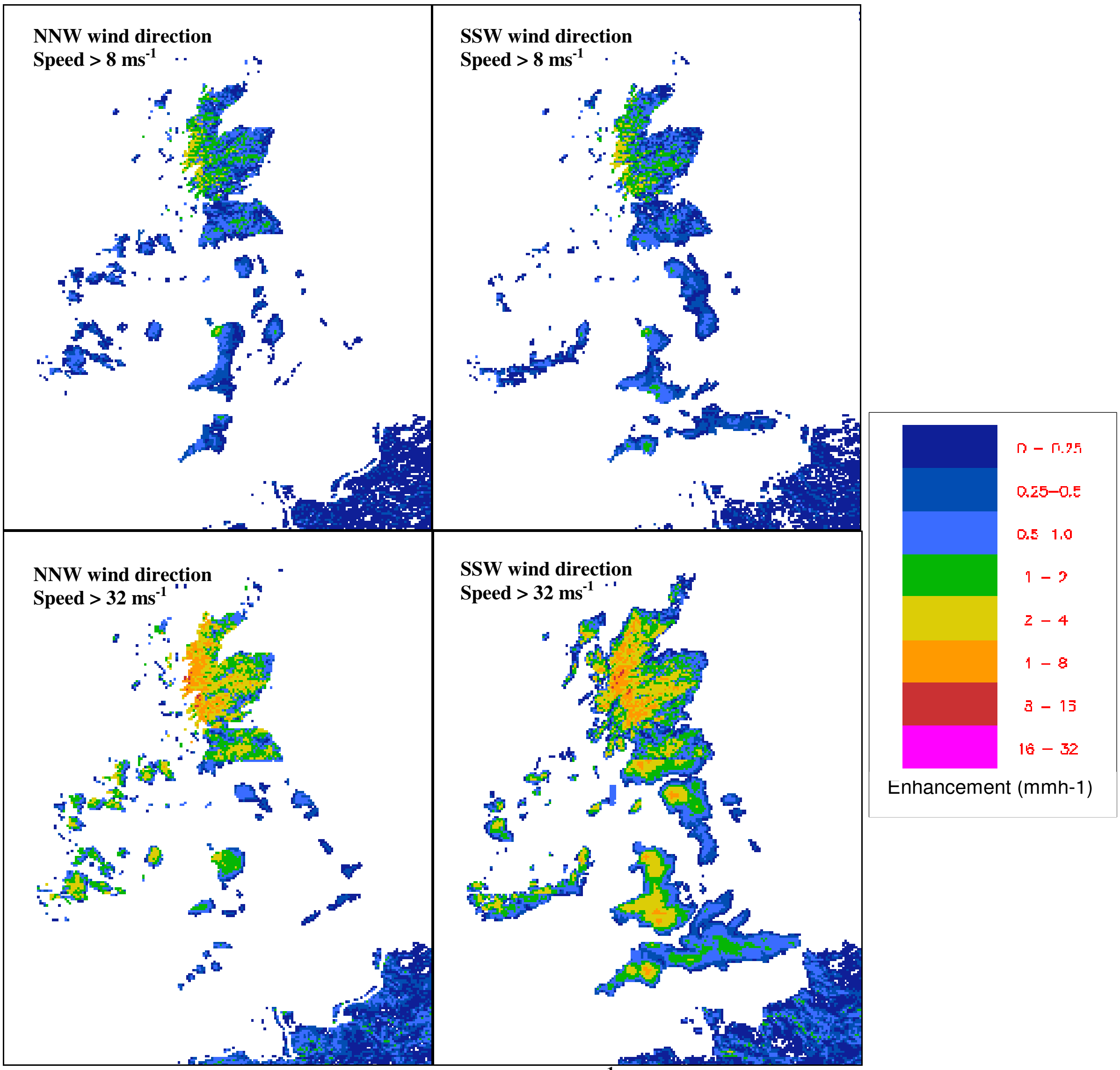


Figure 1.3: Examples of orographic correction fields (in mmh^{-1}) applied to background radar rain rates for wind speeds in excess of 8 ms^{-1} and 32 ms^{-1} from NNW and SSW wind directions.

Wind speed categories:	8-16 ms^{-1}	Wind direction categories:	N	357.75-11.25°
	16-24 ms^{-1}		NNE	11.25-45.0°
	24-32 ms^{-1}		ESE	90.0-135.0°
	>32 ms^{-1}		SSE	135.0-180.0°
			SSW	180.0-225.0°
			WSW	225.0-270.0°
			WNW	270.0-315.0°
			NNW	315.0-357.75°

Table 1.1: List of wind speed and direction categories used to distinguish between orographic correction fields.

The climatology of orographic enhancement applied across England and Wales was developed by Hill (1983) using rain gauge data between 1941 and 1970. Following Hill et al (1981), enhancement was defined as the difference between the mean rainfall rate inland and over the upwind coast. In terms of the VPR sketched in Figure 1.2, the coastal surface rainfall is assumed to represent the background rainfall which would be estimated from radar measurements over upland areas with no account for orographic enhancement. This assumes horizontally uniform rainfall characteristics between the coast and inland regions. An average rainfall intensity map was derived by dividing the average annual rainfall distribution by a smoothed distribution of average annual duration of rain exceeding 0.05 mmh^{-1}. This gave typical values of between 1.5 and 2.5 mmh^{-1} over hilly regions compared with only 0.8 mmh^{-1} over coastal regions. A similar analysis was then applied to rain gauge measurements during frontal systems with fairly constant geostrophic winds between south-easterly and westerly directions when coastal and upland rainfall rates could be compared. Data were classified according to wind direction and speed to reflect their influence on the magnitude and distribution of orographic enhancement (Hill et al. 1981). Maps of the mean rainfall rate, derived by dividing the daily rainfall accumulation field by the duration of rain exceeding 0.05 mmh^{-1}, were produced from interpolated gauge measurements for each case. The mean enhancement for each wind category was then found for each of 7 regions across England and Wales. This was achieved by averaging 10 km gridded rainfall rates from periods with similar wind speed and direction across that region. Enhancement fields for other wind directions were then estimated by scaling the average annual enhancement distribution by typical ratios between the enhancement for previously computed wind categories and the average annual enhancement. The scaling ratio chosen depended on whether the enhancement was applied to a location characterised as being coastal or hilly and on its exposure to maritime winds.

The orographic enhancement applied to other regions is derived from the model by Alpert and Shafir (1989) of orographic rainfall over low hills. This is an extension of the two-dimensional model by Alpert (1986) to three dimensions. The model assumes that moisture convergence due to uplift by hills and mountains is equal to the orographic precipitation enhancement. This gives an expression for the precipitation rate at a point above terrain $Z_s(x,y)$,

$$P \approx \rho q(V \cdot \nabla Z_S + W_l) + E$$

where E is the evaporation rate, ρ, q and $\boldsymbol{V}$ are the mean air density, specific humidity and horizontal velocity in the boundary layer respectively and W_l is the synoptic scale vertical motion. It was shown that the contribution from evaporation was small for relative humidity in excess of 85%. Making this assumption, the net contribution to the precipitation induced by the local topography can be written,

$$P' \approx \frac{\varepsilon r e_S(Z_s) V \cdot \nabla Z_S}{RT(Z_S)}$$

In order to consider advective effects and account for precipitation by upwind clouds, Alpert (1986) proposed computing an area averaged enhancement given by

$$P_0 = f \frac{1}{W_0} \sum_{i=0}^{N} W_i P_i$$

where *f* is a tuning parameter and

$$W_i = e^{-(x_i - x_0)^2 / 2\sigma^2}$$

is calculated for each of *N* upwind distance steps where $\sigma = |V|.t$ for a typical cloud lifetime *t*.

This presents a method for defining orographic corrections for each pixel in the radar domain for each of the wind speed categories used by Hill (1983) based on the local terrain slope $\Delta Z_s/\Delta s$ along the prevailing wind direction associated with each wind direction category in Table 1.1. Computing constant correction fields in this way required some assumptions about suitable values of ρ and q. In principle, this approach might be used in real time with scope for using model derived values of the mean boundary layer humidity.

Limitations of the current method include:

- dependence on two different schemes across the UK
- the Alpert and Shafir (1989) scheme allows for greater spatial variation than Hill (1983)
- application at 5 km horizontal resolution
- assumption that the orographic enhancement process can be described by climatology
- relatively few meteorological inputs are utilised
- variation between individual events, which may be of most significance for effective flood forecasting, is likely to be smoothed by the orographic corrections.
- assumption that the measured background rain rate is independent of any low level orographic enhancement process is likely to be incorrect in most cases.

The actual correction applied to radar data in the VPR correction process may be modified from the constant enhancement fields derived from the model data if the background reflectivity factor is very small (less than an equivalent rainfall intensity of 1/32 mmh^{-1}). In this case, the surface reflectivity factor value Z_{sfc} is scaled by the ratio of the original radar reflectivity measurement to the radar beam power weighted reflectivity factor when this ratio is less than unity. This effectively reduces the difference between Z_{sfc} and the background value, limiting the magnitude of the orographic correction from that specified using the model data.

1.4 Verification of radar data

Verification of radar data quality is conducted routinely as part of the Met Office processing and quality control procedure (Harrison et al. 2000). This involves computing gauge-radar comparison statistics based on average gauge-radar differences over the radar domain and periodic case study analysis of performance during significant high rainfall events. The routine gauge-radar statistics are to be compared with results for upland catchments as part of the data quality assessment conducted in this study.

Longer-term assessments of radar data quality have been conducted to investigate the potential of radar data for hydrological applications. One notable example is the Hydrological Radar Experiment (HYREX) between 1993 and 1996. The main experimental work focussed on the provision of a dense network of 49 rain gauges in the 135 km^2 Brue catchment, Somerset. The terrain elevation ranges across the catchment between 23 m and 153 m AOD. The higher ground was anticipated to induce low level orographic enhancement during periods of south-westerly flow (Wood et al. 2000). Wood et al. (2000) examined the accuracy of rainfall estimates obtained from rain gauges and the operational weather radars located at Wardon Hill (30 km from catchment) and Cobbacombe Cross (70 km from catchment). The analysis compared single gauge measurements with areal averages from eight gauges within a 2 km grid square and from the entire catchment gauge network. Two different 2 km gauge networks were selected with one in an area of low and one in higher relief. Similarly, the 2 km resolution radar data were compared with the 2 km grid square and catchment-wide rain gauge areal rainfall averages. Errors of around 33% and 45% were observed for rain gauge measurements of 4 mm rainfall accumulations in 15 min over the low and high 2 km grid squares respectively, suggesting some influence of terrain elevation on rainfall variability. A standard error of 50% was calculated for radar measurements on a 2 km square. Differences between the accuracy of measuring convective and stratiform rain were not identified. Considering catchment-wide rainfall, HYREX showed a standard error of 65% for single gauge measurements of 4 mm in 15 min and 55% for radar measurements.

Relatively little attention has been specifically given to radar data quality over upland areas, despite the uncertainties involved in radar measurements in such regions. This is partly a result of the limited number of rain gauges in hilly terrain required to determine a ‘ground truth’ surface rainfall pattern. An early study of radar data quality over hilly terrain in north Wales by Harrold et al. (1974) estimated typical errors of at least 20% between rain gauge measurements and calibrated radar data at 20 km range over a 3 hour period. Analysis of radar measurements over the low hills of the Chilterns and North Downs by Kitchen and Blackall (1992) showed that variations due to orographic enhancement shown by rain gauge measurements were underestimated by the radar data. Correction factors applied to the data, based on the climatology deduced by Hill (1983), were shown to be largely unsuccessful in predicting the systematic differences in observed enhancement between particular rainfall events. More recently, Cranston and Black (2006) presented a case study assessment of radar data quality in central Scotland, a region described as having diverse and steep topography. Processing of radar data across this region involves applying the orographic corrections based on the Alpert and Shafir (1989) formulation. Comparisons between 5 km resolution radar and gauge data during 11 storm events during 1999 and 2000 showed no consistent error bias and a 24% mean error in storm rainfall totals. Cranston and Black (2006) concluded that radar data was of sufficient quality to provide a useful quantitative tool for flood warning in steep upland catchments.

2 Catchment selection

Three upland areas, which are broadly analogous to the river catchments of the Upper Exe, Upper Taff and Upper Conwy, have been chosen for the study. All are in regions which have experienced flooding as a result of orographically enhanced rainfall. The catchments provide examples of contrasting topography and each are considered to have sufficient number of rain gauges for useful comparison with radar measurements. The proximity of radar sites and the number of radars offering coverage are different for each catchment, providing the opportunity to assess the influence of weather radar range on data quality. Figure 2.1 shows the location of each of the chosen study areas and the radar coverage provided by the UK radar network in those regions. Each study area considered is approximately 500 km^2 to include a number of upland rain gauges.

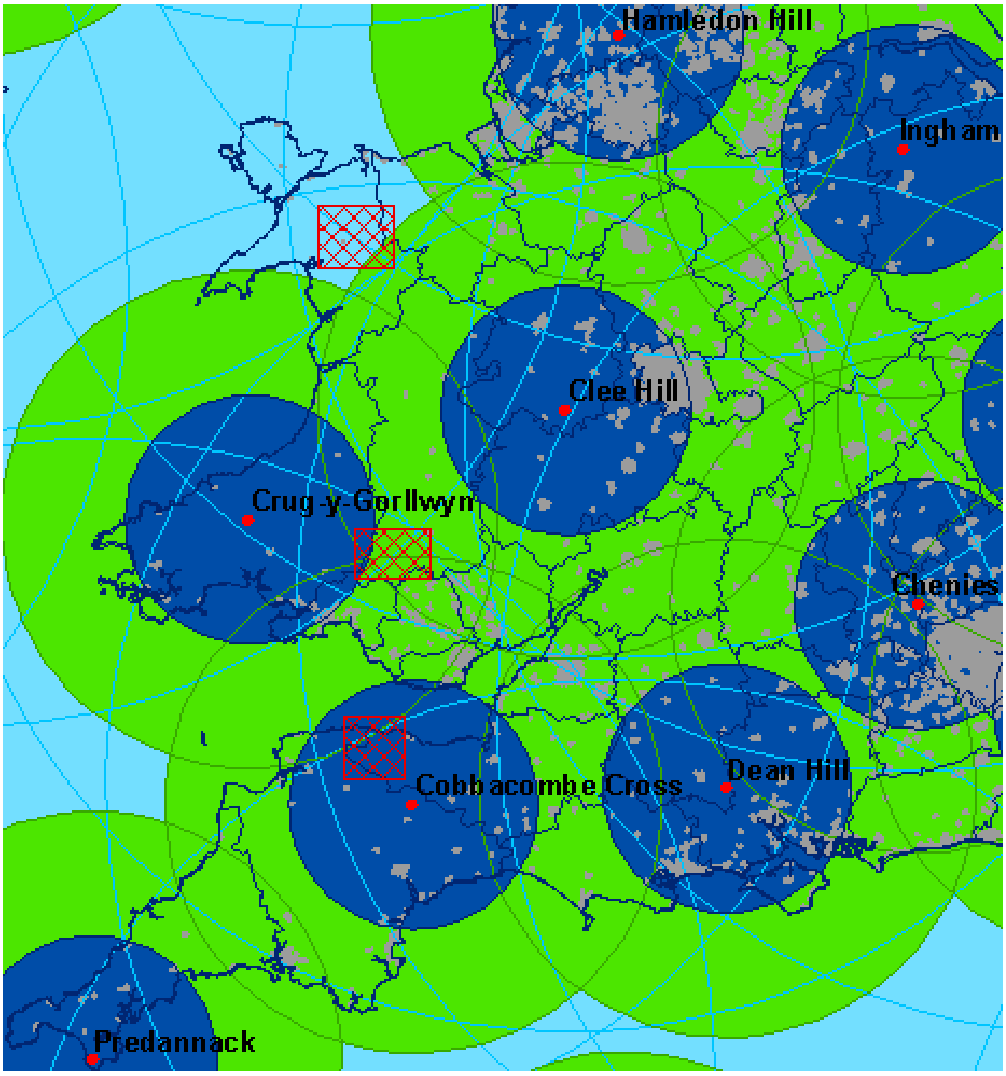


Figure 2.1: Coverage of the weather radar network across the British Isles in the vicinity of the Upper Exe (north Devon), Upper Conwy (north Wales) and Upper Taff (south Wales) study areas. Circles surrounding each radar show regions of radar data coverage at 1 km (dark blue), 2 km (green) and 5 km (light blue) horizontal resolution.

Figure 2.2 illustrates the extent of coverage for the radars providing data across each of the three study areas and their locations relative to the major topographic features. The images highlight parts of the radar domain for which data from upper elevation scans are required, primarily as a result of clutter or beam blockage for lower elevation scans.

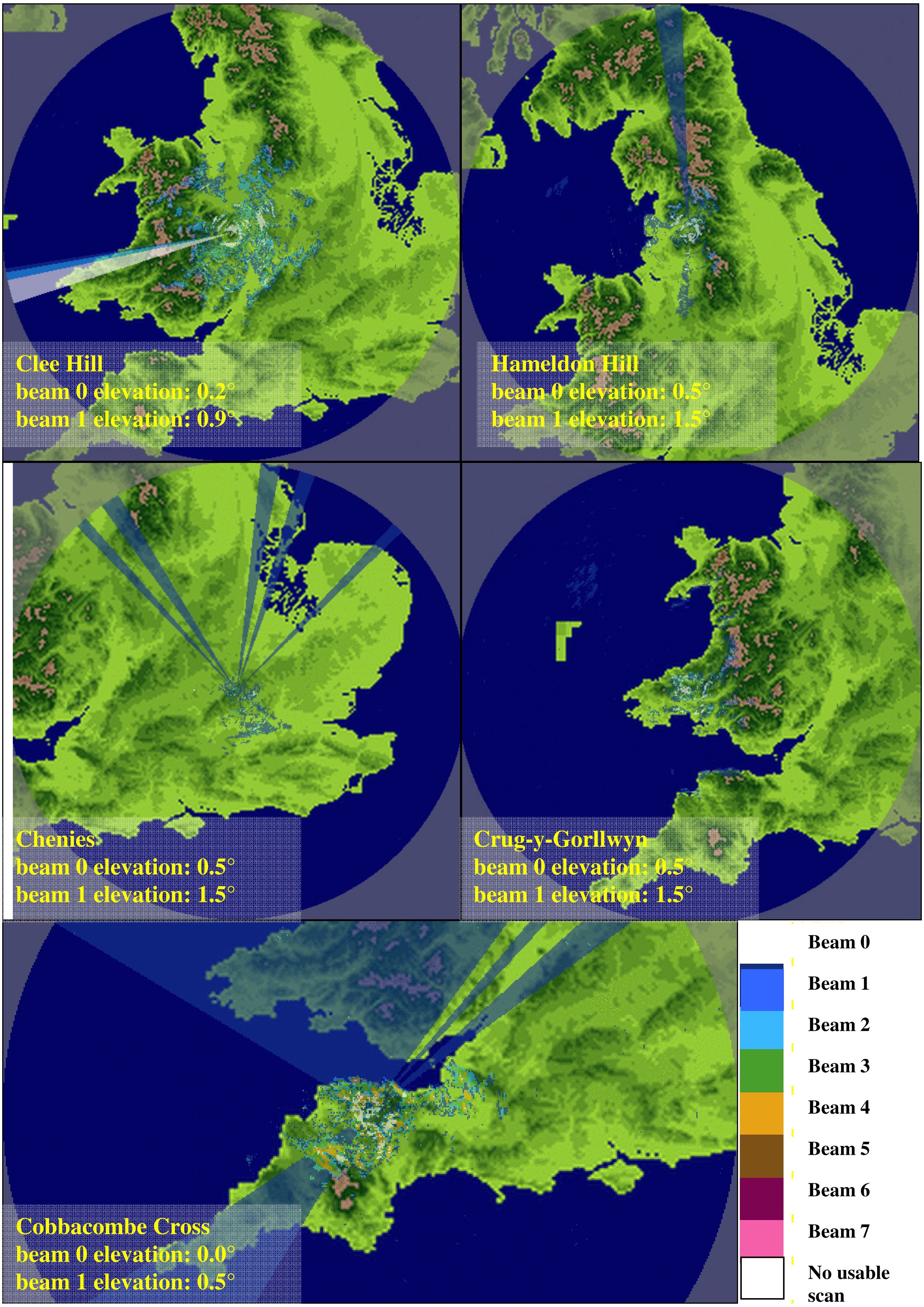


Figure 2.2: Topographic maps showing lowest usable scans for radars with coverage across each of the study areas of interest.

2.1 Upper Exe

The Upper Exe study area is located in North Devon. A map of the study sample area chosen is shown in Figure 2.2. The region is subject to significant orographic rainfall associated with Exmoor. In an extreme case, 228.6 mm of rain fell over Exmoor in one day during the "Lynmouth Storm" of 15th August 1952 (Bleasdale and Douglas, 1952). This event resulted in 34 flood-related fatalities in Lynmouth and Lynton (Burt 2005). More recently, Driscoll et al (1997) assessed the quality of (5 km resolution) radar data over Exmoor during an event on 26-27th June 1997 when persistent heavy rainfall over Exmoor produced a daily accumulation of 120 mm in a 24 hour period.

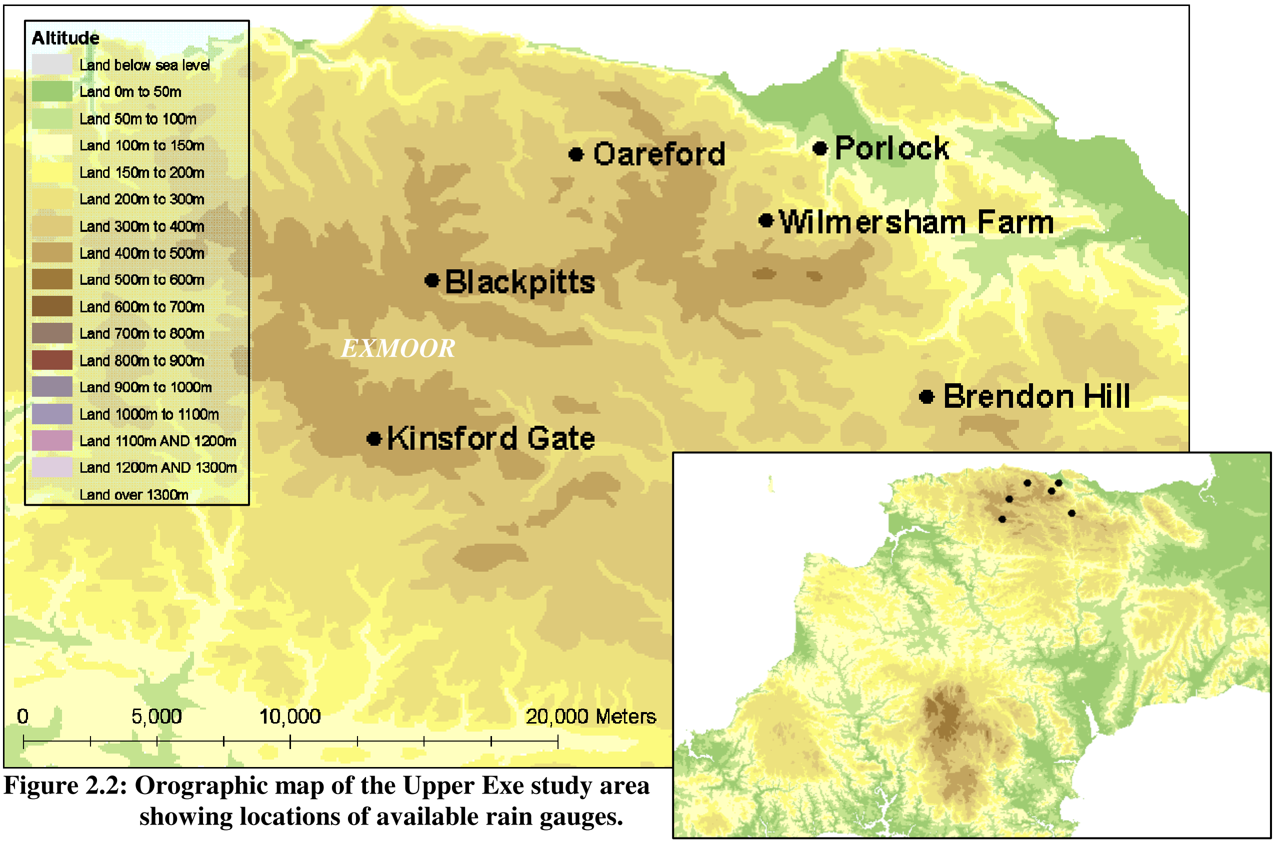


Figure 2.2: Orographic map of the Upper Exe study area showing locations of available rain gauges.

Surface rainfall measurements in the catchment are available from 6 rain gauges provided by the Environment Agency, most of which are sited above 350 m AOD. These are listed in Table 2.1. The highest gauge at Kinsford Gate is at an altitude of 450 m AOD while the lowest gauge at Porlock on the North Devon coast is at 125 m AOD, but in a region with steep terrain gradients. The availability of rain gauge data from the Exe region during the study period is shown in Figure 2.3. The gauge data used in this study were provided as 15 minute rainfall accumulations.

The Upper Exe catchment is a region of good radar coverage. Rainfall data are available across the region at a 1 km and 2 km horizontal resolution from the Cobbacombe Cross radar. Additional radar coverage is provided at a 5 km resolution from radars at Clee Hill (Shropshire), Crug-y-Gorllwyn (Ceredigion), and Predannack (Cornwall). The area of coverage for each radar measuring rainfall over the Upper Exe catchment is illustrated in Figure 2.1. Under normal operational conditions, the data from the Cobbacombe radar are used for this region in the composite radar image. Note that the radar at Dean Hill (Figure 2.1) was not operational during the study period and data from this radar are not considered in this analysis.

Site Name	Easting	Northing	Approx altitude (m)
Kinsford Gate	274470	136528	450
Blackpitts	276380	141750	430
Oareford	281176	145897	343
Wilmersham Farm	287427	143758	350
Brendon Hill	292744	137902	350
Porlock	289242	146083	125

Table 2.1a: Details of available rain gauges in the Upper Exe study area.

	Cobbacombe		Crug-y-G		Clee Hill		Predannack	
	Range (km)	Beam height	Range (km)	Beam height	Range (km)	Beam height	Range (km)	Beam height
Kinsford Gate	29	155	107	1485	165	2260	160	2545
Blackpitts	31	200	103	1425	160	2160	165	2710
Oareford	31	20	101	1480	154	2115	171	2975
Wilmersham Farm	26	220	106	1575	152	2080	177	3355
Brendon Hill	19	140	114	1745	155	2140	173	3030
Porlock	28	225	105	1780	149	2245	177	3355

Table 2.1b: Range of available radars from each rain gauge in the Upper Exe study area and typical height above the surface (in m) of the lowest usable radar scan at each gauge location.

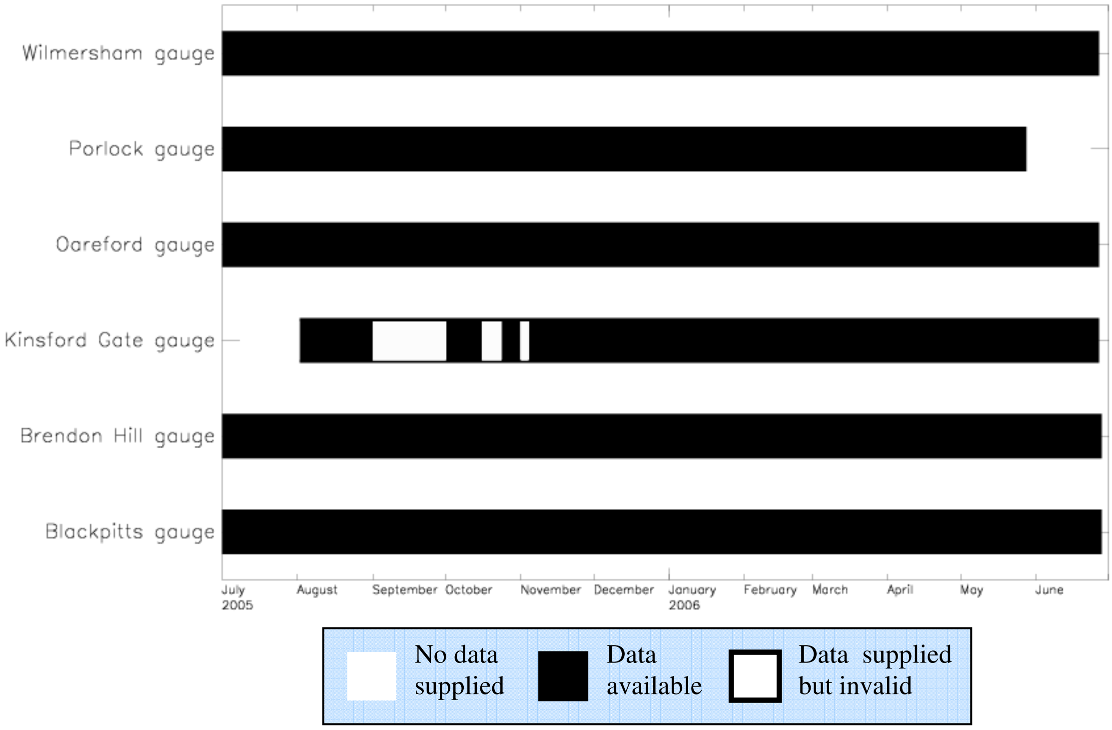


Figure 2.3: Availability of 15 min data from rain gauges in the Upper Exe study area since July 2005.

2.2 Upper Conwy

The Upper Conwy study area is located in North Wales in a region which includes parts of Snowdonia National Park and the Snowdon mountain range. A map of the study sample area is shown in Figure 2.4. This is a region of particularly steep terrain, with terrain rises of over 700 m in a horizontal distance of 500 m. Snowdon has an altitude of 920 m. The area has experienced significant flooding (Sibley 2004) and the use of radar data is of particular importance for flood forecasting in the region since many sub-catchments are without gauges and are prone to fast response times.

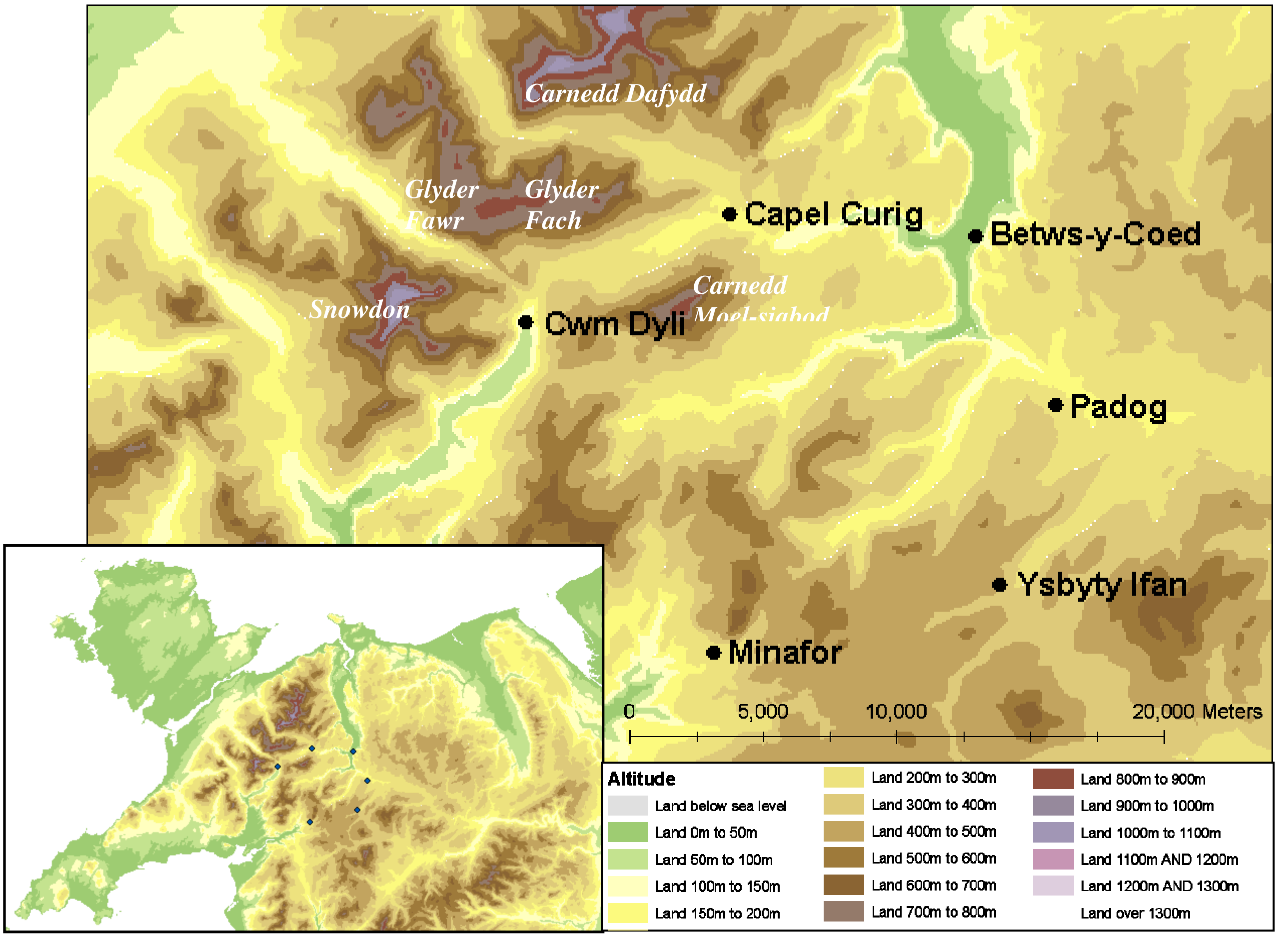


Figure 2.4: Orographic map of the Upper Conwy study area showing locations of available rain gauges.

Surface rainfall measurements in the area are available from 6 rain gauges located at elevations in the range between 100 and 400 m AOD. These gauges are listed in Table 2.2. One gauge is located at Ysbyty Ifan, at an altitude of 392 m AOD, while the lowest gauge is located at Betws-y-Coed at an elevation of just 22 m AOD. The availability of rain gauge data from the Conwy region during the study period is shown in Figure 2.5. Data from all gauges in the Upper Conwy region are available as tip times in 0.2 mm rainfall increments.

In contrast to the Upper Exe, the Upper Conwy study area is a region with some of the poorest radar coverage. Rainfall data are only available at a 5 km horizontal resolution. This is provided from the radars located at Hameldon Hill (Lancashire), Clee Hill and Crug-y-Gorllwyn. The areas of coverage for these radars are illustrated in Figure 2.1. Under normal operational conditions, data from the Clee Hill radar are used for this region in the composite radar image.

Gauge ID	Site Name	Easting	Northing	Approx. elevation (m)
848	Betws-y-Coed	280260	357080	22
861	Cwm Dyli	265400	354200	94
853	Capel Curig	272100	357800	180
999	Minafor(Ffestiniog)	271608	343315	205
1003	Padog	282900	351500	220
1014	Ysbyty Ifan	281060	345590	392

Table 2.2a: Details of available rain gauges in the Upper Conwy study area.

	Clee Hill		Crug-y-G		Hameldon	
	Range (km)	Beam height	Range (km)	Beam height	Range (km)	Beam height
Betws-y-Coed	112	1630	132	2495	124	2365
Cwm Dyli	121	1715	125	2245	138	2630
Capel Curig	118	1585	130	2290	130	2360
Minafor	109	1410	116	1940	139	2550
Padog	106	1340	128	2200	125	2195
Ysbyty Ifan	103	1125	122	1885	130	2145

Table 2.2b: Range of available radars from each rain gauge in the Upper Conwy study area and typical height above the surface (in m) of the lowest usable radar scan at each gauge location.

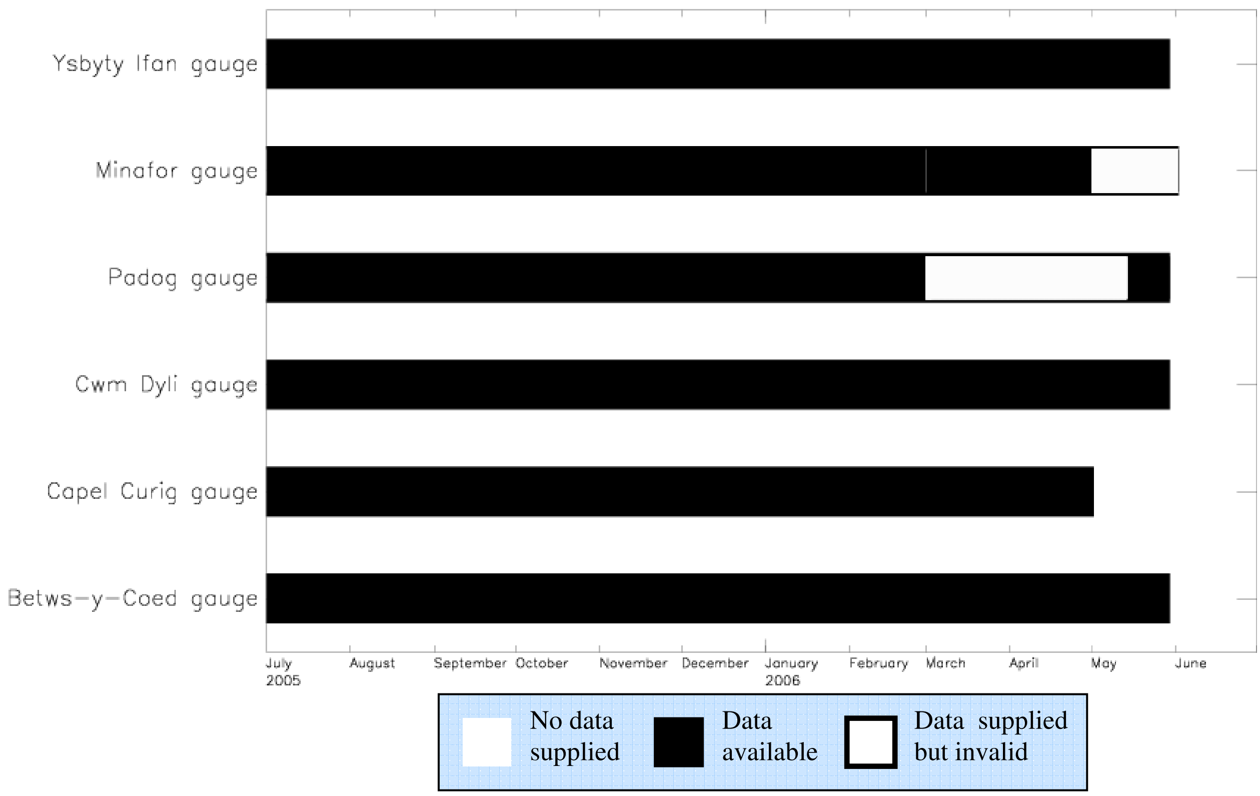


Figure 2.5 Data availability from rain gauges in the Upper Conwy study area since July 2005.

2.3 Upper Taff

The Upper Taff study area located in South Wales comprises most of the Brecon Beacons National Park and the South Wales valleys region. A map of the study sample area chosen is shown in Figure 2.6. South Wales has been the focus of several investigations of the process of orographic enhancement of rainfall (e.g. Browning et al 1974, Hill et al 1981) which led to the developments in radar processing of rainfall data over orography currently used in the Met Office radar data processing chain.

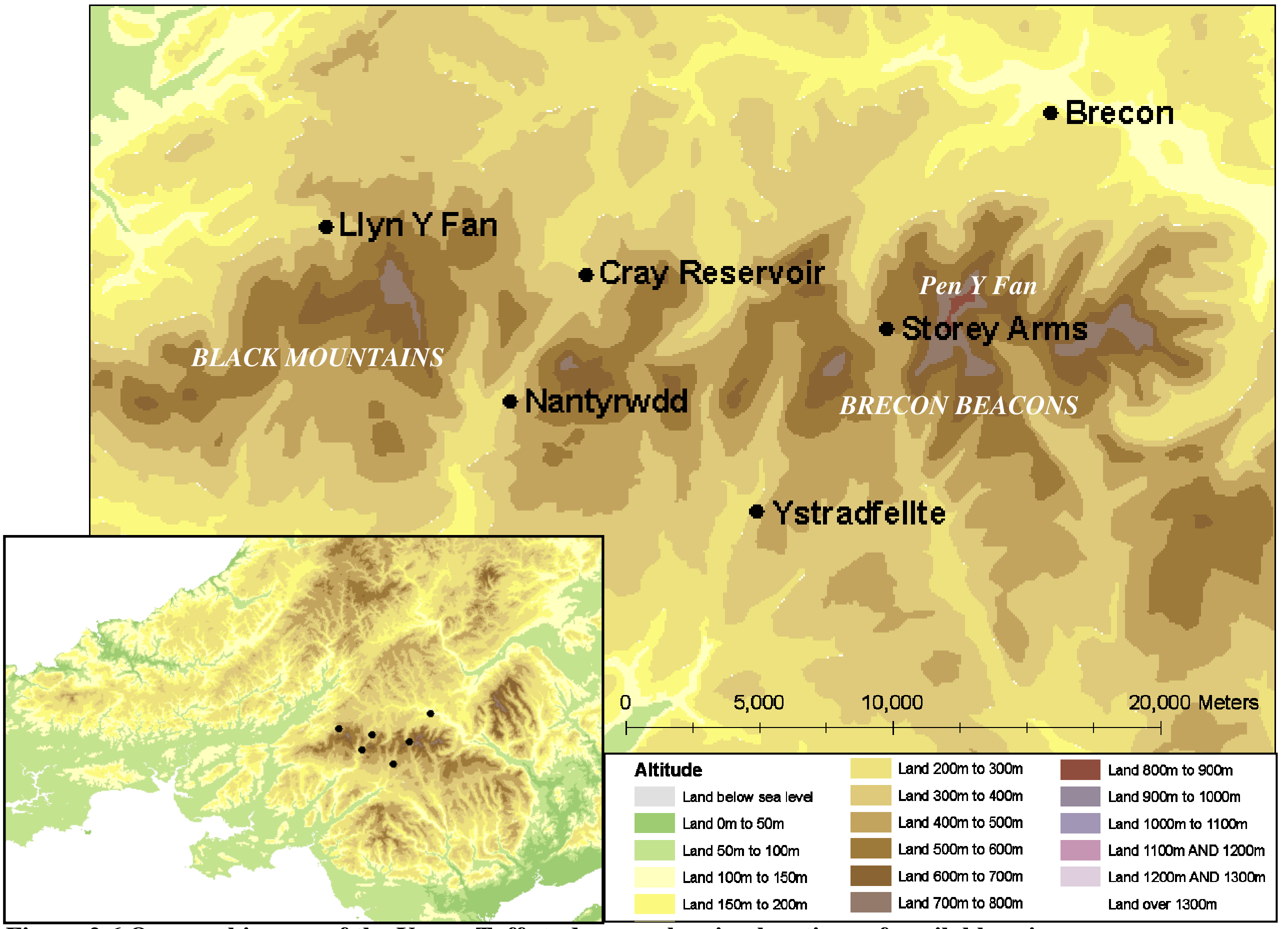


Figure 2.6 Orographic map of the Upper Taff study area showing locations of available rain gauges.

Surface rainfall measurements in the Upper Taff catchment are available from 6 rain gauges, most of which are located at elevations above 300 mm AOD. Details are listed in Table 2.3. The highest gauge is located at Storey Arms at 530 m AOD while that on the outskirts of Brecon is at an altitude of 168 m. The availability of rain gauge data from the Taff region during the study period is shown in Figure 2.7. Data from the Brecon and Ystradfellte gauges are available as tip times in 0.2 mm rainfall increments and data from all other rain gauges are available as 15 minute rainfall accumulations.

Radar coverage is available at a 2 km horizontal resolution from two radars located at Clee Hill and at Crug-y-Gorllwyn. In addition, 5 km horizontal resolution radar data is available from Chenies (Hertfordshire). The areas of coverage for each radar are illustrated in Figure 2.1. Under normal operational conditions, data from the Clee Hill radar are used for this region in the composite radar image.

Gauge ID	Site Name	Easting	Northing	Approx. elevation (m)
891	Brecon	303725	227630	168
844	Llyn Y Fan	279791	223829	264
951	Nantyrwdd	285900	218100	300
806	Ystradfellte	294028	214417	312
900	Cray Reservoir	288405	222259	320
929	Storey Arms	298300	220450	530

Table 2.3a: Details of available rain gauges in the Upper Taff study area.

	Crug-y-G		Clee Hill		Chenies	
	Range (km)	Beam height	Range (km)	Beam height	Range (km)	Beam height
Brecon	72	730	75	1350	200	4100
Llyn Y Fan	49	385	96	1650	223	4785
Nantyrwdd	56	420	94	1585	216	4515
Ystradfellte	65	505	91	1505	208	4220
Cray Reservoir	58	415	90	1480	214	4425
Storey Arms	68	315	84	1150	204	3880

Table 2.3b: Range of available radars from each rain gauge in the Upper Taff study area and typical height above the surface (in m) of the lowest usable radar scan at each gauge location.

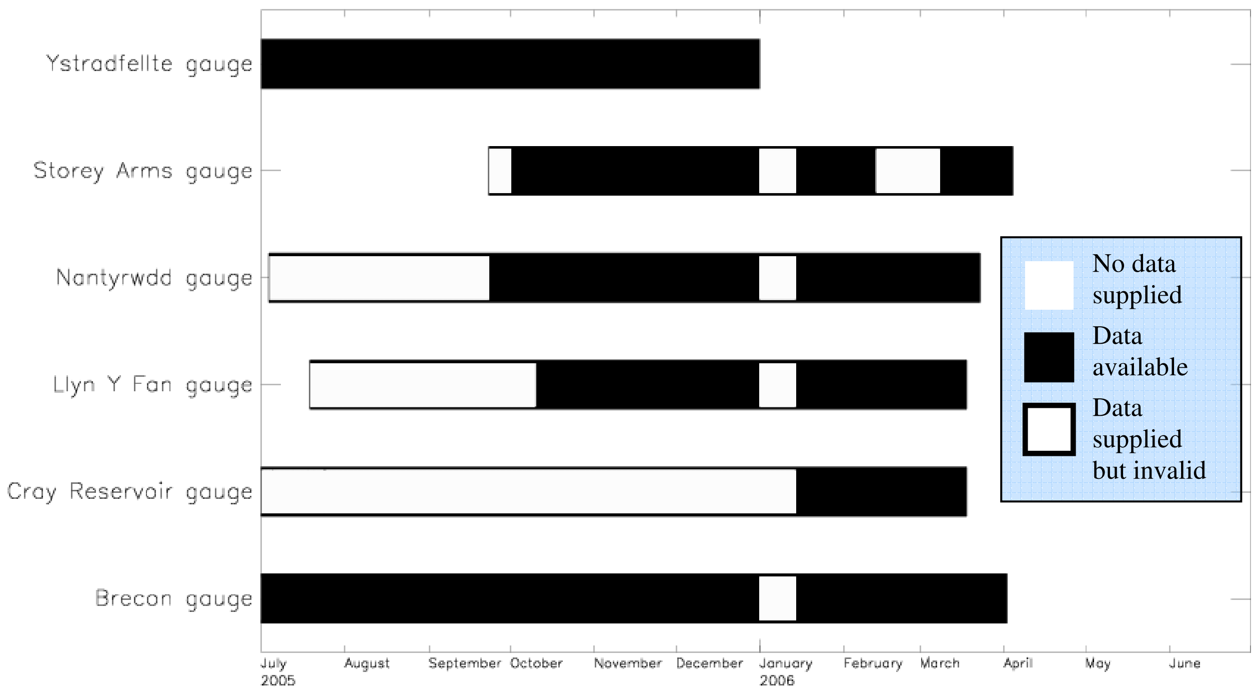


Figure 2.7 Data availability from rain gauges in the Upper Taff study area since July 2005.

3 Study period

The 1 July 2005 to 30 June 2006 study period was generally characterised by lower than average rainfall, with about 94% of the average 1961-1990 rainfall observed across the UK during this period. Figure 3.1 illustrates how the rainfall distribution during the study period varied greatly with extremes of only 49% of the average monthly rainfall measured across the UK during January 2006 and 158% of the average monthly rainfall during May 2006.

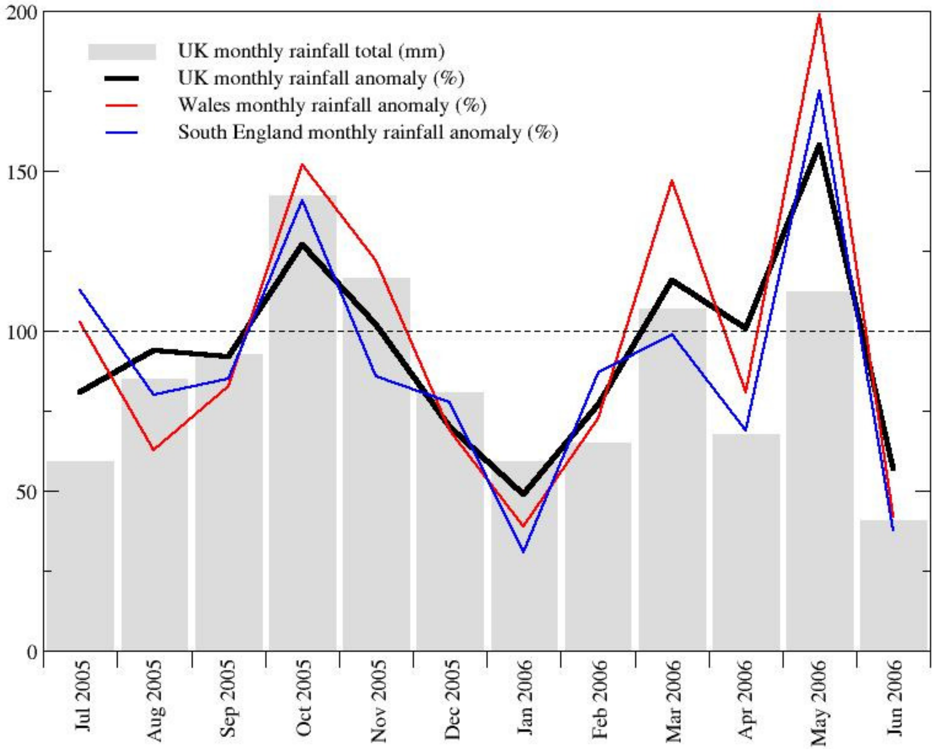


Figure 3.1: Monthly UK rainfall total and percentage anomaly from the 1961-1990 average monthly rainfall during study period.

The relatively low winter rainfall totals is reflected by a below average number of flood warnings issued by the Environment Agency in each study area considered between 1 July 2005 and 30 June 2006. The periods when flood warnings were issued are plotted in Figure 3.2. Six different flood risk events were highlighted by flood warnings issued in the Upper Exe study area and three in each of the Upper Conwy and Upper Taff regions.

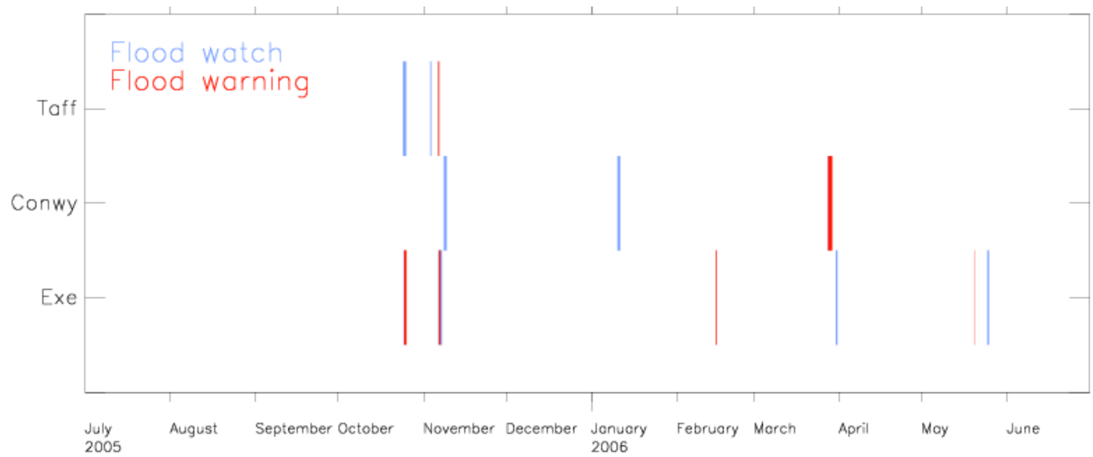


Figure 3.2: Periods of flood watch and warnings issued by the EA in each upland area during the study period.

4 Data analysis

Rain gauge and radar data measured between 1 July 2005 and 30 June 2006 have been extracted and archived specifically for this study. The rain gauge data were generally archived as tip times in 0.2 mm rainfall increments which were translated into 5 min and hourly rainfall accumulations. As identified in Section 2, some gauge data were only available as 15 min accumulations, from which hourly accumulations were computed.

Radar rainfall time series were derived from surface rainfall rate values at each radar pixel within the three study areas of interest from single-site Cartesian radar images at 1, 2 or 5 km horizontal resolution as available. Radar images are produced operationally every 5 min from the raw radar data using a series of quality control and correction processes to remove spurious echoes, correct for range effects and account for variations in the vertical profile of reflectivity. The stages of this processing were summarised by Harrison et al (2000). The surface rainrate values were converted to equivalent 5 min and hourly rainfall accumulations for analysis.

An overview of radar data quality is provided by calculating summary statistics for each gauge-radar comparison. These results are discussed in Section 5. The analysis is confined to a comparison of 1 hour rainfall accumulations measured by the available rain gauges and the corresponding radar estimates. Statistics are computed separately for all data when hourly rainfall accumulations from either the gauge or radar exceeded a given threshold value in order to infer the characteristic radar data quality at different rainfall intensities. Hourly rainfall thresholds of 0.0 mm, 0.4 mm, 1.0 mm, 4.0 mm and 8.0 mm were chosen to minimise the influence of errors associated with the discrete nature of gauge measurements for periods of low rainfall and lack of data at higher threshold values. Note that statistics for the 8.0 mm hourly accumulation threshold can only be computed for a few radar-gauge comparisons and include less than 5 data points.

The rain gauge data are assumed to represent the 'ground truth' of surface rainfall against which the radar data are assessed. A brief survey of potential statistics was conducted and the following are considered to be most suitable and sufficient to provide a robust assessment of radar data quality. The statistical measures of interest are defined in Appendix I. Categorical statistics are computed to relate the proportion of hourly time periods, or events, when rainfall measurements by the radar and gauge were both in agreement in detecting a 'rain' or 'no rain' situation to those when they disagreed. This gives a measure of radar data quality in terms of its ability to correctly diagnose surface rainfall over upland areas with no account made for the quantitative accuracy of the radar measurement. The probability of detection (POD) is the proportion of rain events observed by the gauge which are also observed by the radar. The false alarm rate (FAR) gives the proportion of rain events observed by the radar which are not verified by the surface observation. A perfect system corresponds to POD=1, FAR=0. Continuous statistics are more appropriate to define quantitative accuracy between the time series of hourly gauge and radar data. The bias gives the average error between radar and gauge rainfall measurements, which reveals the dominant trend of the data. Errors can be compensating so an additional measure of mean absolute error, expressed as the root mean square error (RMS) is required. This measure of accuracy might be affected by the magnitude of the values in the initial time series, such that poorly performing radars in light rain could appear more successful in capturing ground truth than relatively accurately performing radars in heavy rain. The root mean square factor (RMSF) is one statistic which attempts to overcome this feature. This can therefore be thought of as a multiplicative error value rather than an additional error term.

In addition, case study periods were selected to assess the use of radar to capture measured surface rainfall distributions during individual events of interest. The most significant periods of rainfall in each study area between 1 July 2005 and 30 June 2006 were identified from rain gauge measurements in terms of the largest daily and hourly rainfall accumulations since these periods are of primary interest for cases of potential flooding. These events are listed in Table 4.1. Each of the periods for which Flood Watch and Flood Warning alerts were issued by the Environment Agency (Figure 3.2) were included using this approach. This analysis is provided in Part II.

Upper Exe	Upper Conwy	Upper Taff
		24/07/2005
	13/08/2005	
	28/09/2005	
11/10/2005	11/10/2005	11/10/2005
		21/10/2005
24/10/2005	24/10/2005	**24/10/2005**
		30/10/2005
	03/11/2005	**03/11/2005**
06/11/2005		**06/11/2005**
	08/11/2005	08/11/2005
	10/01/2006	10/01/2006
27/03/2006	**27/03/2006**	
18/05/2006		
24/05/2006		
26/06/2006		

Table 4.1: List of case study events identified from periods of largest daily and hourly gauge-measured rainfall accumulations in each region. Cases when flood warnings were issued in each region are highlighted in bold.

4.1 Influence of orographic corrections and gauge adjustment on radar data

In order to assess the impact of the orographic corrections applied in the operational processing chain, time series of archived "background" and "corrected" radar data were produced. The background data has no orographic correction applied while the corrected data has undergone additional orographic corrections. In addition, data in the corrected time series have been calibrated against surface rain gauges to correct for mean biases by applying a radar-dependent gauge adjustment factor (GAF) calculated using the scheme described by Seo et al. (1999). The computed adjustment factor for a given radar can vary on an hourly timescale, being updated at 25 minutes past each hour. The background and corrected radar timeseries used in this study are therefore related as,

$$CORRECTED = GAF.(BACKGROUND + OROG)$$

where the term *(BACKGROUND + OROG)* is the radar-derived surface rainfall estimate produced by the VPR correction process outlined in Section 1.3 (Kitchen et al. 1994).

The cumulative influence of both orographic corrections and gauge adjustments applied to the corrected radar data makes isolating the effect of the orographic corrections applied as part of the operational processing chain difficult. While the magnitude of the orographic correction applied at a particular time can be estimated for this study, the impact of that correction on data quality is further scaled by the gauge adjustment factor.

5 Radar data quality overview

5.1 Probability of detection (POD)

Figure 5.1 shows the variation of POD values with gauge-radar range in each of the three upland study areas considered. Typical values are listed in Table 5.1. The data are plotted separately for data when either gauge or radar accumulations are in excess of an hourly rainfall accumulation threshold of interest. Note that a successful detection by the radar refers to a measurement of any magnitude at that time.

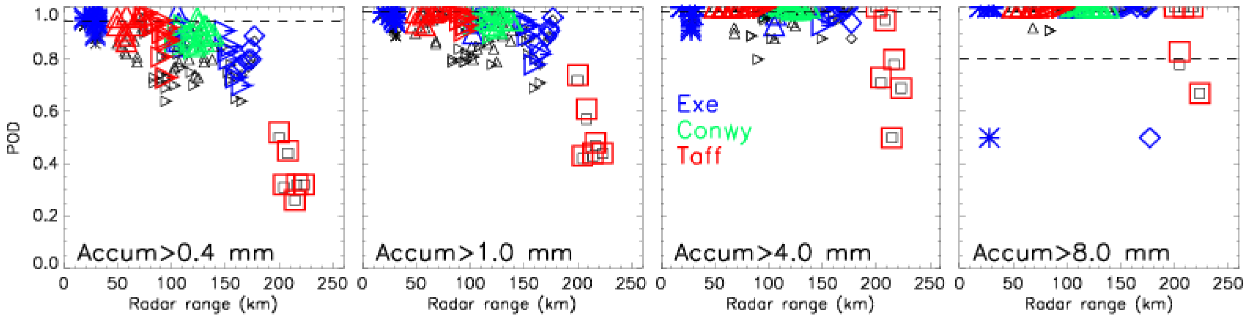


Figure 5.1: Variation of POD with radar range for each hourly accumulation threshold in the Upper Exe, Upper Conwy and Upper Taff study areas. Results for background radar data are shown as small black points. The dashed line shows the POD value of the UK national composite product for the same period.

Region	Radar	Max.	Min.	Avg.
Exe	Cobbacombe (1 km)	0.99	0.94	0.97
Conwy	Clee Hill (5 km)	0.99	0.90	0.95
Taff	Crug-y-G (2 km)	1.00	0.93	0.97

Table 5.1: Maximum, minimum and average POD values calculated for gauge comparisons with the radar typically used in the UK composite product across each study area for accumulations greater than 1 mm.

Figure 5.1 shows a strong decrease of radar performance, signified by decreasing POD values, with increasing radar range for the Upper Exe and Upper Taff study areas. For example, 92% of rainfall events measured by the Porlock gauge in the Upper Exe region are captured in the 5 km resolution data from the nearest radar at Cobbacombe Cross (range 28 km), compared with a POD of only 0.71 for 5 km resolution radar measurements at Predannack (range 177 km). In the Upper Taff region, 98% of rainfall events measured by the Llyn Y Fan gauge are captured in the radar data from Crug-y-Gorllwyn (range 49 km), compared with a POD of only 0.44 for radar measurements at Chenies (range 223 km). The relatively smooth decrease of POD with range shown is to be anticipated, even over flat terrain, due to the increase of radar beam height with range and the resulting increased likelihood of the radar beam overshooting low-level rain. At the range of interest for rainfall at Llyn Y Fan for example, the Chenies radar beam (and minimum height of detectable rainfall) is typically over 4700 m above the surface. Further, the increased beam attenuation with range from the radar is known to limit the ability of successfully detecting rainfall at long range. For the Upper Conwy region, all three available radars are located between 100 km and 150 km of the study area so that radar measurement errors due to beam broadening with range are likely to be similar at all sites. In this case, Figure 5.1 actually shows a tendency for increasing POD values with range. For example, 77% of rainfall events measured by the Capel Curig gauge are captured by the nearest radar at Clee Hill (range 118 km), compared with a POD of 0.87 for radar measurements at Hameldon Hill (range 130 km). The variation of POD values for the Upper Conwy region is perhaps more dependent on the location of each gauge or on the stability and calibration of the measurement hardware of each radar. Figure 5.1 also shows improving POD values at higher rainfall thresholds, such that for the majority of gauges, all hourly accumulations in excess of 4 mm were detected by the available radars. The only cases with a POD less than unity for accumulations of 4 mm or more were for radar measurements across the Upper Taff at particularly long range from Chenies and for gauge measurements at Kinsford Gate and Porlock in the Upper Exe region (all radars).

While Figure 5.1 shows POD values to be a strong function of range, there is also considerable scatter of values for a given range, particularly for measurements in the Upper Exe region. Figure 5.2 suggests the variation of POD values for a given radar across this region can be attributed to variations in gauge altitude. Figure 5.2 also shows that such behaviour is not as clearly identifiable for radar measurements across the Upper Conwy and Upper Taff regions.

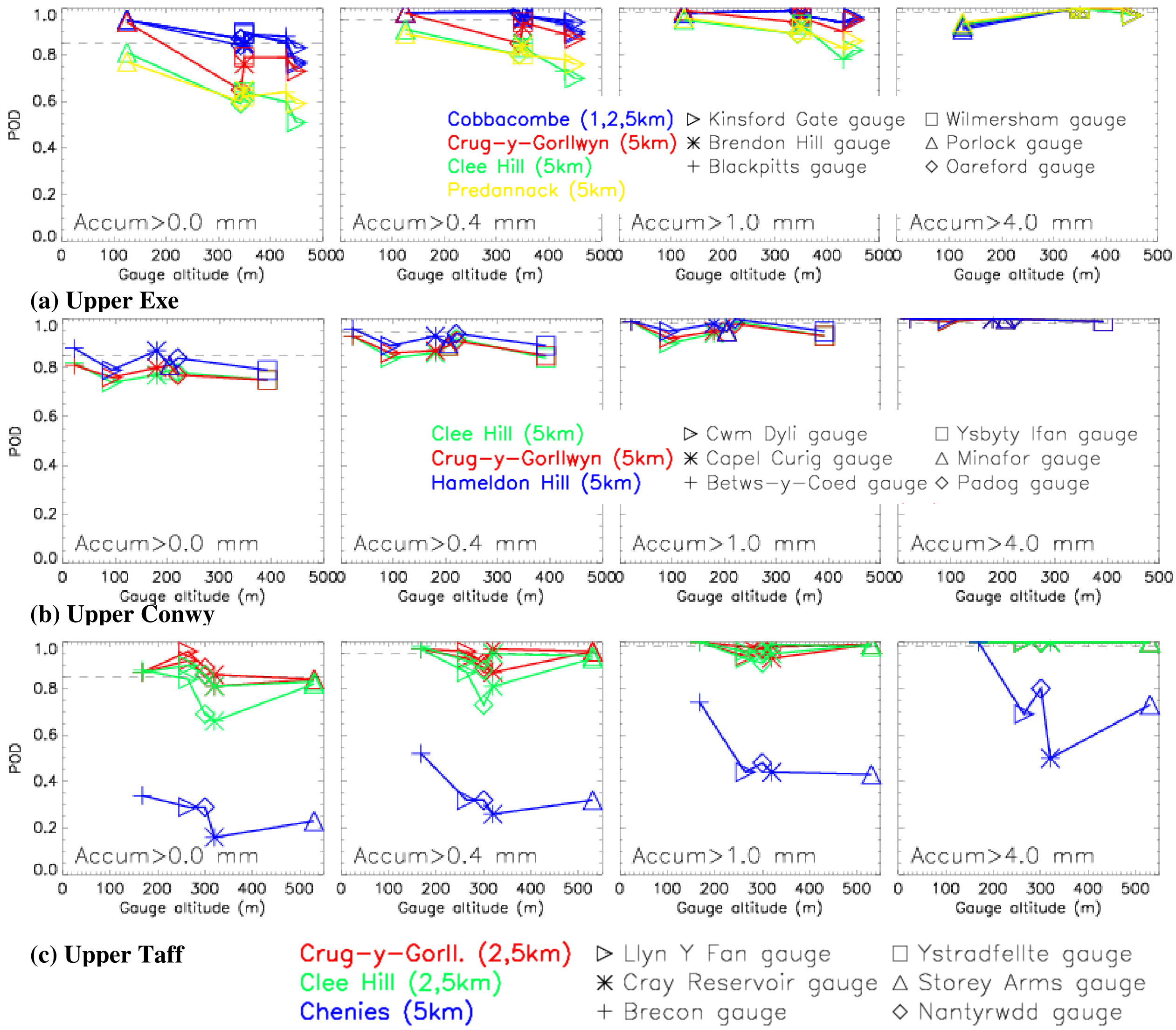


Figure 5.2: Variation of POD with gauge altitude for each hourly accumulation threshold in the (a) Upper Exe, (b) Upper Conwy and (c) Upper Taff study areas.

Figure 5.2(a) shows a strong variation of POD values with gauge altitude in the Upper Exe study area, of comparable magnitude to that with radar range shown in Figure 5.1(a). For example, the lowest POD value at Porlock (125 m AOD) of 0.71 calculated for the Predannack radar [254 events] is similar to the most accurate POD values calculated between 1 km resolution radar data and gauge measurements at Kinsford Gate (450 m AOD) [294 events]. The strong variation of POD values with altitude in this case suggests that the radars miss a significant proportion of low-level orographically induced rainfall, despite the apparently good radar coverage. While Figure 5.2(b) shows largest POD values for the Upper Conwy region were found for comparisons between radar data and surface measurements from the lowest gauge at Betws-y-Coed (22 m AOD) and smallest values for the highest gauge at Ysbyty Ifan (392 m AOD), there is no clear dependence on gauge altitude. This can be attributed to the more complex terrain and resulting rainfall distribution observed across the Upper Conwy area (Figure 2.4) than found across the Upper Exe (Figure 2.2). Figure 5.3 illustrates how local variations in rainfall totals across the region contribute to POD values for each radar-gauge comparison being calculated from considerably different number of events in each rainfall accumulation category, which is directly related to POD. The radars were apparently less likely to capture rainfall in those locations where strongest rainfall occurred. For example, notably low POD values were calculated for measurements at Cwm Dyli (94 m AOD), located in a 600 m deep NE-SW oriented valley to the south of Glyder Fawr and Glyder Fach mountains and to the west of Snowdon. For hourly rainfall accumulations in excess of 1 mm, a POD value of 1.0 is calculated for radar measurements from Hameldon Hill and gauge measurements at Padog (220 m AOD) [355 events] compared with a value of 0.95 for Hameldon Hill data and gauge measurements at Cwm Dyli (94 m AOD) [793 events].

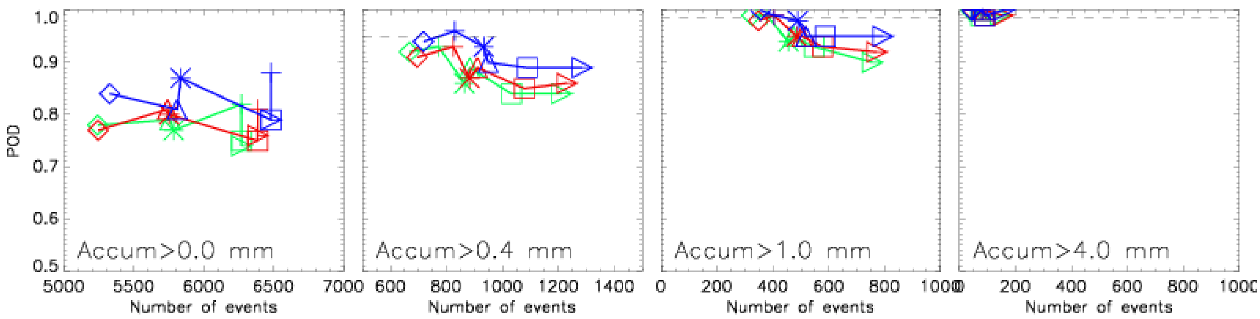


Figure 5.3: Variation of POD with number of rainfall events for each hourly accumulation threshold in the Upper Conwy study area. See Figure 5.2(b) for an explanation of symbols.

Even larger contrast of POD values is shown in Figure 5.2(c) across the Upper Taff region, which cannot be explained by the number of events or gauge altitude. For hourly rainfall accumulations in excess of 1 mm, comparisons between 2 km resolution data from Clee Hill and Crug-y-Gorllwyn radars with gauges at Brecon (168 m AOD) [157 events] and Storey Arms (530 m AOD) [205 events] give best results, both showing POD values of 1.0 and 0.99 respectively. For radar measurements from Clee Hill, corresponding POD values of 0.95 [65 events], 0.93 [177 events] and 0.91 [246 events] are calculated for the gauge measurements at Cray Reservoir, Llyn Y Fan and Nantyrwdd. The relatively good performance at Brecon can be attributed to the gauge being located in a relatively low and flat region (Figure 2.6). While being located at the greatest altitude, the radar beam height is lowest above the Storey Arms gauge, increasing the likelihood of successfully measuring the low-level rainfall across the Brecon Beacons range. Figure 5.4 shows the variation of POD values in this region with radar beam height. Interestingly, for hourly rainfall accumulations in excess of 1.0 mm the POD values for radar measurements from Clee Hill show a clear decrease with increasing beam height above the ground, as might be anticipated, while those for Crug-y-Gorllwyn data show the opposite behaviour.

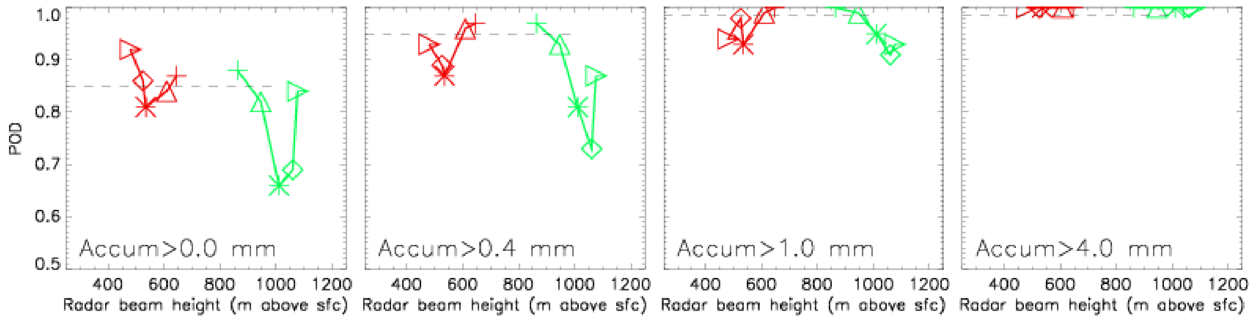


Figure 5.4: Variation of POD with the typical radar beam height above the ground for each hourly accumulation threshold in the Upper Taff study area. See Figure 5.2(c) for an explanation of symbols.

The availability of radar data at 1, 2 and 5 km resolution in the Upper Exe and at 2 and 5 km resolution in the Upper Taff region enables analysis of the impact of resolution on data quality. Figure 5.5 shows that POD values are generally insensitive to the radar data resolution in the Upper Exe region. There is some improvement of POD values for radar data at 5 km resolution across the Upper Taff area, suggesting that on average the less detailed data allows better agreement with surface gauge measurements.

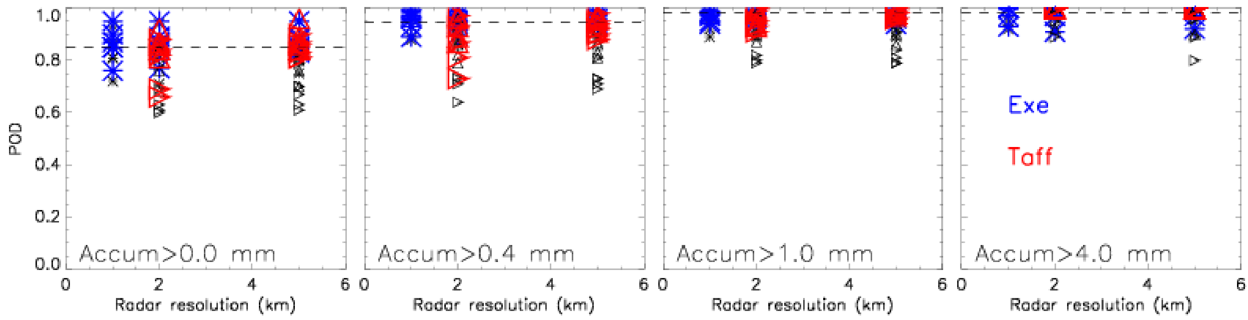


Figure 5.5: Variation of POD with radar data resolution for Cobbacombe Cross data in the Upper Exe study area and Clee Hill and Crug-y-Gorllwyn data in the Upper Taff region for each hourly accumulation threshold.

Figures 5.1 and 5.5 highlight how POD values are improved, by typically 10%, for corrected radar data than background data even for an accumulation threshold of 0.0 mm. This is partly due to the slightly different data availability for each case which results from the method of archiving the radar data. More importantly, differences in cases with the same number of background and corrected data points highlights the influence of orographic corrections in magnifying low rainfall values above the lowest rainfall measurement value of 0.03125 mmh^{-1} (1/32 mmh^{-1}). This highlights a strong sensitivity of rainfall values to whether orographic corrections are applied when low background values are measured by the radar.

Summary

- The current radar network is successful in identifying typically 97% of hourly rainfall accumulations in excess of 1 mm across upland areas in England and Wales.
- On average, highest POD values were found for the Upper Exe region as a result of the availability of radars at closest range. No sensitivity to radar data resolution was observed.
- POD values across the Upper Exe region are sensitive to gauge altitude while those across the Upper Conwy and Taff regions reflect more complex terrain and rainfall distributions.

5.2 False alarm ratio (FAR)

The variation of FAR with radar range across each study area is plotted in Figure 5.6. Typical values are listed in Table 5.2. This shows less systematic behaviour than displayed by the POD values with similar values found for each of the three study areas of interest, comparable with that for UK national composite product.

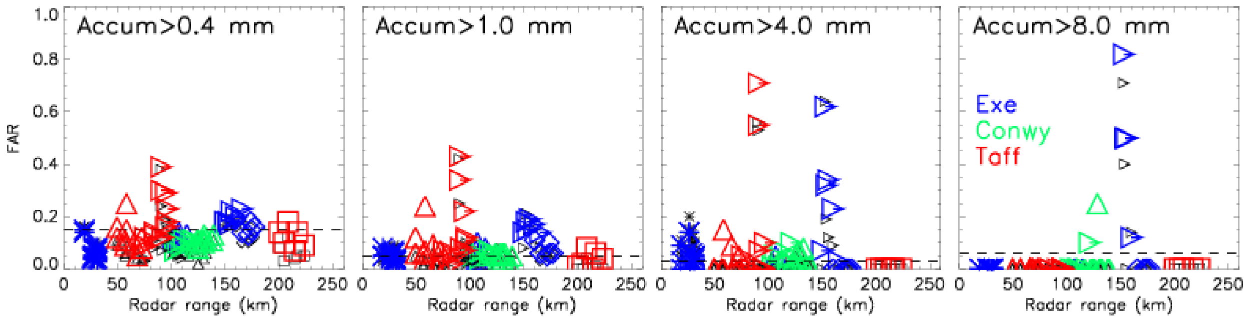


Figure 5.6: Variation of FAR with radar range for each hourly accumulation threshold in the Upper Exe, Upper Conwy and Upper Taff study areas. Results for background radar data are shown as small black points. The dashed line shows the FAR value of the UK national composite product for the same period.

Region	Radar	Max.	Min.	Avg.
Exe	Cobbacombe (1 km)	0.08	0.03	0.05
Conwy	Clee Hill (5 km)	0.08	0.04	0.06
Taff	Crug-y-G (2 km)	0.12	0.01	0.06

Table 5.2: Maximum, minimum and average FAR values calculated for gauge comparisons with the radar typically used in the UK composite product across each study area for accumulations greater than 1 mm.

For an hourly accumulation in excess of 1.0 mm, values in the Upper Exe study area range between 0.19 (Brendon Hill gauge, Clee Hill radar) and 0.03 (Porlock gauge, Cobbacombe radar). Figure 5.6 shows values increasing with increasing range due to the increased likelihood of errors due to anaprop conditions for example. There is no systematic variation with gauge altitude or radar data resolution with results apparently more radar-dependent for each rainfall accumulation threshold. In the Upper Conwy study area values range between 0.08 (Betws-y-Coed gauge, Clee Hill radar) and 0.02 (Cwm Dyli gauge, Crug-y-Gorllwyn and Hameldon Hill radars). In the Upper Taff region FAR values range between 0.43 (Cray Reservoir gauge, 2 km Clee Hill radar) and 0.01 (Storey Arms gauge, Crug-y-Gorllwyn radar). A large FAR value of 0.22 was also calculated for 2 km Clee Hill data comparisons with gauge measurements at Nantyrwdd, perhaps indicating a systematic problem with the Clee Hill measurements in this region. One potential factor in this case is that the lowest elevation scan from Clee Hill is at 0.2° while most other radars scan at 0.5°, making the Clee Hill measurements more susceptible to ground clutter. This is illustrated in Figure 2.2. As observed for POD results, some improvement between FARs of radar data at 2 and 5 km data is evident for results across the Upper Taff region.

5.3 Root mean square error (RMS)

Figure 5.7 shows the variation of RMS values with range from the radar across each study area. Typical values are listed in Table 5.3.

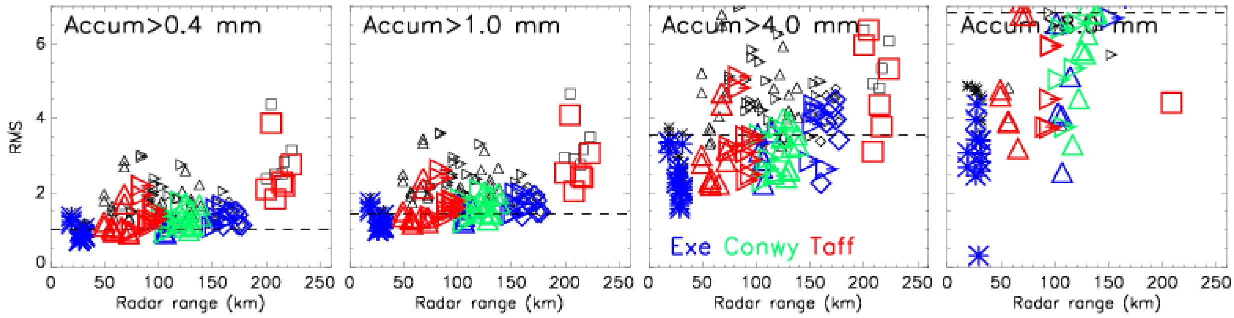


Figure 5.7: Variation of RMS with radar range for each hourly accumulation threshold in the Upper Exe, Upper Conwy and Upper Taff study areas. Results for background radar data are shown as small black points. The dashed line shows the RMS value of the UK national composite product for the same period.

Region	Radar	Max.	Min.	Avg.
Exe	Cobbacombe (1 km)	1.75	0.97	1.18
Conwy	Clee Hill (5 km)	2.09	1.20	1.59
Taff	Crug-y-G (2 km)	2.39	1.17	1.54

Table 5.3: Maximum, minimum and average RMS values calculated for gauge comparisons with the radar typically used in the UK composite product across each study area for accumulations greater than 1 mm.

As for the categorical (i.e. rain or no-rain) statistics discussed in Sections 5.1 and 5.2, Figure 5.7 shows generally decreasing radar data quality with range from the radar, such that best quantitative agreement between the radars and surface gauges occurs for measurements from Cobbacombe Cross across the Upper Exe region. This is to be anticipated since it is well known that errors due to beam overshooting and attenuation are likely to increase with range from the radar site. Indeed, the level of agreement for these data is better than the corresponding statistics computed for the UK national composite product. Figure 5.8 suggests that the level of agreement in generally independent of the radar data resolution.

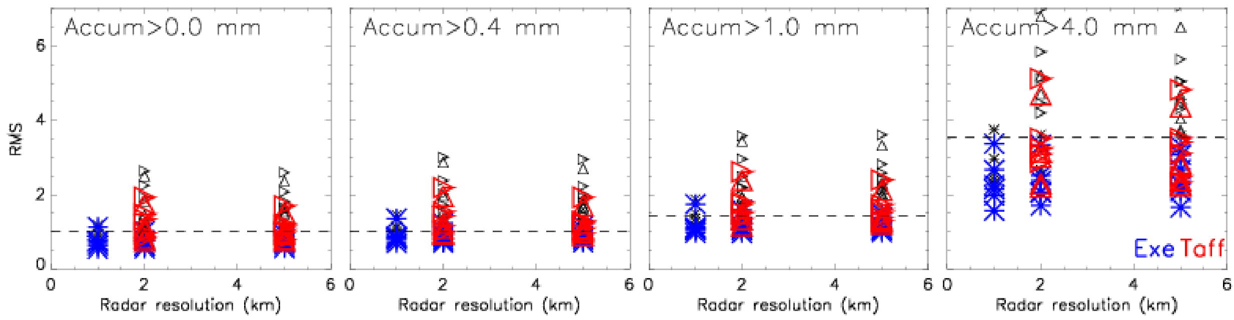


Figure 5.8: Variation of RMS with radar data resolution for Cobbacombe Cross data in the Upper Exe study area and Clee Hill and Crug-y-Gorllwyn data in the Upper Taff region for each hourly accumulation threshold. The dashed line shows the RMS value of the UK national composite product for the same period.

The range of RMS values computed for each study area is highlighted in Figure 5.9. This suggests that values tend to increase with gauge altitude, particularly in the Upper Exe and Upper Taff regions.

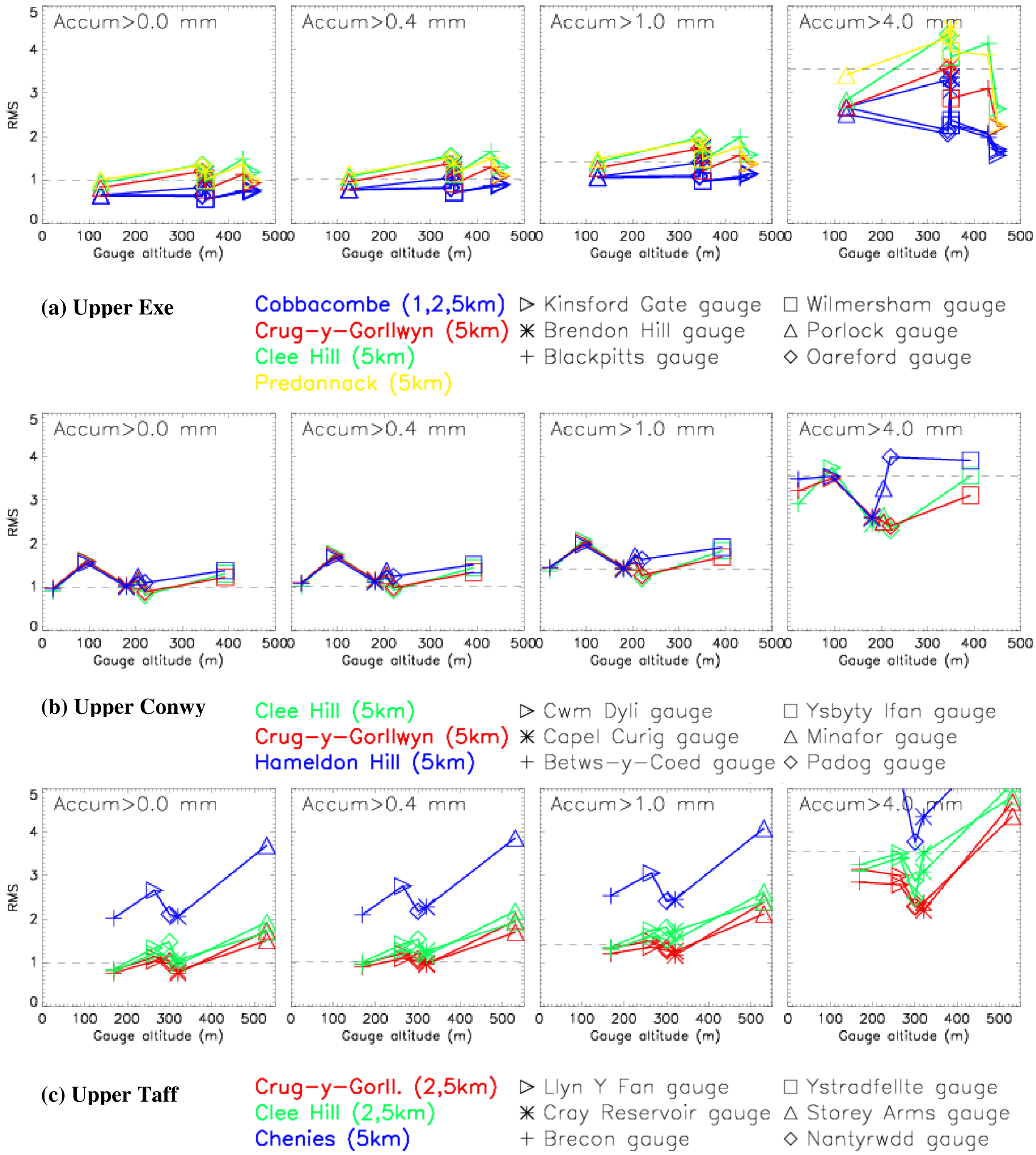


Figure 5.9: Variation of RMS with gauge altitude for each hourly accumulation threshold in the (a) Upper Exe, (b) Upper Conwy and (c) Upper Taff study areas. The dashed lines show the RMS value of the UK national composite product for the same period.

For the 1 and 2 km resolution radar data from Cobbacombe Cross in the Upper Exe region, RMS values tend to be similar for all gauges except Kinsford Gate (450 m AOD) while for all available radars smallest RMS values are found for comparisons with gauge data at Porlock (125 m AOD). Figure 5.9(c) shows stronger variation of RMS values with gauge altitude across the Upper Taff region. The agreement between radar data and gauge measurements at Brecon (168 m AOD) is of similar magnitude to RMS values for the UK national radar composite and typically twice as good as that calculated with the Storey Arms gauge (530 m AOD). While Figure 5.2 suggested that a relatively high proportion of rainfall events at Storey Arms were captured by each radar, Figure 5.9

clearly shows relatively poor quantitative accuracy of the magnitude of that rainfall measurement. This result suggests that there is scope for improving the adjustments to account for the orographic enhancement process. In comparison, the RMS values plotted in Figure 5.9(b) show generally good quantitative agreement between radar and gauge measurements across the Upper Conwy region, despite its more complex terrain (Figure 2.4). Further indication of a link between data quality and altitude is shown, with lowest RMS values for all three available radars occurring for gauge measurements at Betws-y-Coed (22m AOD). With the exception of RMS values for the Cwm Dyli site, Figure 5.9(b) shows generally decreased data quality with increased gauge altitude and values for the highest gauge at Ysbyty Ifan (392 m AOD) are typically 50% higher than those for Betws-y-Coed or the national average. Least agreement between gauge and radar data across the Upper Conwy region occurs for gauge measurements at Cwm Dyli (94 m AOD). In this case, the gauge location in a steep valley within the region of highest terrain is likely to bring most complex rainfall distributions, which the radars apparently fail to capture to the same level of accuracy found in other locations. The availability of radar data (and the application of orographic corrections) at only 5 km horizontal resolution in this region may contribute to the relatively poor data quality in this region where considerable changes in terrain occurs within small distances.

Figure 5.7 indicates generally smaller RMS values computed for the corrected radar data than when comparing the background radar timeseries with gauge measurements. The magnitude of this improvement is illustrated in Figure 5.10, with typical values listed in Table 5.4. Largest fractional differences of up to 0.75 occur within the Upper Taff study area. The improvement shown in Figure 5.10 is partly a result of the gauge adjustment scaling applied to the background data. Figure 5.10(a) shows a striking variation of the improvement with gauge altitude. Given that the gauge adjustment process is applied to all data for a given radar, this relationship must be highlighting the relative benefit of applying the current orographic correction processing to radar data across the Upper Exe region.

Region	Radar	Max.	Min.	Avg.
Exe	Cobbacombe (1 km)	0.32	0.07	0.18
Conwy	Clee Hill (5 km)	0.67	0.37	0.56
Taff	Crug-y-G (2 km)	0.66	0.44	0.49

Table 5.4: Maximum, minimum and average fractional change of RMS values between background and corrected radar data calculated for gauge comparisons with the radar typically used in the UK composite product across each study area for accumulations greater than 1 mm.

Summary

- The current radar network is generally less accurate in measuring rainfall across the Upper Taff and Upper Conwy regions than on average across all regions of the UK.
- On average, lowest RMS values were found for the Upper Exe region as a result of the availability of radars at closest range. No sensitivity to radar data resolution was observed.
- RMS values across each of the upland regions show some variation with gauge altitude, with values up to twice as large at the highest gauges relative to more low-lying sites.
- Application of the orographic correction scheme leads to improvements in radar data quality by up to 75%. The magnitude of the improvement across the Upper Exe area increases with increasing altitude.

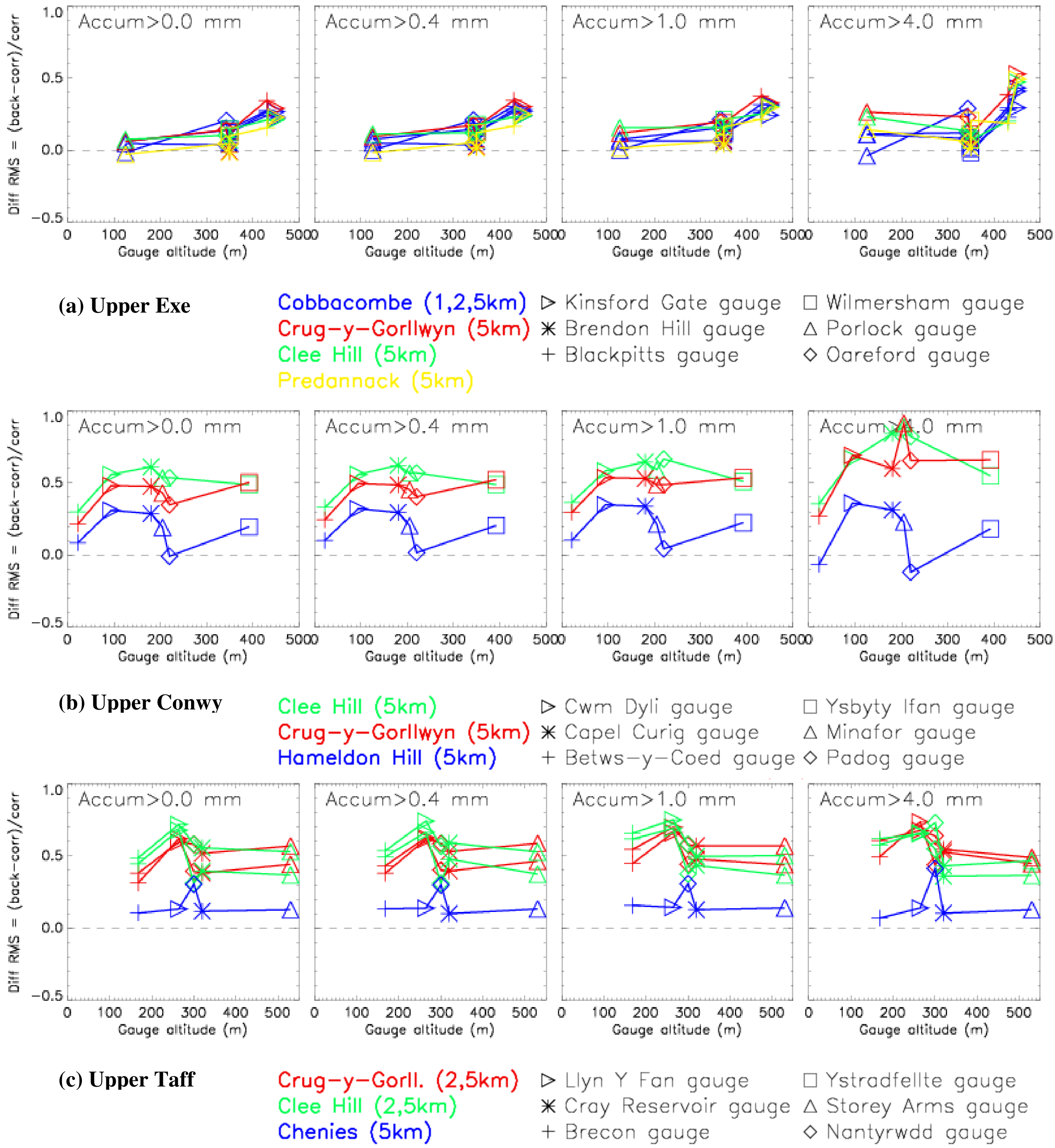


Figure 5.10: Fractional change of RMS between background and corrected radar data with gauge altitude for each hourly accumulation threshold in the (a) Upper Exe, (b) Upper Conwy and (c) Upper Taff study areas. The dashed line shows the RMS value of the UK national composite product for the same period.

5.4 Root mean square factor (RMSF)

The variation of RMSF values for each hourly rainfall accumulation threshold with range from the radar in each upland region is plotted in Figure 5.11. Typical values are listed in Table 5.5. As shown by the RMS statistics in Figure 5.7, the dominant trend for all accumulation thresholds is decreasing quantitative agreement between radar rainfall estimates and gauge measured surface values with increasing range between the radar and site of interest. Similar to the results shown in Figure 5.8, RMSF values are generally insensitive to radar data resolution.

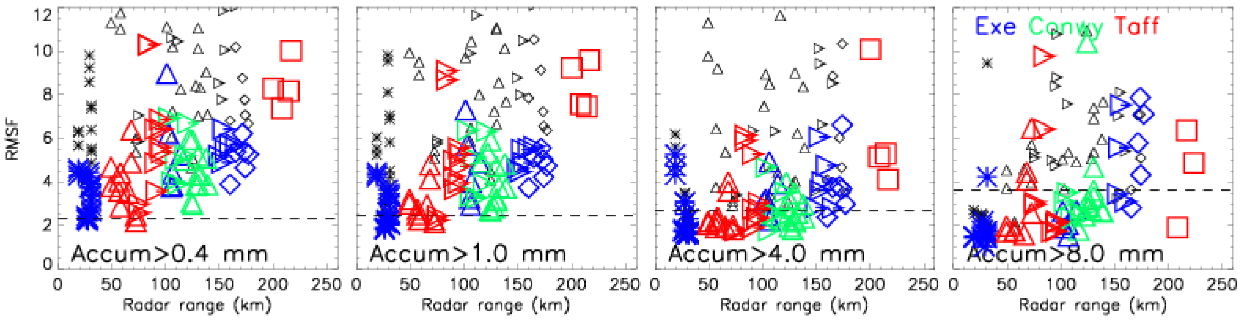


Figure 5.11: Variation of RMSF with gauge altitude for each hourly accumulation threshold in the (a) Upper Exe, (b) Upper Conwy and (c) Upper Taff study areas. The dashed line shows the RMSF value of the UK national composite product for the same period.

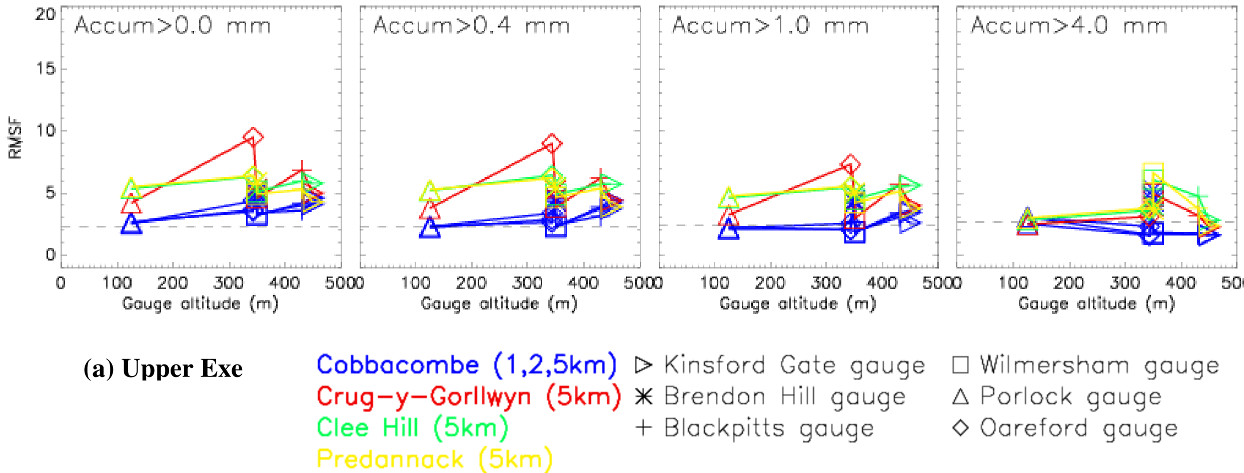
Region	Radar	Max.	Min.	Avg.
Exe	Cobbacombe (1 km)	4.44	1.85	2.89
Conwy	Clee Hill (5 km)	6.37	3.27	4.72
Taff	Crug-y-G (2 km)	4.78	2.13	3.02

Table 5.5: Maximum, minimum and average RMSF values calculated for gauge comparisons with the radar typically used in the UK composite product across each study area for accumulations greater than 1 mm.

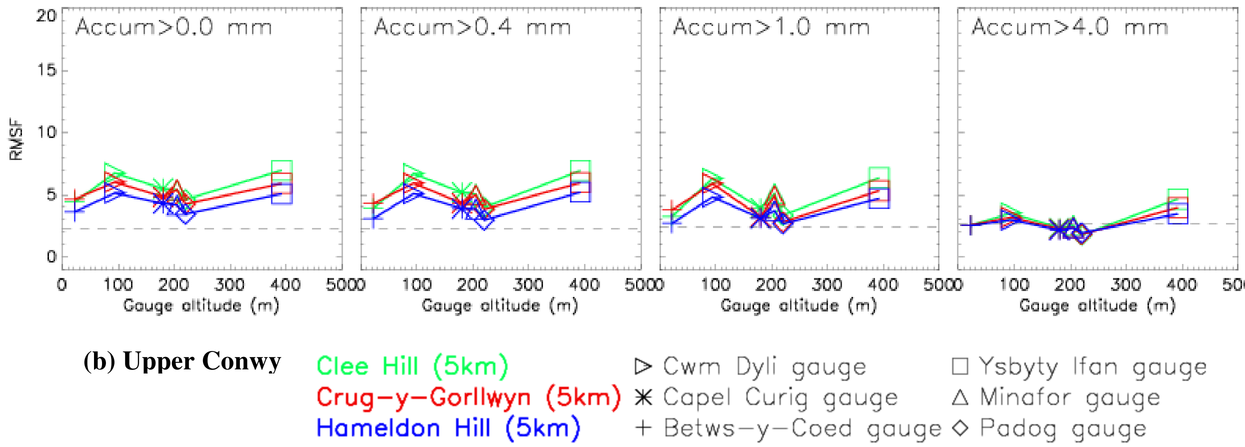
Figure 5.11 shows RMSF values at ranges of up to 150 km in all three upland regions to be up to three times greater than the corresponding values describing the agreement between the UK national radar composite product and surface gauges. This suggests systematically poorer radar performance across upland regions than observed in more lowland areas.

The RMSF values plotted in Figure 5.12 show similar behaviour with gauge altitude to the RMS results plotted in Figure 5.9. For radar data from Cobbacombe Cross within the Upper Exe region for hourly accumulations in excess of 1 mm, RMSF values for the Kinsford Gate gauge (450 m AOD) are about 3.5 [260 events] compared with a value of about 2.0 for the Porlock gauge (125 m AOD) [185 events]. In the Upper Conwy region, RMSF values at Ysbyty Ifan (392 m AOD) range between 6.37 and 4.71 for the Clee Hill [485 events] and Hameldon Hill [536 events] radars respectively. Corresponding values at the lowest gauge in this region at Betws-y-Coed (22 m AOD) are typically half the Ysbyty Ifan results, ranging between 3.78 and 2.71 for comparisons with the Crug-y-Gorllwyn [373 events] and Hameldon Hill [377 events] radars respectively. Interestingly, Figure 5.12 suggests best quantitative agreement between rainfall measurements from each gauge with data from the Hameldon Hill radar than found for Crug-y-Gorllwyn or Clee Hill, despite the closer proximity of Clee Hill to the study area. The RMSF values for the Cwm Dyli gauge are consistently higher than found for all other gauges in the Upper Conwy region, similar to the behaviour identified in Figure 5.9. Similarly, the strong increase of RMS values with gauge altitude in the Upper Taff region is replicated by RMSF values. For hourly accumulations in excess of 1 mm, the best result for the Storey Arms gauge (530 m AOD) of 4.14 (Crug-y-Gorllwyn, 5 km) [305 events] is almost twice as large as the corresponding result at Brecon (168 m AOD) of 2.25.

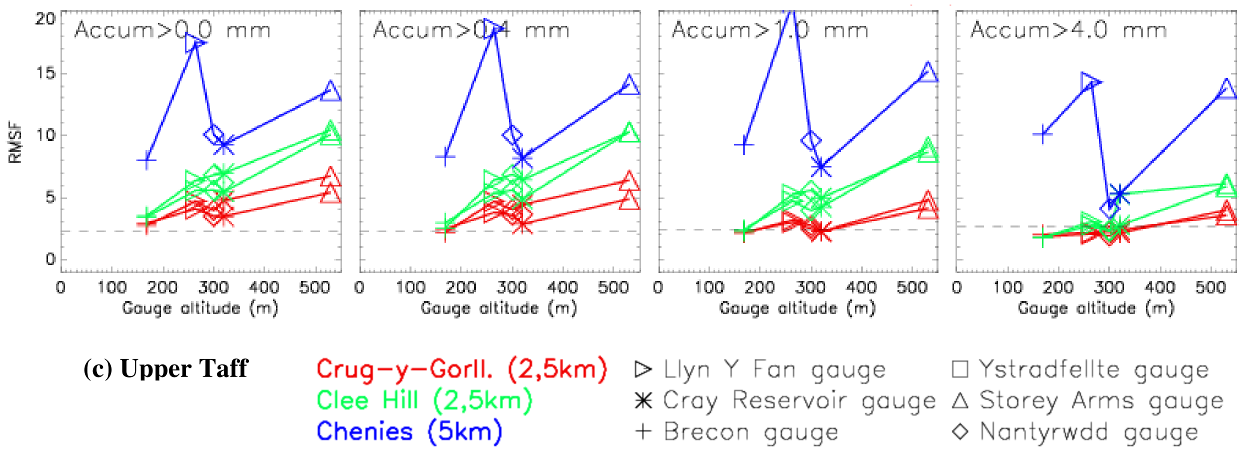
Figure 5.13 illustrates the improvement between RMSF values between background and corrected radar data, quantifying the typical impact of applying the orographic correction scheme to radar data across upland regions. Typical values are listed in Table 5.6. Similar to the behaviour shown in Figure 5.10, the improvement in the Upper Exe region is altitude dependent while larger improvements of up to 5 times the corrected value are found in the Upper Conwy and Upper Taff study areas where the magnitude of the change is more similar for each gauge comparison with a given radar.



(a) Upper Exe



(b) Upper Conwy



(c) Upper Taff

Figure 5.12: Variation of RMSF with gauge altitude for each hourly accumulation threshold in the (a) Upper Exe, (b) Upper Conwy and (c) Upper Taff study areas.

Region	Radar	Max.	Min.	Avg.
Exe	Cobbacombe (1 km)	1.84	0.18	0.85
Conwy	Clee Hill (5 km)	5.19	1.96	3.31
Taff	Crug-y-G (2 km)	3.92	1.38	2.88

Table 5.6: Maximum, minimum and average fractional change of RMSF values between background and corrected radar data calculated for gauge comparisons with the radar typically used in the UK composite product across each study area for accumulations greater than 1 mm.

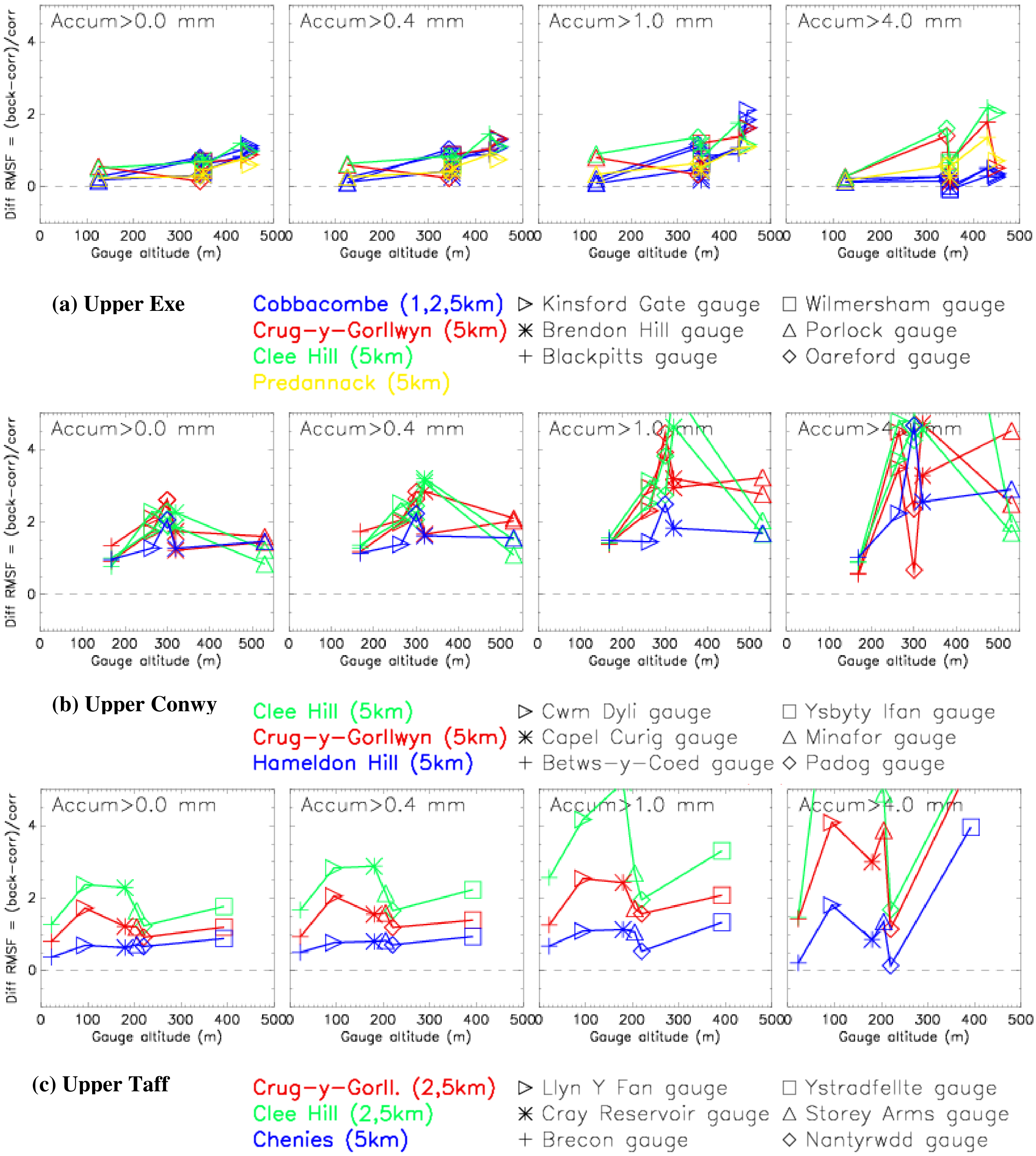


Figure 5.13: Fractional change of RMSF between background and corrected radar data with gauge altitude for each hourly accumulation threshold in the (a) Upper Exe, (b) Upper Conwy and (c) Upper Taff study areas.

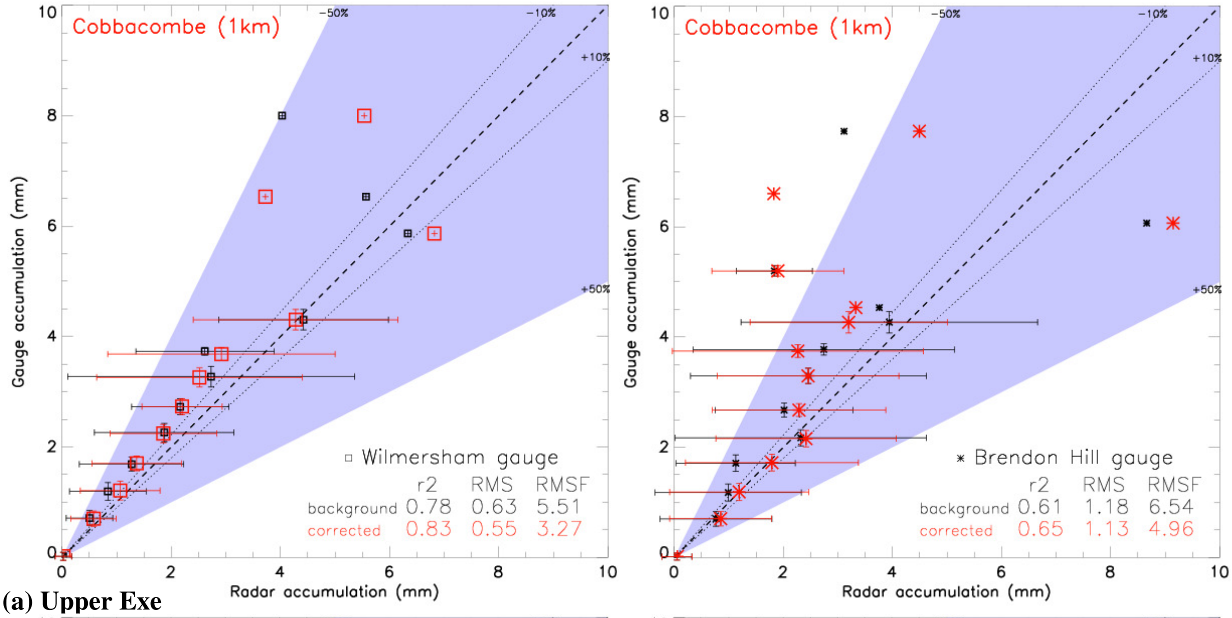
5.5 Impact of orographic corrections

The correlation between gauge and radar rainfall values in each study area is useful to illustrate the improved agreement between radar measurements with surface rainfall values achieved by applying the current operational orographic correction scheme to the background radar data. Figure 5.11 shows a selection of correlation plots illustrating the best and worst cases of agreement between gauge measurements and data from the radar typically used in the operational UK national radar composite product in each area (i.e. lowest and highest overall RMSF values). Contingency tables describing the relative distribution of hourly rainfall accumulations for each gauge-radar pair are shown in Tables 5.1, 5.2 and 5.3.

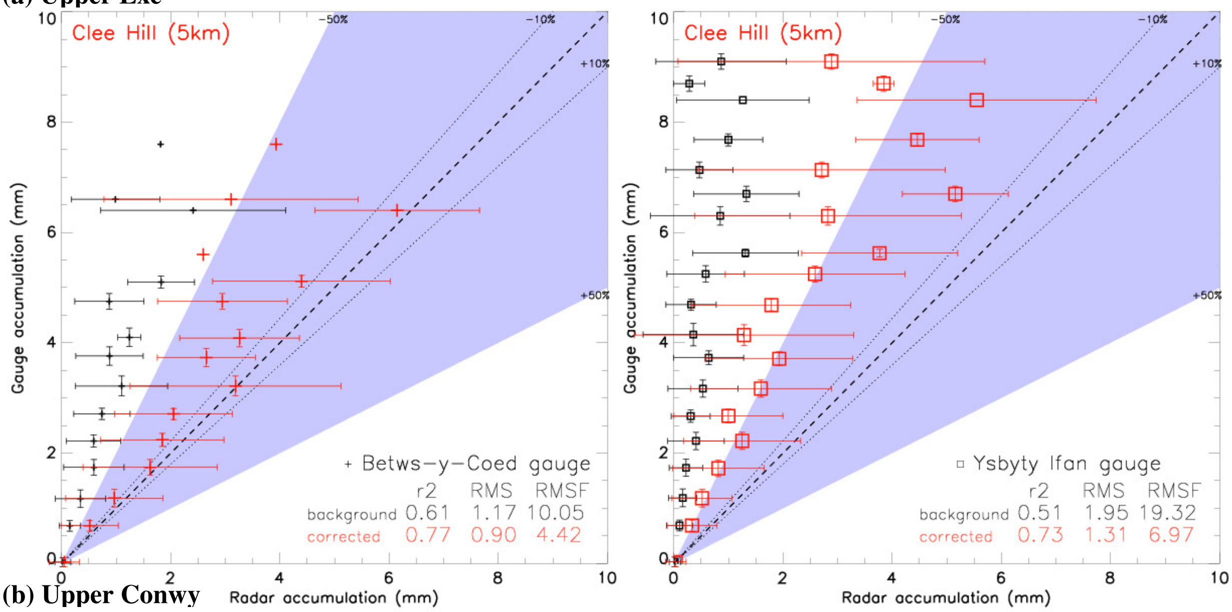
The plots in Figure 5.11 illustrate that while best agreement between the radar data and gauge measurements occurs across the Upper Exe region, the orographic correction processing applied to the background radar data has biggest impact on improving data quality in the Upper Conwy and Upper Taff regions. In both cases the correlation between background radar and gauge data shows a systematic underestimation of surface rainfall by between about 50% and 85% over the entire range of rainfall accumulations. Application of orographic corrections and the subsequent scaling by gauge adjustment factors leads to a shift of radar rainfall estimates to higher values closer to that measured by the surface gauges. For the cases of Betws-y-Coed and Brecon gauges, the lowest in the Upper Conwy and Upper Taff regions respectively, this process completely corrects (on average) the initial underestimation of background values at least for hourly rainfall accumulations of less than 5 mm. For the cases of Ysbyty Ifan and Storey Arms gauges, the highest in the Upper Conwy and Upper Taff regions respectively, the correction decreases the initial underestimation but corrected radar data remain on average typically 50% lower than the corresponding gauge measurements. Correlation plots for the other gauge-radar comparisons display similar trends with differences between plots reflecting the quantitative trends in data quality discussed in Sections 5.3 and 5.4. While considerably improving radar data quality, the application of orographic corrections is clearly insufficient to fully account for observed surface rainfall in upland regions.

As discussed in Section 4.1, the difference between background and corrected radar data is an indication of the cumulative effects of correcting for orographic effects and scaling by a gauge adjustment factor. During the study period, the gauge adjustment factors for Cobbacombe Cross ranged between 2.60 and 0.64 (mean 1.15) and those for Clee Hill ranged between 2.45 and 0.91 (mean 1.60) and Crug-y-Gorllwyn ranged between 2.32 and 0.81 (mean 1.42). Therefore, on average the cumulative effect of applying both orographic corrections and gauge adjustment to the background radar data will have been to increase rainfall estimates, improving agreement between the radar data and gauge measurements. Taking into account the typical gauge adjustment applied to the data, it can be estimated that typically half the improvement to data quality of about 50% found for radars in the Upper Conwy and Upper Taff regions can be attributed to the addition of an orographic corrections. The rest of the improvement in agreement between radars and gauges is a result of scaling the enhanced background radar data by the gauge adjustment factor.

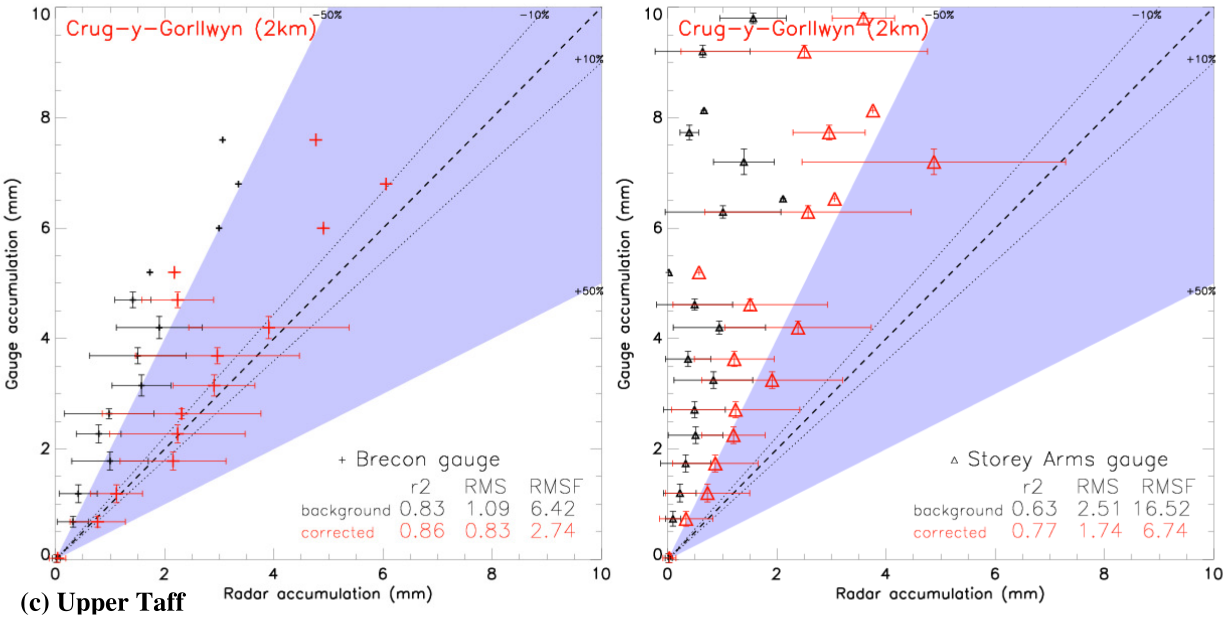
OVERLEAF:- Figure 5.11: Correlations between radar and gauge data for gauge sites with the lowest and highest RMSF values in the (a) Upper Exe, (b) Upper Conwy and (c) Upper Taff study areas when compared with radar data from the radar typically used in the national composite product in each region. Background radar data are plotted in black, corrected data in colour. Values show averaged hourly rainfall accumulations from the radar in 0.5 mm gauge accumulation bands. Error bars show the standard deviation of values from that average. Summary statistics (correlation coefficient r^2, RMS, RMSF) for all data are listed on each plot.



(a) Upper Exe



(b) Upper Conwy



(c) Upper Taff

	Hourly rain (mm)	Background radar (Cobb 1 km)						Corrected radar (Cobb 1 km)						
		0.0-0.2	0.2-0.4	0.4-1.0	1.0-4.0	4.0-8.0	>8.0	0.0-0.2	0.2-0.4	0.4-1.0	1.0-4.0	4.0-8.0	>8.0	
Wilmersham gauge	0.0-0.2	**87.7**	0.53	0.19	0.14	0.05	0.00	**86.7**	0.82	0.25	0.13	0.03	0.00	87.9
	0.2-0.4	3.89	**0.51**	0.30	0.04	0.00	0.00	3.58	**0.76**	0.44	0.02	0.00	0.00	4.79
	0.4-1.0	1.55	0.76	**1.06**	0.33	0.00	0.00	1.04	1.10	**1.37**	0.39	0.00	0.00	3.91
	1.0-4.0	0.35	0.18	0.81	**1.44**	0.05	0.02	0.13	0.11	0.93	**2.02**	0.06	0.00	3.25
	4.0-8.0	0.00	0.00	0.00	0.04	**0.90**	0.00	0.00	0.00	0.00	0.06	**0.05**	0.00	0.11
	>8.0	0.00	0.00	0.00	0.00	0.02	**0.00**	0.00	0.00	0.00	0.00	0.02	**0.00**	0.02
		93.5	1.97	2.36	1.99	0.21	0.02	91.4	2.79	3.00	2.62	0.16	0.00	

		Background radar (Cobb 1 km)						Corrected radar (Cobb 1 km)						
Rain gauge	0.0-0.2	**88.1**	1.12	1.14	0.32	0.07	0.00	**86.9**	1.35	1.29	0.41	0.06	0.00	90.0
	0.2-0.4	2.84	**0.32**	0.46	0.28	0.04	0.00	2.61	**0.57**	0.57	0.36	0.03	0.00	4.14
	0.4-1.0	1.14	0.49	**0.58**	0.65	0.05	0.00	0.90	0.61	**0.74**	0.80	0.03	0.00	3.08
	1.0-4.0	0.39	0.35	0.47	**0.88**	0.14	0.02	0.31	0.28	0.55	**1.24**	0.24	0.00	2.63
	4.0-8.0	0.00	0.00	0.00	0.14	**0.02**	0.04	0.00	0.00	0.00	0.13	**0.05**	0.02	0.19
	>8.0	0.00	0.00	0.00	0.00	0.00	**0.00**	0.00	0.00	0.00	0.00	0.00	**0.00**	0.00
		92.5	2.28	2.64	2.26	0.32	0.05	90.7	2.82	3.15	2.94	0.41	0.02	

Table 5.1: Contingency tables showing percentage of (a) background and (b) corrected Cobbacombe Cross radar (1 km) and gauge hourly rainfall totals at Wilmersham Farm (top) and Brendon Hill (bottom) in the Upper Exe study area within each threshold accumulation group.

	Hourly rain (mm)	Background radar (Clee 5 km)						Corrected radar (Clee 5 km)						
		0.0-0.2	0.2-0.4	0.4-1.0	1.0-4.0	4.0-8.0	>8.0	0.0-0.2	0.2-0.4	0.4-1.0	1.0-4.0	4.0-8.0	>8.0	
Betws gauge	0.0-0.2	**83.0**	0.48	0.37	0.18	0.00	0.00	**81.2**	1.09	0.78	0.41	0.05	0.00	83.5
	0.2-0.4	5.62	**0.44**	0.23	0.05	0.02	0.00	4.64	**0.80**	0.73	0.27	0.00	0.02	6.46
	0.4-1.0	3.88	0.76	**0.53**	0.05	0.00	0.00	2.31	1.01	**1.45**	0.77	0.00	0.00	5.54
	1.0-4.0	1.46	0.65	1.16	**0.67**	0.00	0.00	0.49	0.30	0.91	**2.19**	0.16	0.00	4.05
	4.0-8.0	0.02	0.02	0.07	0.33	**0.00**	0.00	0.00	0.00	0.02	0.24	**0.19**	0.00	0.45
	>8.0	0.00	0.00	0.00	0.00	0.00	**0.00**	0.00	0.00	0.00	0.00	0.00	**0.00**	0.00
		94.0	2.34	2.36	1.29	0.02	0.00	88.6	3.19	3.89	3.88	0.40	0.02	

		Background radar (Clee 5 km)						Corrected radar (Clee 5 km)						
Ysbyty gauge	0.0-0.2	**78.7**	0.37	0.42	0.19	0.00	0.00	**76.9**	0.93	0.67	0.35	0.02	0.00	78.9
	0.2-0.4	5.57	**0.23**	0.14	0.00	0.00	0.00	5.20	**0.51**	0.45	0.16	0.00	0.00	6.32
	0.4-1.0	6.10	0.53	**0.32**	0.02	0.00	0.00	4.40	0.94	**1.28**	0.46	0.00	0.00	7.08
	1.0-4.0	3.84	0.92	0.95	**0.48**	0.00	0.00	1.84	1.02	1.52	**2.17**	0.06	0.00	6.61
	4.0-8.0	0.48	0.16	0.12	0.32	**0.00**	0.00	0.10	0.06	0.08	0.49	**0.30**	0.00	1.04
	>8.0	0.04	0.00	0.04	0.04	0.00	**0.00**	0.00	0.00	0.02	0.03	0.05	**0.00**	0.10
		94.0	2.34	2.36	1.29	0.02	0.00	88.4	3.46	4.01	3.67	0.43	0.00	

Table 5.2: Contingency tables showing percentage of (a) background and (b) corrected Clee Hill radar (5 km) and gauge hourly rainfall totals at Betws-y-Coed (top) and Ysbyty Ifan (bottom) in the Upper Conwy study area within each threshold accumulation group.

	Hourly rain (mm)	Background radar (Crug 2 km)						Corrected radar (Crug 2 km)						
		0.0-0.2	0.2-0.4	0.4-1.0	1.0-4.0	4.0-8.0	>8.0	0.0-0.2	0.2-0.4	0.4-1.0	1.0-4.0	4.0-8.0	>8.0	
Brecon gauge	0.0-0.2	**87.8**	0.31	0.22	0.00	0.00	0.00	**86.9**	0.88	0.57	0.10	0.00	0.00	88.4
	0.2-0.4	4.22	**0.67**	0.14	0.02	0.00	0.00	3.05	**0.91**	0.95	0.12	0.00	0.00	5.04
	0.4-1.0	1.92	0.93	**0.81**	0.12	0.00	0.00	0.72	0.72	**1.60**	0.74	0.00	0.00	3.77
	1.0-4.0	0.46	0.41	0.91	**0.74**	0.00	0.00	0.00	0.00	0.62	**1.77**	0.12	0.00	2.51
	4.0-8.0	0.00	0.00	0.02	0.24	**0.00**	0.00	0.00	0.00	0.00	0.14	**0.12**	0.00	0.26
	>8.0	0.00	0.00	0.00	0.02	0.02	**0.00**	0.00	0.00	0.00	0.02	0.00	**0.00**	0.02
		94.4	2.33	2.11	1.15	0.02	0.00	88.6	2.51	3.75	2.89	0.24	0.00	

		Background radar (Crug 2 km)						Corrected radar (Crug 2 km)						
Storey gauge	0.0-0.2	**79.6**	0.48	0.53	0.00	0.00	0.00	**78.4**	1.16	0.92	0.10	0.00	0.00	80.6
	0.2-0.4	4.11	**0.15**	0.05	0.00	0.00	0.00	3.68	**0.39**	0.19	0.05	0.00	0.00	4.30
	0.4-1.0	4.69	0.68	**0.29**	0.00	0.00	0.00	3.53	0.92	**0.77**	0.44	0.00	0.00	5.66
	1.0-4.0	3.97	1.06	1.89	**0.73**	0.00	0.00	1.35	0.87	2.37	**2.95**	0.10	0.00	7.64
	4.0-8.0	0.34	0.15	0.24	0.48	**0.00**	0.00	0.05	0.10	0.15	0.73	**0.19**	0.00	1.21
	>8.0	0.10	0.00	0.19	0.29	0.00	**0.00**	0.00	0.00	0.05	0.39	0.10	**0.05**	0.58
		92.8	2.51	3.19	1.50	0.00	0.00	87.0	3.43	4.45	4.64	0.39	0.05	

Table 5.3: Contingency tables showing percentage of (a) background and (b) corrected Crug-y-Gorllwyn radar (2 km) and gauge hourly rainfall totals at Brecon (top) and Storey Arms (bottom) in the Upper Taff study area within each threshold accumulation group.

5.6 Summary

Analysis of statistics computed to compare all background and corrected radar data collected between July 2005 and June 2006 with corresponding surface gauge measurements across upland regions shows several features:

- Radar data quality decreases with range over upland areas, as observed for measurements over lowland areas.
- The current radar network is successful in detecting typically 97% of hourly rainfall accumulations in excess of 1 mm across upland areas in England and Wales, similar to that captured by the UK national radar network across all regions.
- The quantitative agreement between radar and gauge data across the Upper Exe region is comparable with that on average across the rest of the UK but less accurate across the Upper Taff and Upper Conwy regions.
- RMS and RMSF values increase, indicating worsening data quality, with gauge altitude. Data quality at the highest locations is typically half as good as that across adjacent more low-lying locations. This is particularly clear in the Upper Exe and Upper Taff regions.

- Application of the orographic correction scheme leads to improvements in radar data quality by up to 75% but by typically 50%. The magnitude of the improvement across the Upper Exe area increases with increasing altitude.
- In low-lying parts of the upland study areas where background radar measurements underestimate the surface rainfall by half, the correction process gives relatively good agreement with gauge measurements on average.
- In more upland parts of the three study areas, the correction is insufficient to match surface measurements and corrected radar data remain up to 50% smaller than the corresponding gauge rainfall accumulations.

PART II: CASE STUDY ANALYSIS

13 August 2005

August 2005 was a notably dry month across the UK, with Wales receiving only 63% of the average monthly rainfall for August for example. Several frontal incursions and thundery episodes did bring periods of rainfall however, some of which were sufficiently intense to cause flash flooding and power loss on Tyneside and in Northern Ireland towards the end of the month. The case of 13 August 2005 across the Upper Conwy study area is one example of such an episode.

All but one of the rain gauges in the Upper Conwy region recorded one of the ten highest daily rainfall accumulations during the study period on 13 August 2005, with the Cwm Dyli gauge measuring 50.2 mm and the Minafor gauge measuring 39.8 mm for example. The highest hourly rainfall accumulation of 16.2 mm was also measured at Cwm Dyli on this day between 0900 and 1000 UTC.

6.1 Synoptic background

The rain was associated with the passage of an occluded front and trailing cold front, illustrated in Figure 6.1, moving eastward or south-eastward across the British Isles. The rain became very heavy in places and further heavy showers developed following the first band of rain.

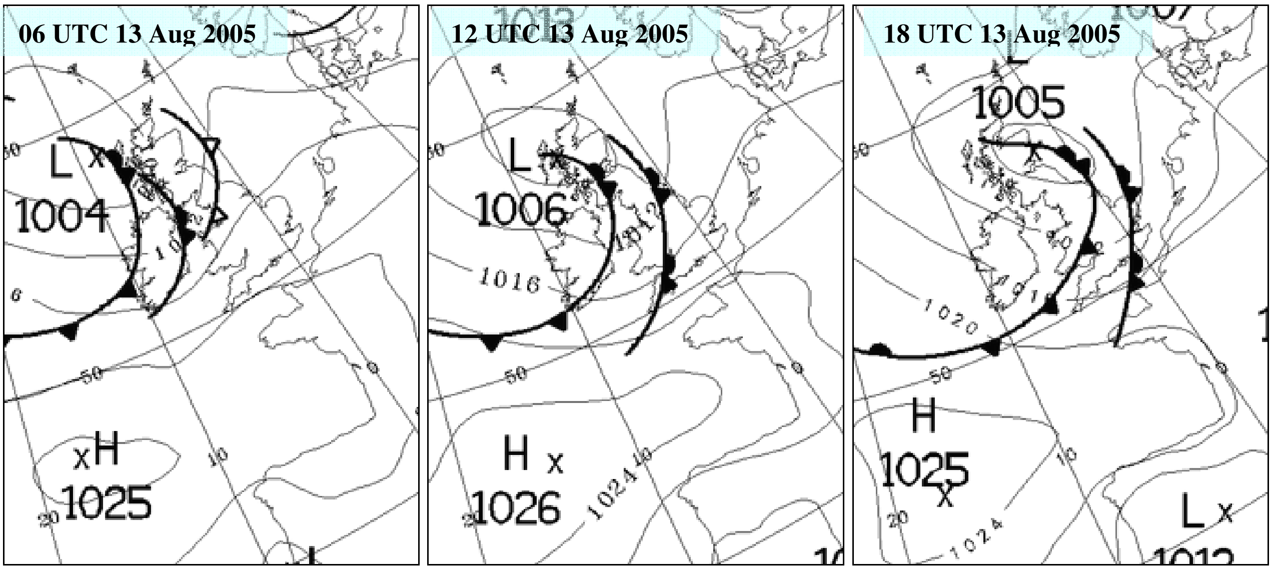


Figure 6.1: Surface pressure analysis chart for 0600 UTC, 1200 UTC and 1800 UTC on 13 August 2005.

6.2 Orographic correction

Figure 6.2 shows an example of the Met Office mesoscale model output at the 800 m level which was used to determine the orographic correction field applied to radar data. This is shown in Figure 6.2(d). The model data shows relative humidities in excess of 85% during the period of rainfall across each of the three study areas and winds typically greater than 26 ms^{-1} from a westerly or south-westerly direction. The generally high wind speeds predicted by the model implies that corrections of up to 4 mmh^{-1} were applied to the background radar data across the Upper Conwy and Upper Taff regions and up to 2 mmh^{-1} across the Upper Exe region during this event.

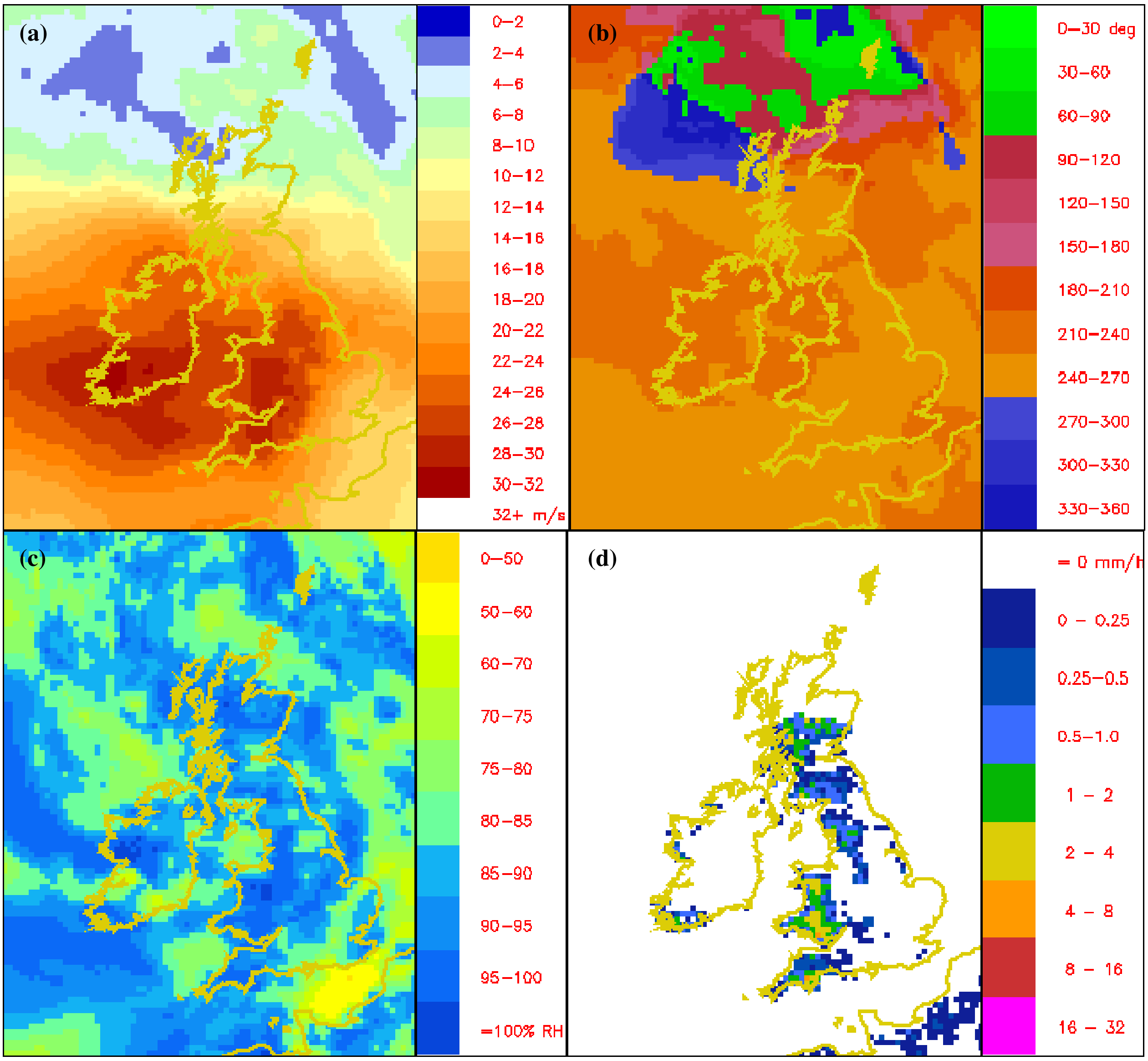


Figure 6.2: Met Office mesoscale model output for 1200 UTC on 13 August 2005 showing (a) wind speed, (b) wind direction and (c) relative humidity at the 800m level used to derive the orographic correction factors shown in (d). Note that figures show 15 km data, but 5 km output was originally applied to the radar data.

6.2 Comparison between radar and gauge accumulations: Upper Conwy

Figure 6.3 shows time series plots comparing the rain gauge and radar rainfall data at each gauge site across the Upper Conwy study area during 13 August 2005. Comparison of the gauge measurements shows considerable spatial variability across the region, with the Padog gauge measuring a total accumulation of only 18.6 mm during the event compared with over 50 mm at Cwm Dyli. This spatial variability is reflected in the images of corrected radar accumulations across the region, shown in Figure 6.4. In agreement with the gauge measurements, largest rainfall accumulations during the period occurred immediately in the lee of Snowdon with gradually decreasing rainfall totals across the surrounding region. In this case rainfall accumulations over upland areas were up to three times higher than over nearby coastal areas. Figure 6.4 also shows relatively little spatial variation in the background radar data, suggesting that the success of the corrected radar data in capturing the observed variability between gauge measurements was almost entirely a result of the magnitude of the orographic corrections applied across the region.

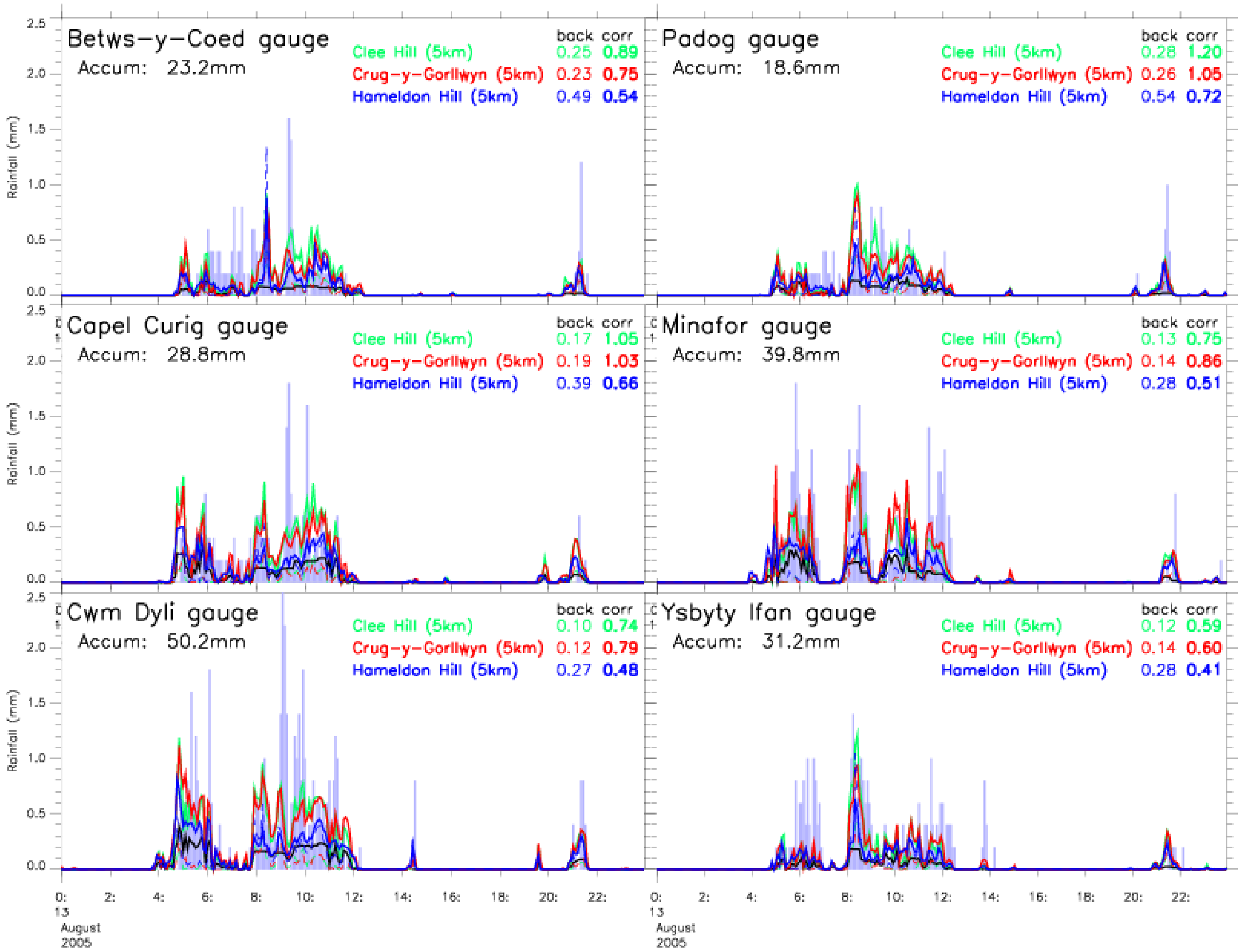


Figure 6.3: Time series of 5 minute rain gauge measurements (bars) and background (- - - -) and corrected (──) radar measurements for the closest pixel to each gauge site on 13 August 2005. The total rainfall accumulation measured by each gauge during the event is listed along with the ratio of total radar to gauge accumulations for each radar (corrected values are in bold). The orographic correction applied to radar data is plotted in black.

Figure 6.3 also shows considerable variability between the temporal patterns at each gauge site. While the Betws-y-Coed, Padog and Capel Curig gauges in the north-east of the region show rainfall persisting between about 0500 UTC and 1230 UTC, peaking at about 0900 UTC, the measurements at Cwm Dyli and Ysbyty Ifan show two distinct episodes of rainfall and the Minafor gauge shows three episodes during this period. This temporal structure is particularly well captured by each of the radars. The continuous rainfall observed at Betws-y-Coed and Padog is less well represented however with a clear underestimation of rainfall between 0630 UTC and 0800 UTC.

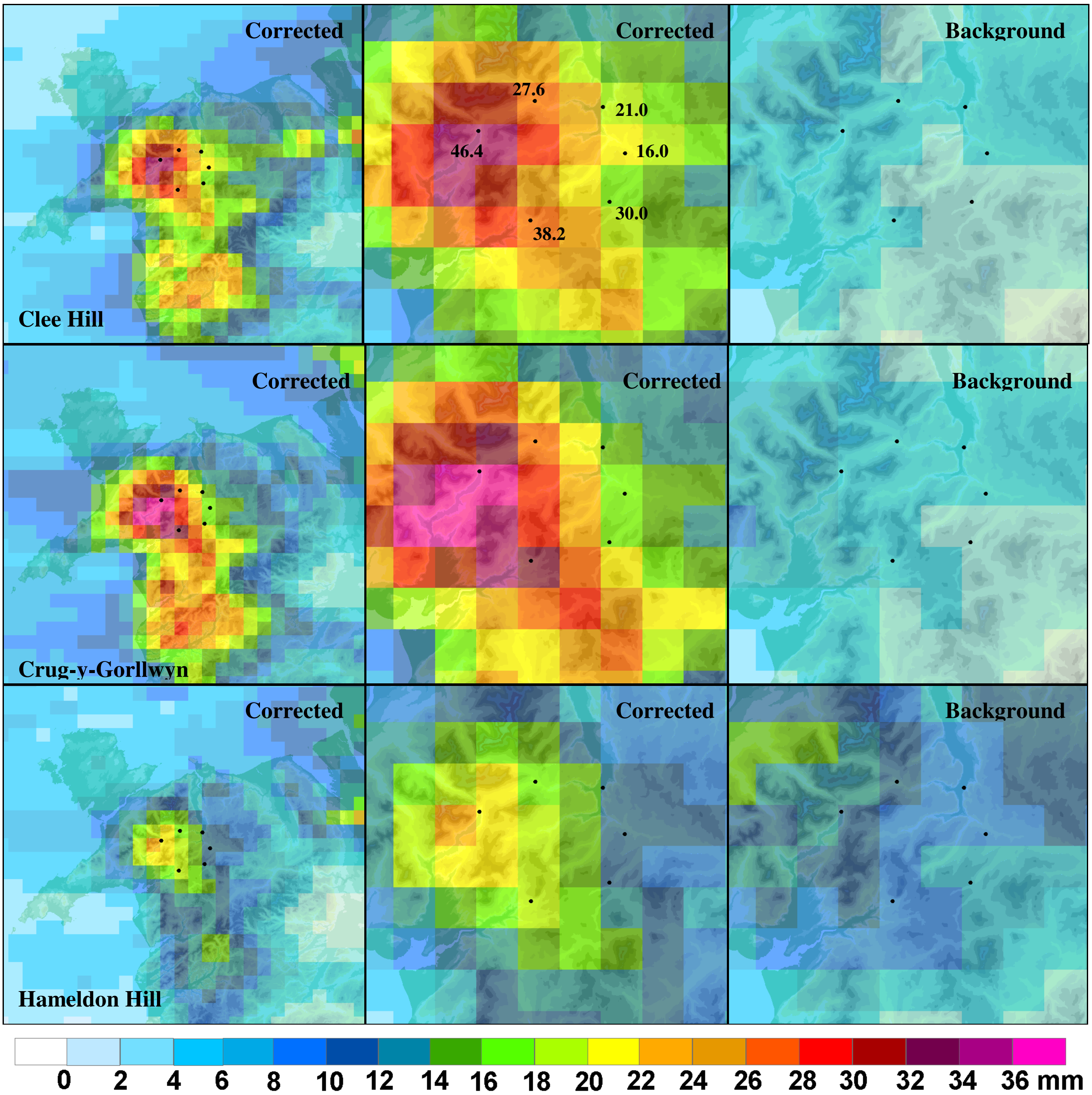


Figure 6.4: Comparison of 12 hour rainfall accumulations from each available radar across the Upper Conwy region between 0200 UTC and 1400 UTC on 13 August 2005. Black circles indicate rain gauge locations with labels showing the corresponding rain gauge accumulation over the same period in mm.

A measure of the overall radar performance during the event is provided by the ratios of the total rainfall accumulation for each pair of gauges and radars listed in Figure 6.3. These show that,

- Orographic corrections improve the accuracy of radar measurements, typically halving the difference between background radar and gauge accumulations. For the cases of Clee Hill and Crug-y-Gorllwyn radar data at Padog and Capel Curig, the correction completely removes the underestimation between background radar and gauge rainfall.
- Quantitative agreement between gauges and radar data from Hameldon Hill is particularly poor even after application of orographic corrections. The radar data typically underestimates the measured surface rainfall by 50%.
- Worst agreement between radar and gauge measurements occurred at Ysbyty Ifan where only 60% of the total gauge accumulation was captured by any radar.

Each of these results are illustrated by the correlation between radar and gauge measurements plotted in Figure 6.5. The most consistent behaviour is evident for radar measurements from Hameldon Hill which systematically underestimate hourly gauge rainfall totals above 2 mm. This underestimate is largely due to apparently inappropriate gauge adjustment factors being used to scale the surface rainfall estimate derived from the VPR processing. No such consistent relationship between gauge measurements and the radar data from the Clee Hill and Crug-y-Gorllwyn is evident, with considerable variation of both background and corrected accumulations shown over the entire rainfall range. For hourly rainfall accumulations less than about 6 mm, Figure 6.5 shows periods when both radars overestimated surface rainfall totals and the applied orographic corrections were too large by up to 2 mmh^{-1}. For higher rainfall accumulations, the background radar rainfall values were apparently too small leading to rainfall underestimation by typically up to 50%.

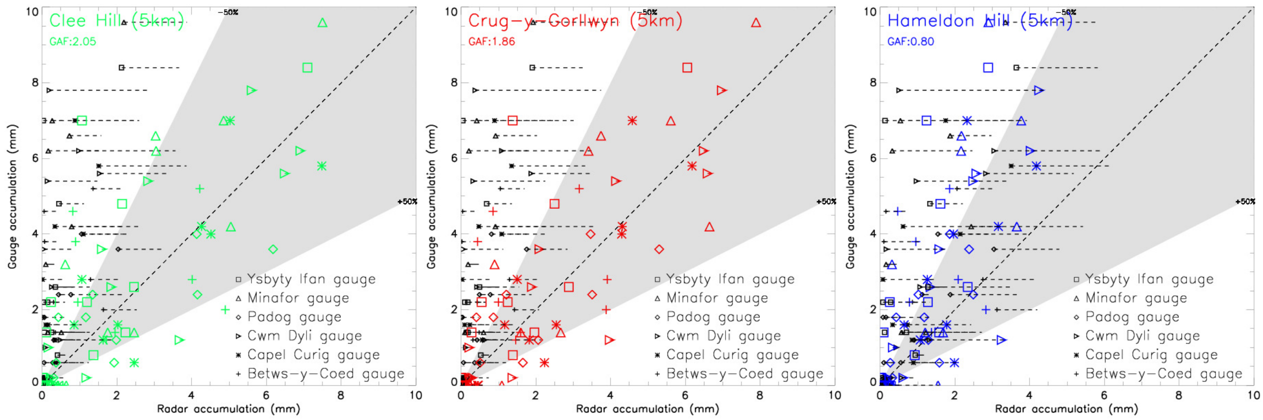


Figure 6.5: Correlation between hourly gauge measurements in the Upper Conwy study area and background (small points) and corrected (large points) radar data from (a) Clee Hill, (b) Crug-y-Gorllwyn and (c) Hameldon Hill during 13 August 2005. Horizontal lines show the magnitude of the orographic correction applied to the background data in each case.

Figure 6.3 shows that rainfall underestimation by as much as 75% was a particular problem for radar performance at Ysbyty Ifan during the first rainfall episode between about 0500 UTC and 0700 UTC. Table 1.1 shows the background and corrected hourly accumulation values derived from each radar with Ysbyty Ifan gauge totals between 0600 UTC and 0700 UTC. As shown in Figure 6.5, orographic corrections were applied to notably small background radar estimates.

Gauge		Radar	Background	Back + Orog	Corrected
Ysbyty Ifan	7.0 mm	Clee Hill	0.026 mm	0.54 mm	1.06 mm
		Crug-y-Gorllwyn	0.042 mm	0.74 mm	1.37 mm
		Hameldon Hill	0.128 mm	1.41 mm	1.24 mm

Table 6.1: Comparison between background and corrected radar hourly rainfall accumulations between 0600 and 0700 UTC on 13 August 2005 and gauge measured hourly accumulation at Ysbyty Ifan, Upper Conwy.

The second prominent failure of the radar measurements during this event is the inability to capture the intensive rainfall spikes in the rainfall time series, notably at Cwm Dyli, Capel Curig and Betws-y-Coed between 0900 UTC and 1000 UTC and at Minafor throughout the morning. This is perhaps a result of regions of localised convection embedded within the larger-scale frontal system. Sample radar images during this period are shown in Figure 6.6. Table 6.2 summarises the hourly radar rainfall accumulations between 0900 UTC and 1000 UTC with gauge measurements at Cwm Dyli when the peak hourly accumulation during the entire study period was measured. Note for clarity these data are not included in Figure 6.5.

Gauge		Radar	Background	Back + Orog	Corrected
Cwm Dyli	16.2 mm	Clee Hill	1.23 mm	3.16 mm	6.14 mm
		Crug-y-Gorllwyn	0.97 mm	2.67 mm	4.99 mm
		Hameldon Hill	2.27 mm	4.56 mm	2.82 mm

Table 6.2: Comparison between background and corrected radar hourly rainfall accumulations between 0900 and 1000 UTC on 13 August 2005 and gauge measured hourly accumulation at Cwm Dyli, Upper Conwy.

Figure 6.4 and Table 6.2 clearly illustrate that the orographic correction has a beneficial impact on radar data quality during this time, but that the particularly high rainfall accumulations measured at the surface were not captured. It seems that it is not possible to replicate the high spatial variability of the rainfall pattern observed at the surface with background radar estimates at 5 km resolution. Were such rainfall patterns a result of locally large orographic enhancement rather than embedded convection then even if radar measurements were available at higher spatial resolution, the influence of possible rainfall intensification within individual steep valleys such as at Cwm Dyli is not currently captured by the orographic correction fields which are also defined at a 5 km resolution. Rather, the correction factors in the vicinity of Cwm Dyli are likely to reflect the larger scale terrain features such as Glyder Fawr and Glyder Fach. It is therefore anticipated that consideration of radar data at smaller spatial resolution might improve the agreement between the background radar rainfall and gauge measurements while application of corrections at a similar resolution might increase the correction applied where slopes are locally very steep.

The rainfall underestimation by the radar at Hameldon Hill is further illustrated by the radar images in Figure 6.6. All three radars with coverage over the Upper Conwy region are at ranges within 30 km of each other for all gauge sites, with Hameldon Hill and Crug-y-Gorllwyn radars both about 130 km away from most gauges. This implies that relatively poor radar performance from Hameldon Hill is not simply due to differences in radar range. Further, Figures 6.4 and 6.6 show generally lower rainfall estimates from Hameldon Hill over the whole area shown independent of the terrain altitude. The differences between radar rainfall estimates from each radar is clearly highly dependent on the different gauge adjustment factors used to scale the surface rainfall rate derived from the VPR correction processing. Figure 6.5(c) shows how the gauge adjustment factor of about 0.8 has the effect of reducing surface rainfall estimates from the Hameldon Hill radar, decreasing data quality relative to the gauges across the Upper Conwy region. This suggests that the gauge adjustment factor, derived from a comparison of radar data with gauge measurements across the entire region of radar coverage, is unsuitable to modify rainfall estimates across the Upper Conwy region. This is significant since although measurements from Clee Hill are generally used in the operational composite radar image, the Hameldon Hill radar is next closest to the Betws-y-Coed and Padog gauges so that rainfall estimates derived from Hameldon Hill would be used to cover the north-east part of the region should data from Clee Hill be unavailable. While beyond the scope of this study, this perhaps gives some indication that a more sophisticated technique for deriving the composite radar product from available data is possibly of value. At present the closest available radar is generally used for each pixel under the assumption that this is of best quality.

Case summary

- High spatial variability is generally missed by radars, but captured well by corrections
- Radars miss morning rain at Ysbyty Ifan, perhaps as background rain rates are too small
- Radars do not capture very intensive rainfall, perhaps triggered by embedded convection
- Particularly poor performance by Hameldon Hill radar – detrimental impact of GAF?

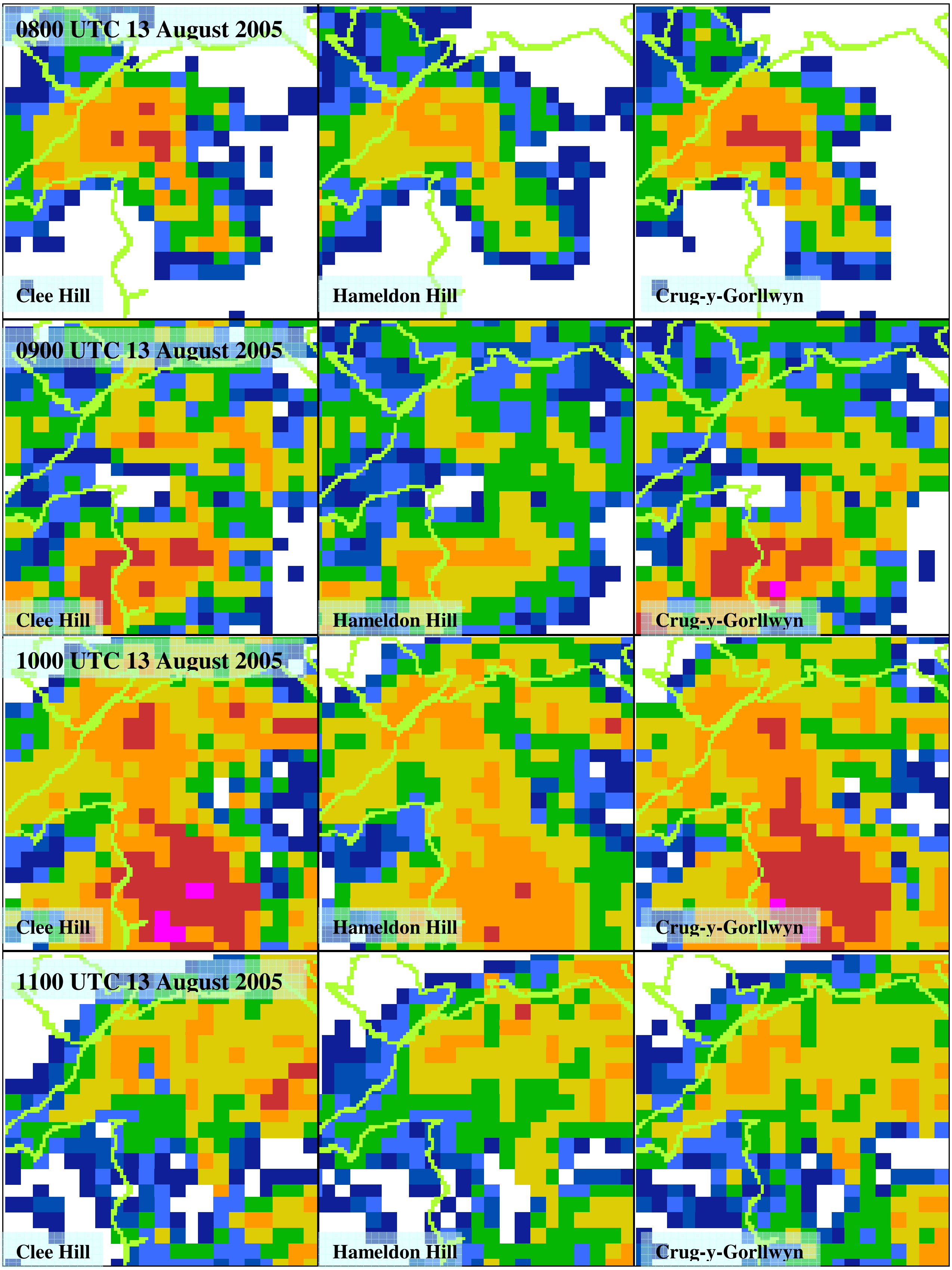


Figure 6.6: Comparison of 5 km radar data showing rainfall across the Upper Conwy catchment during the morning of 13 August 2005.

28 September 2005

The last week of September 2005 was a period of generally unsettled weather when several Atlantic weather systems crossed the UK. The heaviest rainfall associated with one of these systems occurred on 28 September 2005 when four of the six rain gauges across the Upper Conwy study area recorded in excess of 30 mm rainfall within 6 hours. The rain was intense at times, peaking by mid-afternoon when 12.2 mm rain accumulated within an hour at Cwm Dyli for example.

7.1 Synoptic background

Figure 7.1 shows surface pressure charts during the afternoon of 28 September 2005. These illustrate the passage of a frontal system from the west across the UK within a period of 12 hours. The associated band of persistent rain was accompanied by strong, gusty and locally squally winds. Some heavy pulses of rain were embedded in these larger scale rain areas. The first rainfall across western parts of the UK was associated with the passage of a warm front from the south-west which was replaced about 4 hours later by more intense rainfall associated with the passage of the trailing cold front from the north-west. This structure is illustrated by the UK national composite radar image shown in Figure 7.1(c). Further isolated showers developed during the evening behind the cold front.

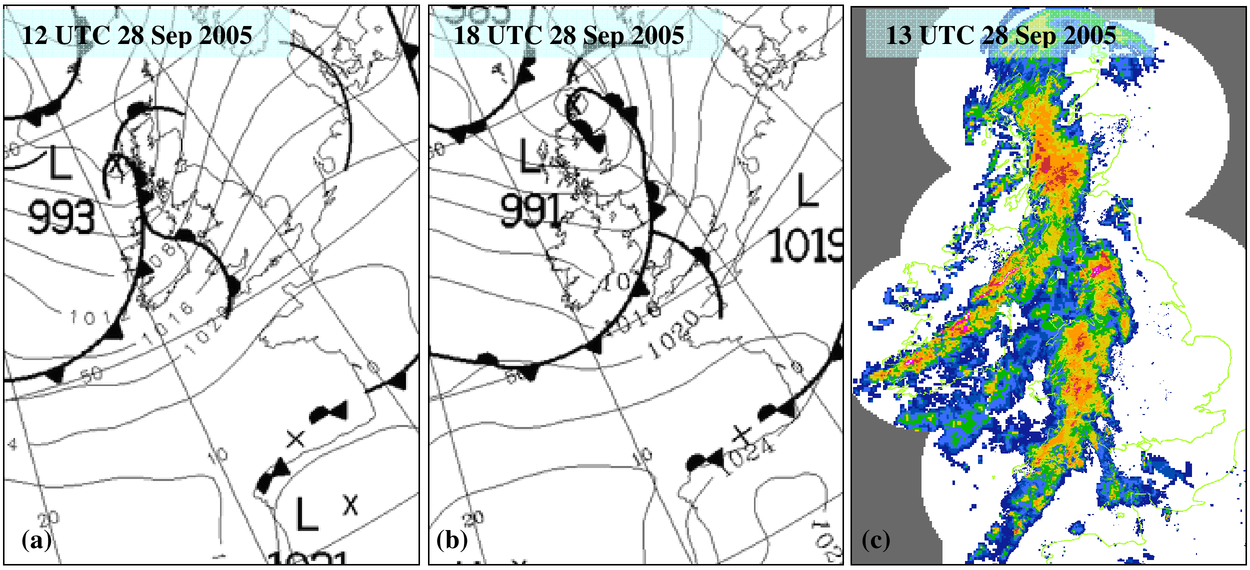


Figure 7.1: Surface pressure analysis chart for (a) 1200 UTC and (b) 1800 UTC on 28 September 2005. (c) Composite radar image showing rainfall associated with warm and trailing cold front s across western UK.

7.2 Orographic correction

Figure 7.2 shows the orographic correction field derived from the mesoscale model output for 1200 UTC on 28 September 2005. This shows that corrections of up to 2 mmh^{-1} were applied to background radar data across each of the three upland regions considered. The magnitude of the orographic correction factors increased in time as the region of high wind speeds (> 32 ms^{-1}) shown in Figure 7.2(a) crossed the UK. Figure 7.3 shows that correction factors of up to 4 mmh^{-1} were derived from the model output at 1800 UTC for example. Critically, no corrections were applied to radar data across north Wales by this time. This is because relative humidities of about

80% were predicted by the model in this region, below the threshold required to apply corrections.

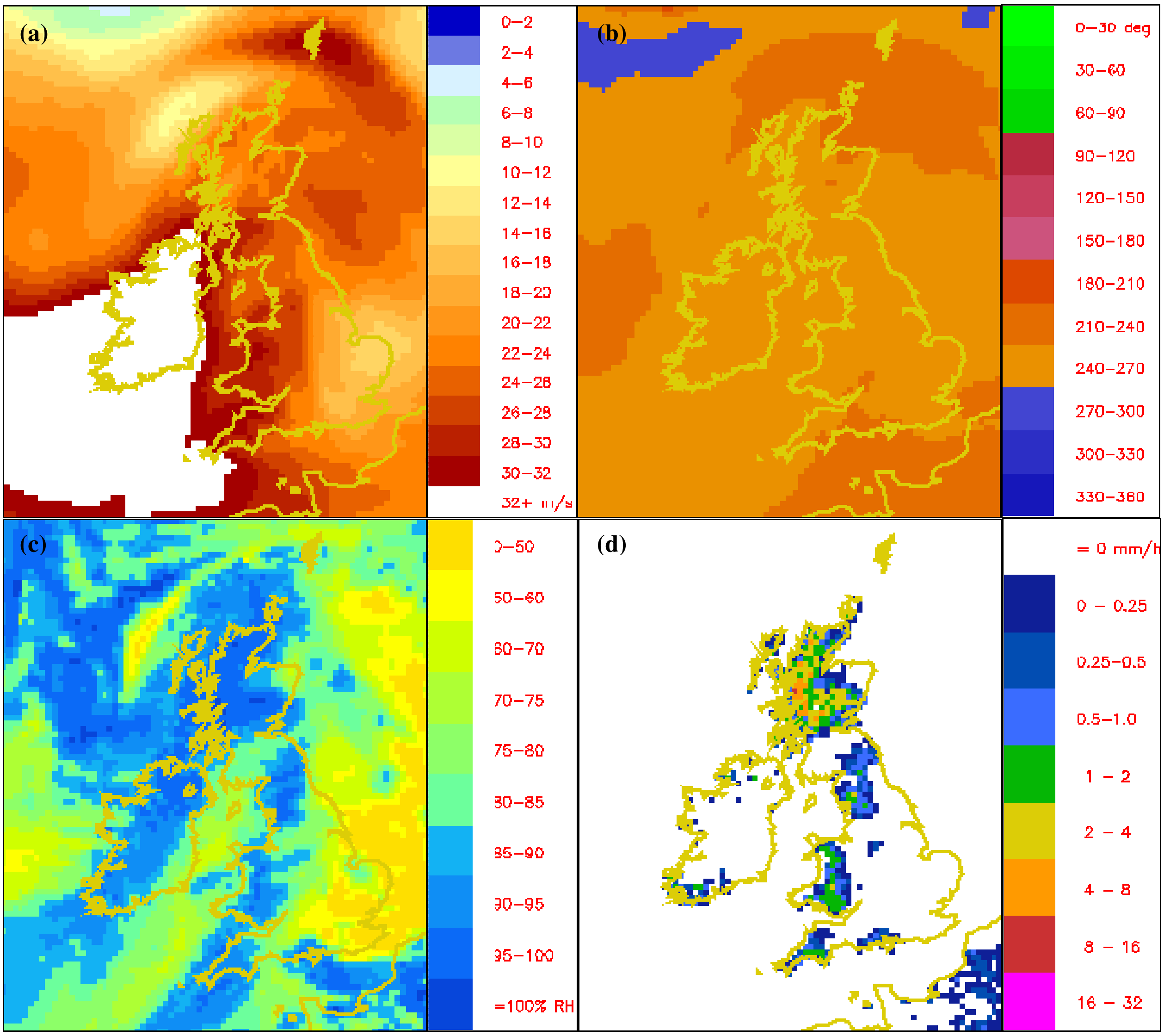


Figure 7.2: Met Office mesoscale model output at 800 m for 1200 UTC on 28 September 2005 showing (a) wind speed, (b) wind direction and (c) relative humidity used to derive the orographic correction factors in (d).

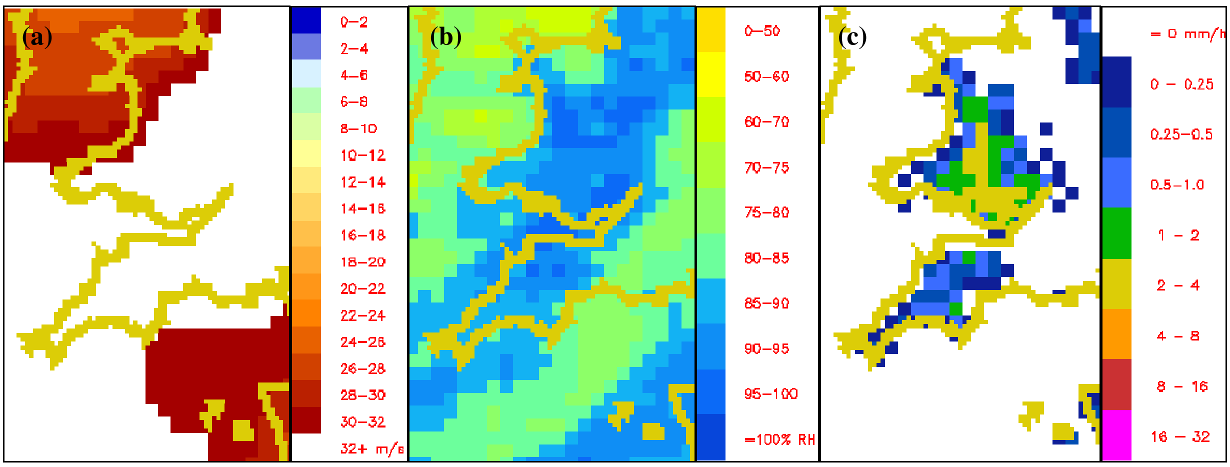


Figure 7.3: Met Office mesoscale model output for 1800 UTC on 28 September 2005 showing (a) wind speed and (b) relative humidity at 800m used to derive the field of orographic correction factors in (c).

7.3 Comparison between radar and gauge accumulations: Upper Conwy

Figure 7.4 shows 5 minute rainfall accumulations measured by each gauge across the Upper Conwy region during 28 September 2005. The total accumulation and temporal variation of rainfall at each site are broadly similar, indicative of large scale frontal rainfall. The radar accumulations illustrated in Figure 7.5 suggest that strongest rainfall during this period occurred to the south-east of the region nearest the Ysbyty Ifan gauge, with a secondary region of stronger rainfall in the vicinity of Cwm Dyli where largest orographic corrections were applied.

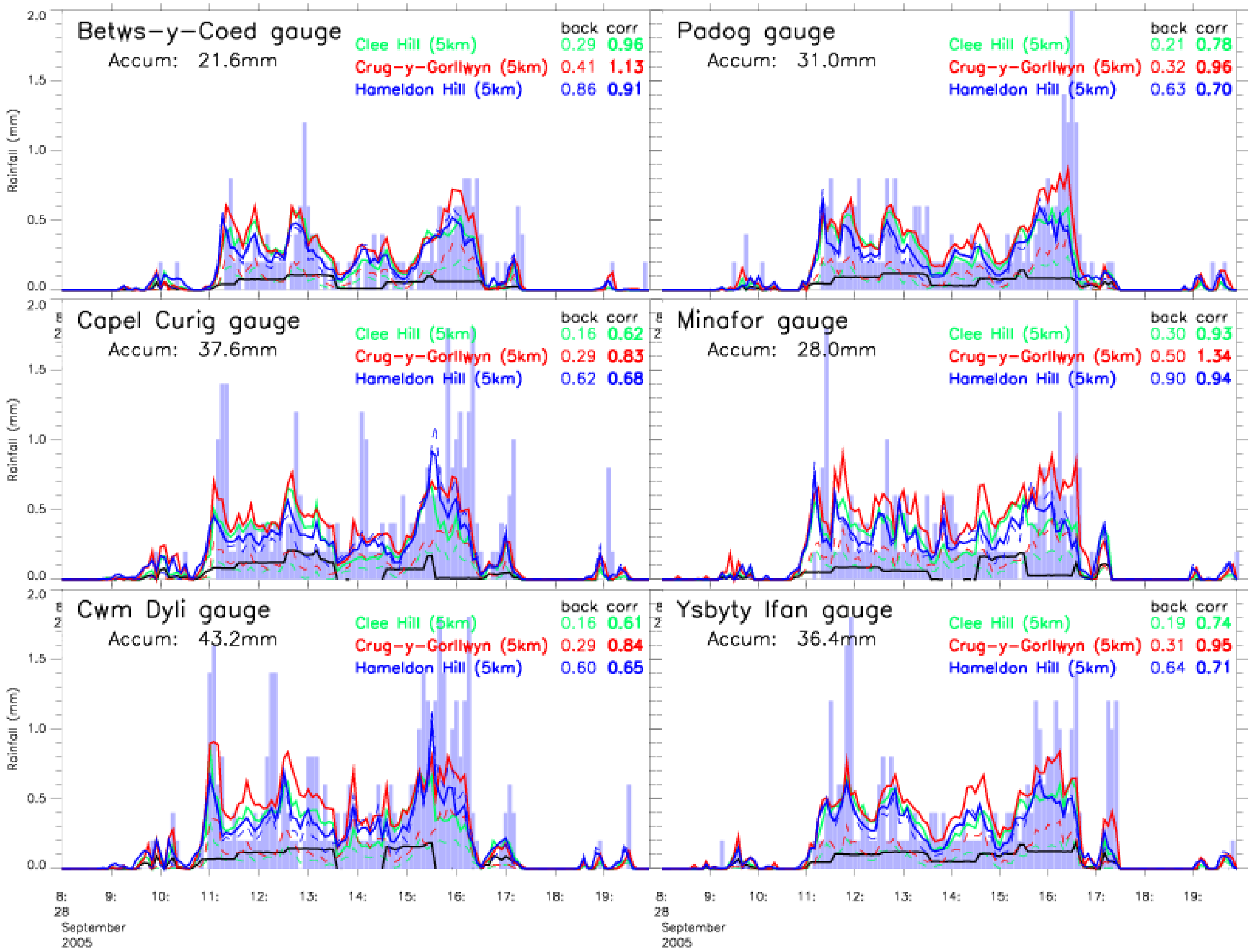


Figure 7.4: Time series of 5 minute rain gauge measurements (bars) and background (- - - -) and corrected (—) radar data for the closest pixel to each gauge site on 28 September 2005. The total rainfall accumulation measured by each gauge during the event is listed along with ratios of radar to gauge accumulations.

There is good qualitative agreement between corrected radar and gauge measurements shown in Figure 7.4, largely as a result of the time-varying orographic correction applied. In particular, the radars are successful in capturing the general magnitude of the synoptic scale rainfall, and the duration of the heavier rainfall associated with the cold front between about 1500 UTC and 1630 UTC. The radar time series do not capture the local scale variations in rainfall however which bring periods of intense rain to Capel Curig, Cwm Dyli, Minafor and Ysbyty Ifan gauges in particular. The ratio of radar to gauge accumulations during this event listed in Figure 7.4 reveal that:

- Radars generally underestimate the measured surface rainfall by up to 40%.
- Orographic corrections improve the accuracy of radar measurements, typically halving the

difference between background radar and gauge accumulations.

- The corrections applied to Crug-y-Gorllwyn radar data completely remove the rainfall underestimation shown by the background data at Betws-y-Coed and Minafor gauges.
- Best agreement between radar and gauge measurements at each site is achieved using Crug-y-Gorllwyn data, worst quantitative agreement occurs with Hameldon Hill data.

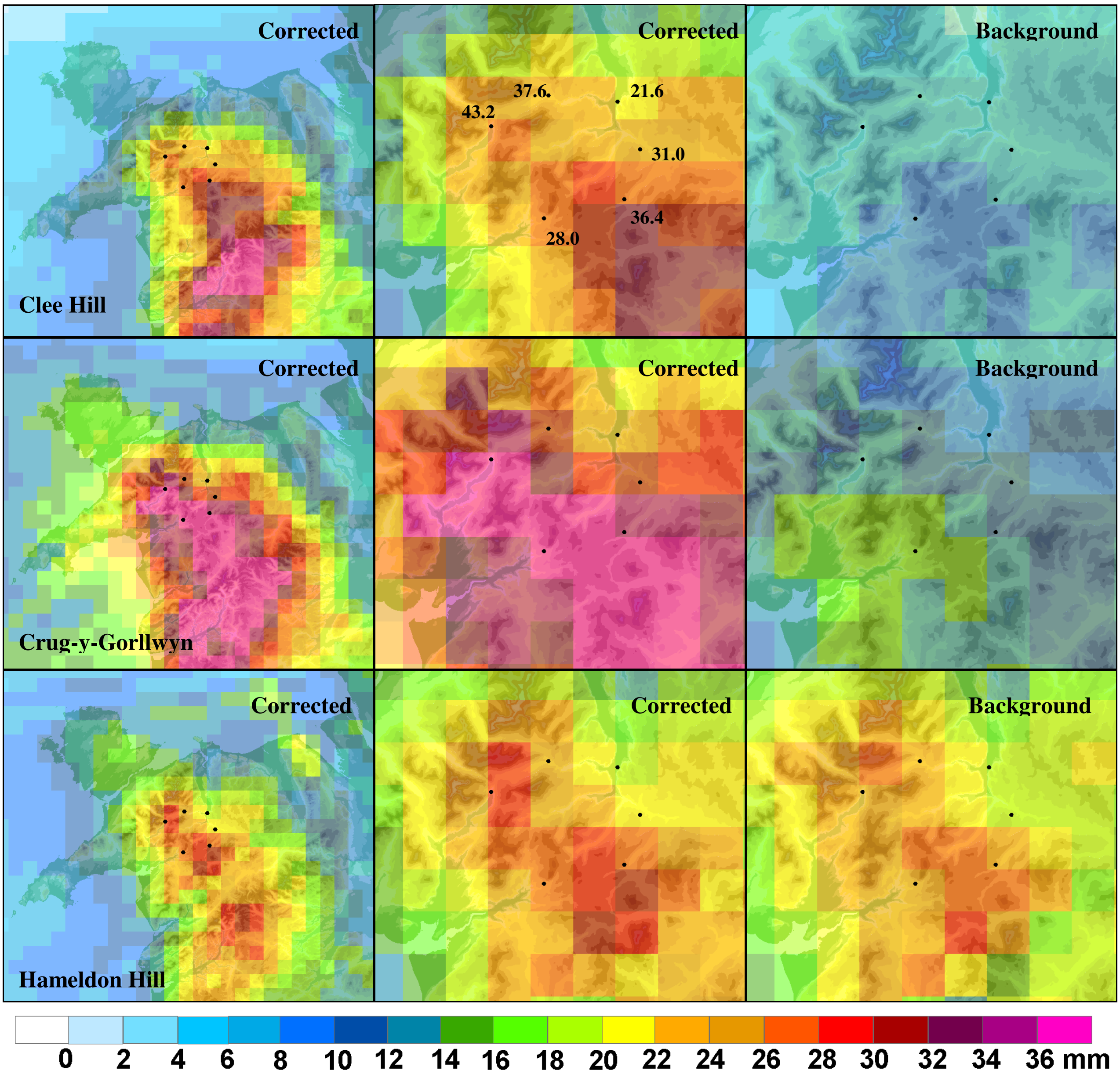


Figure 7.5: Comparison of 12 hour rainfall accumulations from each available radar across the Upper Conwy region between 0800 UTC and 2000 UTC on 28 September 2005. Black circles indicate rain gauge locations with labels showing the corresponding rain gauge accumulation over the same period in mm.

The generally lower rainfall values derived from the Clee Hill radar data shown in Figure 7.4 is particularly significant since this was included across the Upper Conwy region in the operational UK national composite radar product during this period. The correlation between radar and gauge measurements shown for each radar in Figure 7.6 shows that both the Clee Hill and Hameldon Hill data are actually in good agreement with gauge measurements for hourly accumulations of between about 2 and 5 mm. The corrections applied to Crug-y-Gorllwyn data were too large in this range, leading to an overestimate of surface rainfall. This is particularly evident in the time series for Minafor shown in Figure 7.4. For hourly accumulations of less than 2 mm, Figure 7.6 highlights a consistent underestimation by all radars for all gauge locations. For hourly rainfall accumulations in excess of 5 mm the Clee Hill and Hameldon Hill radars clearly underestimate the surface rainfall even with an orographic correction of up to 2 mm applied. Larger background rainfall values derived from the Crug-y-Gorllwyn radar led to closer correlation between radar and gauge values in Figure 7.6(b). The considerable difference between radar output from Crug-y-Gorllwyn and Clee Hill is illustrated in Figures 7.7 and 7.8 which show radar images at 1400 UTC and 1630 UTC depicting rainfall across the Upper Conwy region associated with the warm and cold fronts respectively.

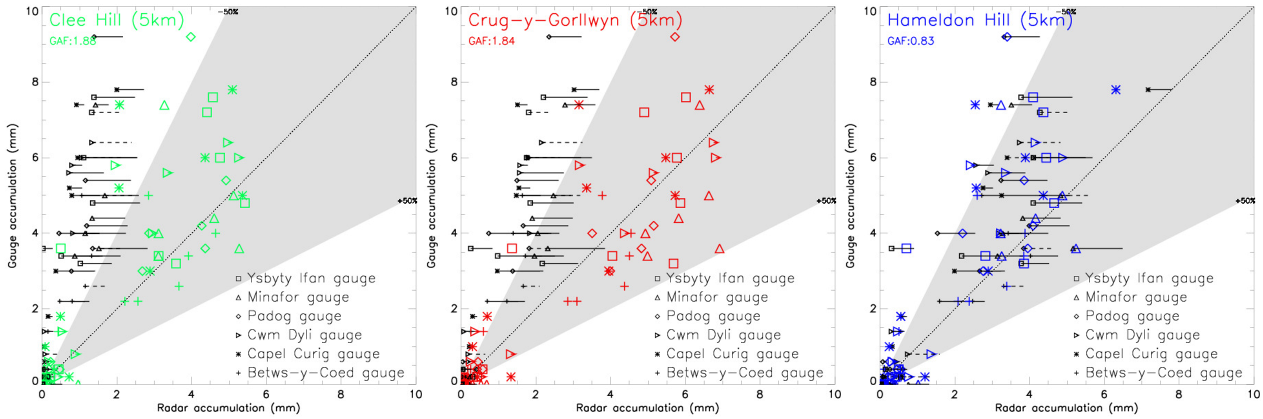


Figure 7.6: Correlation between hourly gauge measurements in the Upper Conwy study area and background (small points) and corrected (large points) radar data from (a) Clee Hill, (b) Crug-y-Gorllwyn and (c) Hameldon Hill during 28 September 2005. Horizontal lines show the magnitude of the orographic correction applied to the background data in each case.

Some of the error at higher rainfall accumulations might be attributed to the lack of orographic corrections applied during the latter part of the cold front period at the Cwm Dyli and Capel Curig gauges. As discussed in Section 7.2, this is because model relative humidity values dropped below 85% across the north of the study region. In contrast, the variation between gauge time series in Figure 7.4 suggests that considerable orographic forcing took place at this time. The dependence of the current orographic correction scheme on model relative humidity therefore prevented better agreement between gauge and radar rainfall values during this event.

Even when larger corrections were applied to the data, such as at the beginning of the event, the radars were unable to capture the locally intense rainfall distribution highlighted by the gauge measurements. This failure contributes significantly to the underestimation of total rainfall accumulation by each radar during the event illustrated by the ratio of gauge and radar totals listed in Figure 7.4. It appears that the currently available horizontal resolution of radar rainfall data across the Upper Conwy study area is insufficiently small to reflect the small-scale rainfall variation observed at the surface. Features such as intensive rainfall within the valley at Cwm Dyli (94 m AOD) were not very well measured by any of the available radars. Rather, the radar measurements tend to show values which reflect the rainfall on a more regional scale.

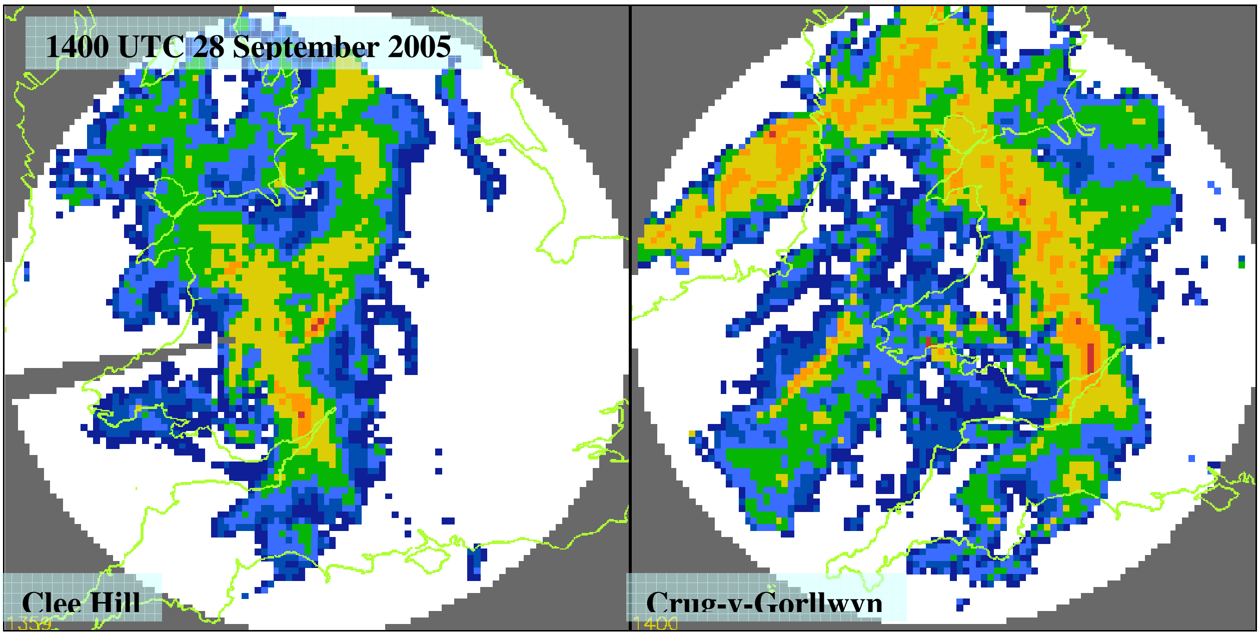


Figure 7.7: Comparison of 5 km radar data from Clee Hill and Crug-y-Gorllwyn showing rainfall associated with the warm front across the Upper Conwy region.

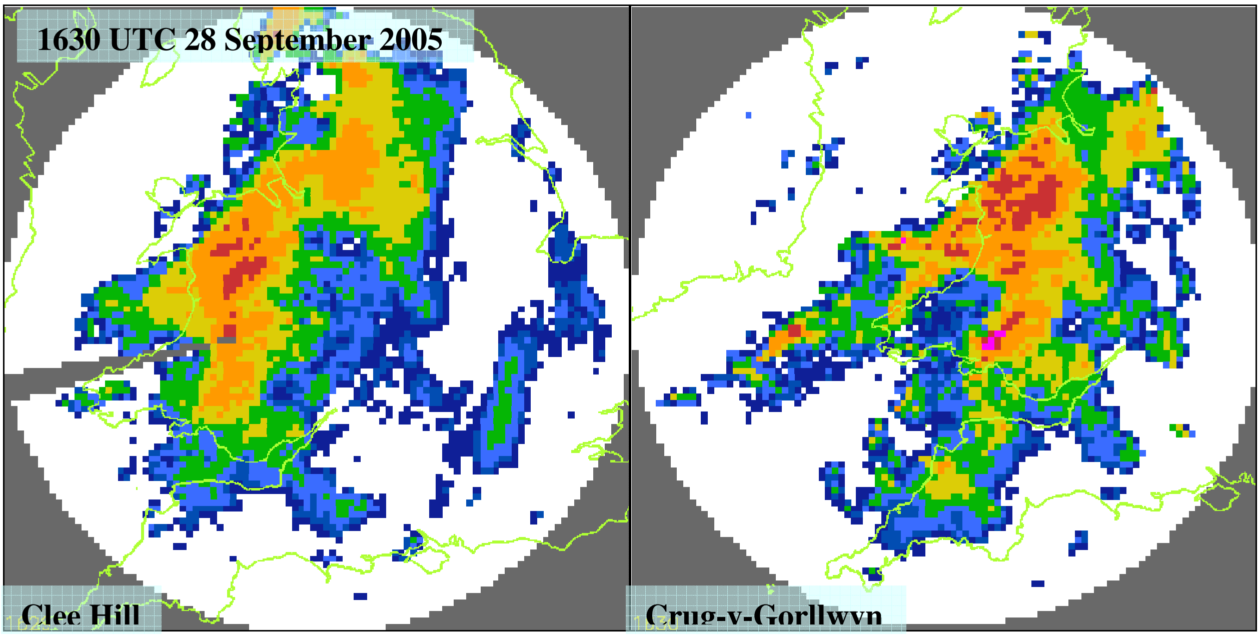


Figure 7.8: Comparison of 5 km radar data from Clee Hill and Crug-y-Gorllwyn showing rainfall associated with the cold front across the Upper Conwy region.

Case summary

- High spatial variability of rainfall is not captured particularly well by the available radars
- Clee Hill and Hameldon radars are in good agreement with gauges for accum <5 mmh^{-1}
- Crug-y-Gorllwyn radar overestimates surface rainfall for accumulations < 5 mmh^{-1}
- Radars do not capture very intensive rain, perhaps influenced by local topography or triggered locally by embedded convection at a sub-pixel scale.

7.4 Comparison between radar and gauge accumulations: Upper Taff

Figure 7.9 shows a comparison between available radar data and gauge measurements at Brecon (168 m AOD) and Nantyrwdd (300 m AOD) in the Upper Taff region during 28 September 2005. Unfortunately, gauge data from other locations in the region were unavailable during this period. The rainfall distribution across the Upper Taff area is illustrated by the rainfall accumulations presented in Figure 7.10. This shows the influence of substantial orographic enhancement leading to increased rainfall totals along the southern lee edge of the Brecon Beacons range.

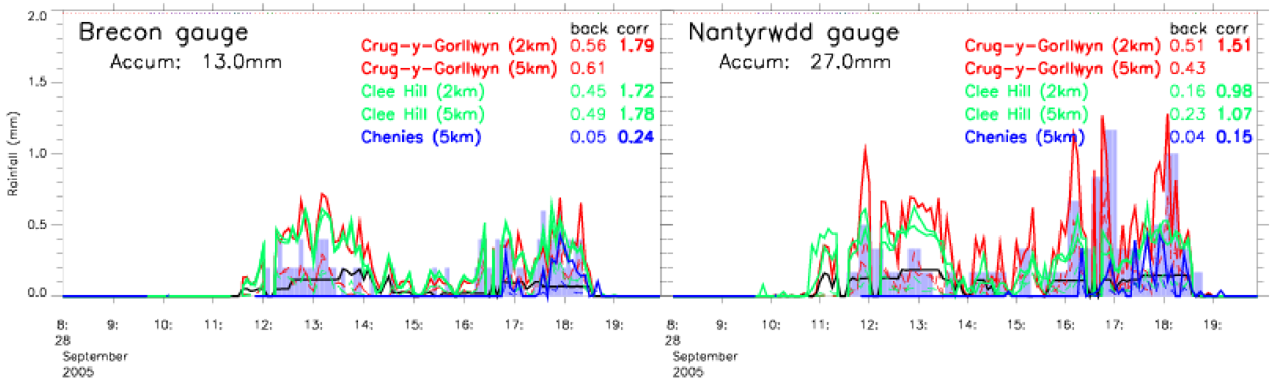


Figure 7.9: Time series of 5 minute rain gauge measurements (bars) and background (- - - -) and corrected (—) radar data for the closest pixel to each gauge site on 28 September 2005. The total rainfall accumulation measured by each gauge during the event is listed along with ratios of radar to gauge accumulations.

The time series plotted in Figure 7.9 indicate considerable rainfall overestimation by the Crug-y-Gorllwyn and Clee Hill radars, giving rainfall values up to twice as large as the surface gauge measurements, during the first period of rainfall associated with the passage of the warm front. This leads to the considerable bias between corrected radar and gauge data listed in Figure 7.9. There is generally much better agreement between radar and gauge data during the second period of rainfall after about 1500 UTC associated with the trailing cold front. Figure 7.9 shows how gauge measurements at Nantyrwdd were similar to those at Brecon during the first period of rain but values are up to two times greater at Nantyrwdd during the second period, perhaps indicative of stronger orographic forcing at this time. Despite this difference, the orographic corrections applied during this event, plotted in Figure 7.9, were actually higher during the first event leading to the overestimation of surface rainfall values observed.

The data from the Chenies radar shown in Figure 7.9 demonstrate very poor agreement with the corresponding gauge measurements. The radar completely missed the rainfall associated with the warm front. This is likely to be due to the radar beam overshooting the rain band at such long range of over 200 km. The rainfall associated with the cold front was identified after about 1600 UTC, but rainfall values underestimated the gauge measurements, particularly at Nantyrwdd. This poor performance is not considered to be of great significance since data from the Chenies radar would only be used in the UK national composite product across the region if both Crug-y-Gorllwyn and Clee Hill radars were unavailable.

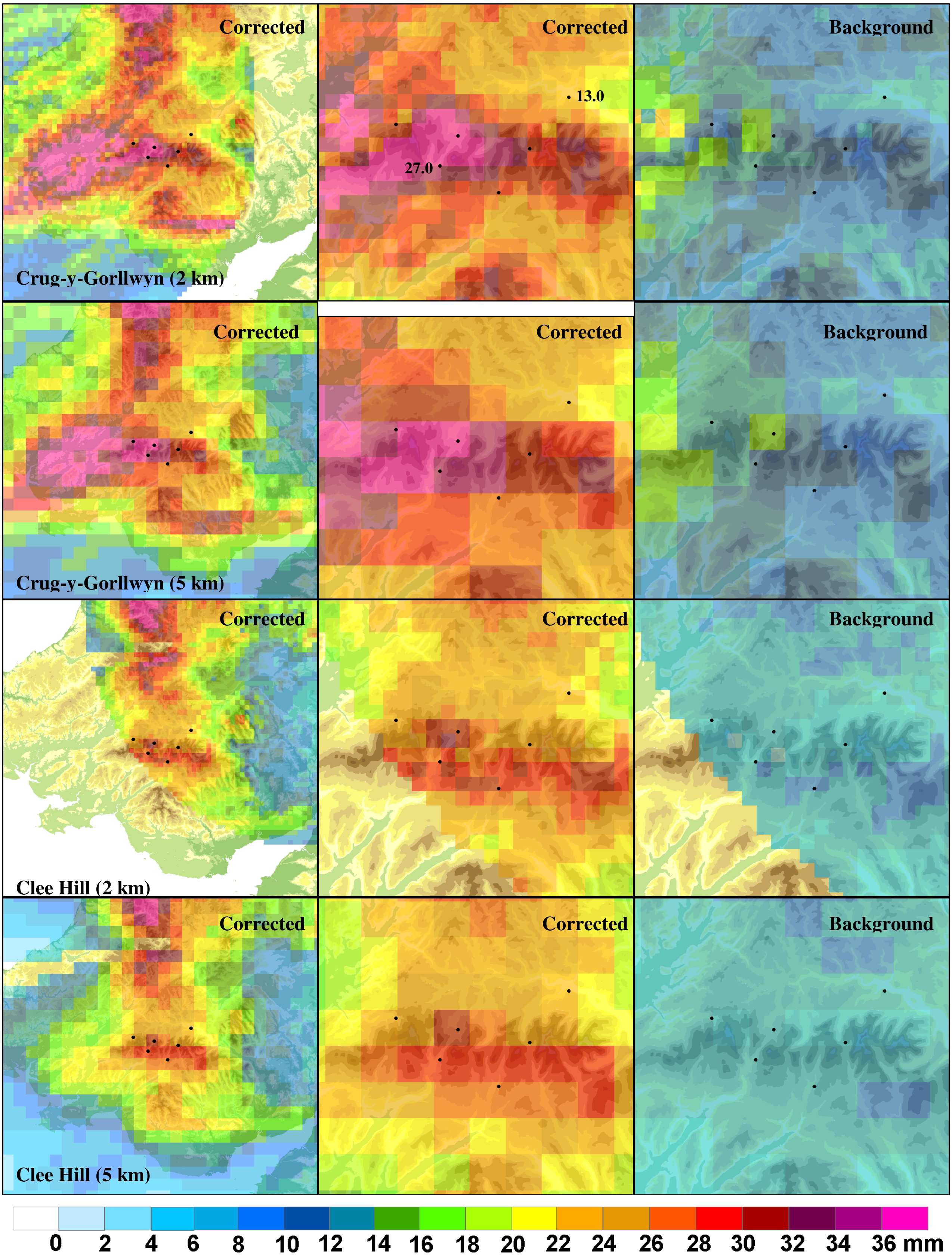


Figure 7.10: Comparison of 12 hour rainfall accumulations from each available radar across the Upper Taff region between 0800 UTC and 2000 UTC on 28 September 2005. Black circles indicate rain gauge locations with labels showing the corresponding available rain gauge accumulation over the same period in mm.

7.5 Comparison between radar and gauge accumulations: Upper Exe

Figure 7.11 shows time series plots of the rainfall distribution across the Upper Exe study area during 28 September 2005. The gauge measurements in Figure 7.11 show three main rainfall episodes during this period. The first between 1200 UTC and 1400 UTC is associated with the warm front. This was followed by showers between 1600 UTC and 1800 UTC before heavier rainfall again between 1900 UTC and 2030 UTC associated with the passage of the cold front across the region. While this structure is replicated at all gauge sites (and by all available radars), Figure 7.11 highlights considerable variation between the magnitude of rainfall across the Upper Exe region during this event. This is reflected by the total gauge accumulations listed, ranging between 25.0 mm falling in 12 hours at Blackpitts and 8.2 mm at Brendon Hill. The relatively low rainfall measured at Brendon Hill is perhaps a result of rain shadowing in the lee of Exmoor, particularly from the south-eastward moving cold front. This feature is illustrated by the distribution of radar rainfall accumulations across the Upper Exe region plotted in Figure 7.12. In contrast to the rainfall accumulations across the Upper Conwy region shown in Figure 7.5, the background radar data at close range from Cobbacombe Cross clearly captures much of the spatial variability of surface rainfall.

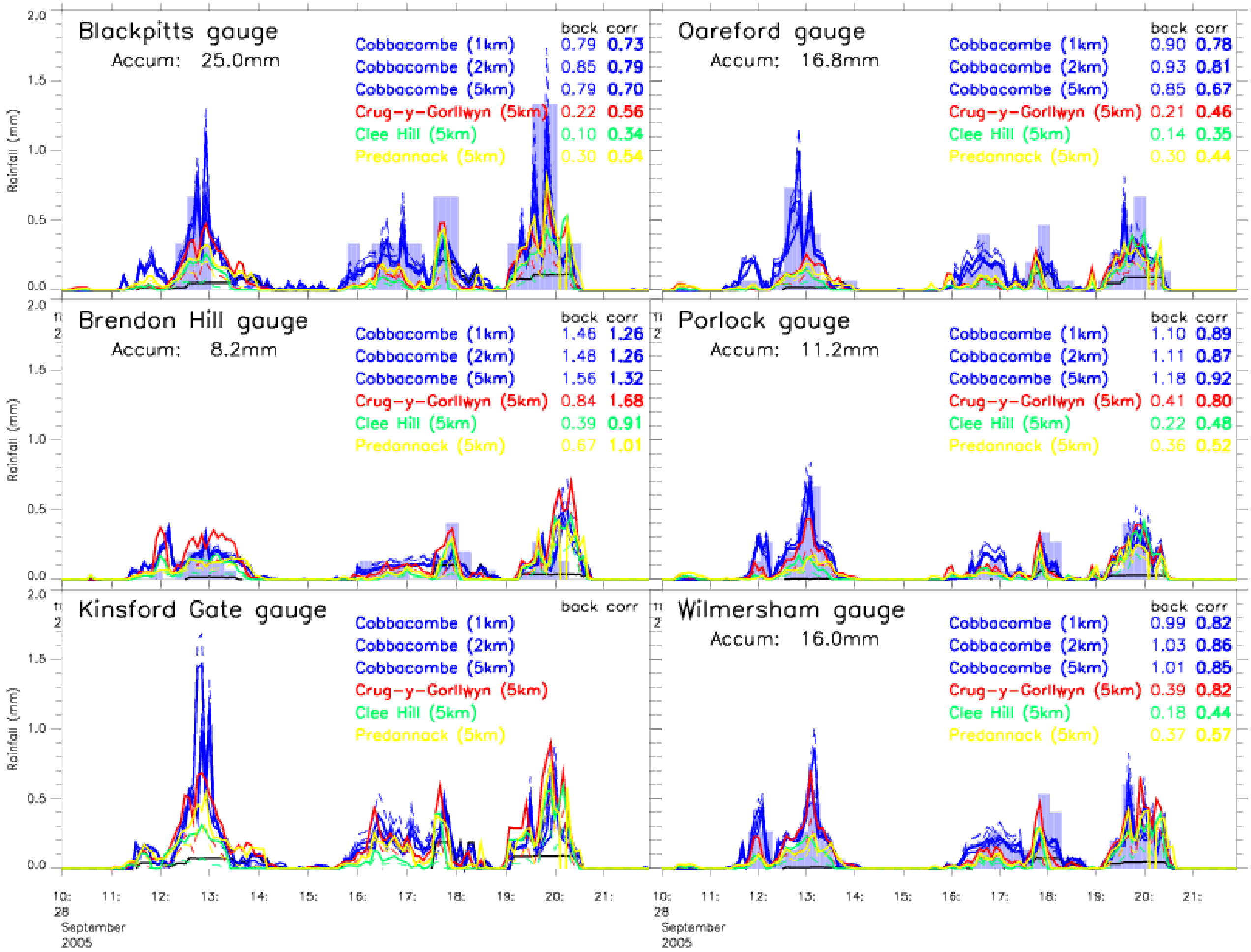


Figure 7.11: Time series of 5 minute rain gauge measurements (bars) and background (- - - -) and corrected (—) radar data for the closest pixel to each gauge site on 28 September 2005. The total rainfall accumulation measured by each gauge during the event is listed along with ratios of radar to gauge accumulations.

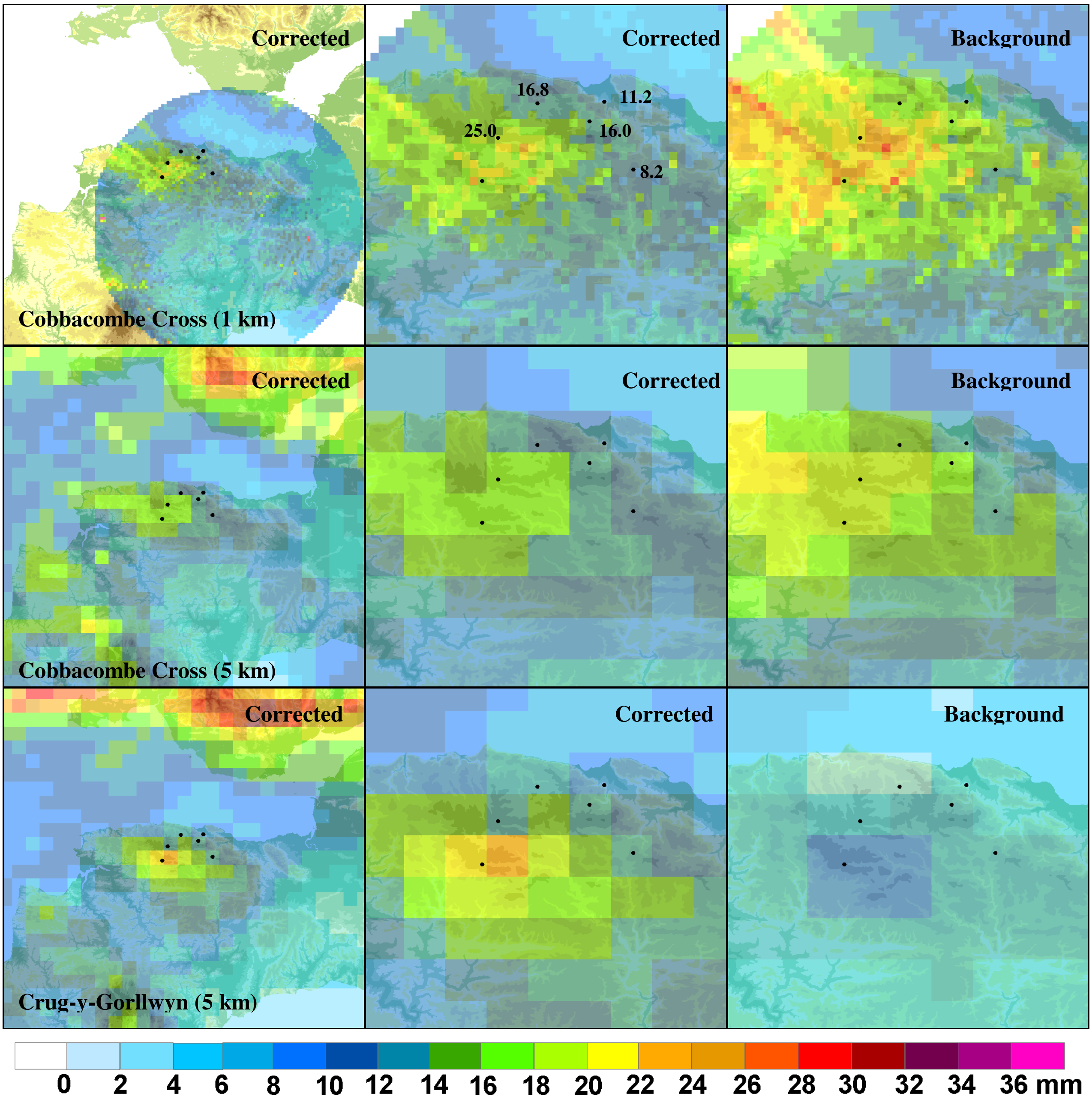


Figure 7.12: Comparison of 12 hour rainfall accumulations from a selection of available radars across the Upper Exe region between 0800 UTC and 2000 UTC on 28 September 2005. Black circles indicate rain gauge locations with labels showing the corresponding available rain gauge accumulation over the same period in mm.

The ratios of total radar to gauge rainfall accumulations during the event listed for each radar-gauge pair in Figure 7.11 summarise radar performance during the event. These show that:

- Radars generally underestimate measured surface rainfall by up to 50%
- Cobbacombe and Crug-y-Gorllwyn radars overestimate measured rainfall at Brendon Hill.
- Orographic corrections improve the accuracy of radar measurements, typically reducing the difference between background radar and gauge accumulations by 30%.
- Best agreement between radar and gauge measurements at each site is achieved using Cobbacombe Cross data, worst quantitative agreement occurs with Clee Hill data.
- Accuracy of 1 and 2 km data from Cobbacombe Cross is better than 5 km data for all but the Porlock gauge. Best agreement occurs between gauge and 2 km resolution radar data.

These results are further illustrated by the correlation plots between gauge and radar measurements during this period shown in Figure 7.13.

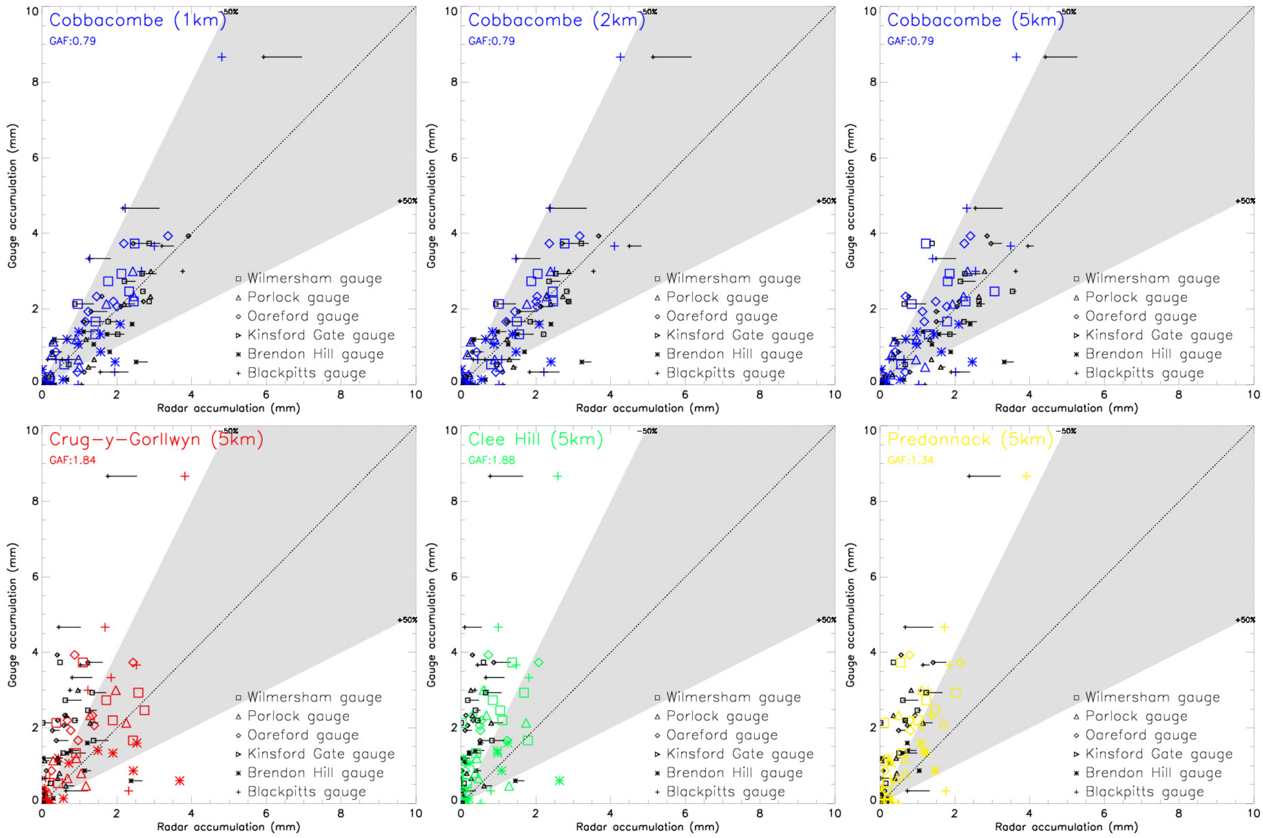


Figure 7.13: Correlation between hourly gauge measurements in the Upper Exe study area and background (small points) and corrected (large points) radar data from available radar across the region during 28 September 2005.

The relatively poor performance by the Clee Hill radar across the Upper Exe region is perhaps a result of attenuation of the radar beam by rainfall across Wales during this period or due to the radar beam overshooting the rain band at long range. This is illustrated by the radar images shown in Figures 7.7 and 7.8. At 1400 UTC the image from Crug-y-Gorllwyn shows a region of rainfall at a rate of up to 2 mmh^{-1} across the Upper Exe study area while that from Clee Hill suggests that the warm front has already cleared leaving dry conditions across the region. At 1630 UTC the image from Crug-y-Gorllwyn shows an extensive region of rainfall extending across much of Devon and Cornwall while rainfall in the Clee Hill image is limited to only Exmoor. These images are indicative of background rainfall estimates from Clee Hill being affected by attenuation of the radar beam as it passes through the considerable region of rainfall across Wales. The time series in Figure 7.11 show much closer agreement between rainfall estimates from each radar from about 1900 UTC as the cold front passed when the spatial extent of the rainfall was more limited. This is illustrated by the radar images in Figure 7.14. Note that data from Clee Hill would only be used in the operational composite radar product across this region if both Cobbacombe and Crug-y-Gorllwyn radars were unavailable

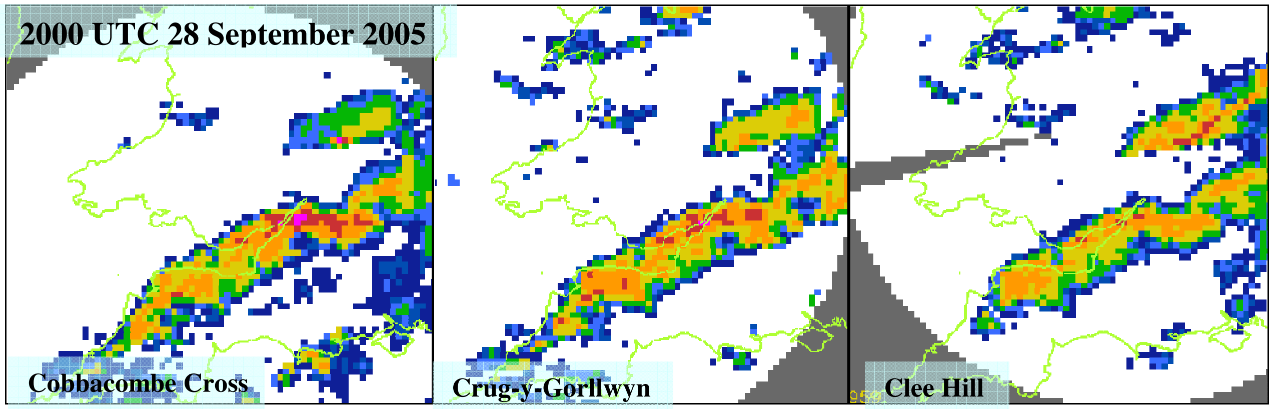


Figure 7.14: Comparison of 5 km radar data from Cobbacombe Cross, Crug-y-Gorllwyn and Clee Hill showing rainfall associated with the cold front across the Upper Exe region.

Figure 7.11 shows particularly poor agreement between the available radar data and gauge measurements at Brendon Hill. Significantly, the Cobbacombe Cross and Crug-y-Gorllwyn data, which show best agreement with gauge data at all other sites, tend to overestimate the measured rainfall. This is perhaps because the site is located in a rain shadow region towards the lee of Exmoor. Were this to be the case, it might be anticipated that such a feature would be better represented by higher resolution radar data. While the time series in Figure 7.11 show a small improvement between 2 km and 5 km data at this site, the results are generally inconclusive.

The overall agreement between gauge data and Cobbacombe Cross radar data shown in Figures 7.11 and 7.13 is improved for radar data at 2 km horizontal resolution compared with the 5 km resolution data at all gauge sites across the Upper Exe region. It is interesting to note that statistically better agreement occurs with 2 km data than with 1 km data. This is thought to be because while both the 1 and 2 km data capture much more spatial variation of rainfall than 5 km data, the 2 km data are less sensitive to the detailed rainfall distribution at each gauge site, masking sources of error between gauge and radar measurements such as wind drift. The benefit of using 1 km resolution data can be highlighted by considering estimates of the rainfall maximum measured at Blackpitts during the passage of the cold front. This was only captured by the rainfall estimates based on 1 km resolution data from Cobbacombe Cross. Sample images at this time are shown in Figure 7.15. Tables 7.1 and 7.2 list the corresponding 5 min and hourly rainfall accumulations.

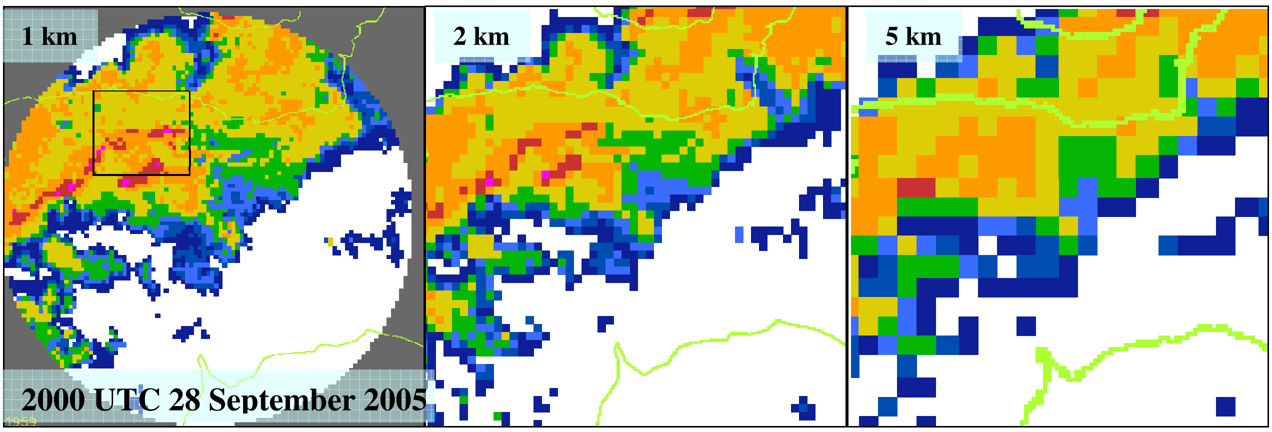


Figure 7.15: Comparison of radar data from Cobbacombe Cross at 1 km, 2 km and 5 km horizontal resolution showing rainfall associated with the cold front across the Upper Exe region.

Gauge		Radar	Background	Back + Orog.	Corrected
Blackpitts	1.3 mm	Cobbacombe (1 km)	1.73 mm	1.84 mm	1.27 mm
		Cobbacombe (2 km)	1.25 mm	1.37 mm	0.94 mm
		Cobbacombe (5 km)	0.67 mm	0.77 mm	0.53 mm
		Crug-y-Gorllwyn (5km)	0.40 mm	0.51 mm	0.70 mm
		Clee Hill (5 km)	0.17 mm	0.28 mm	0.44 mm
		Predannack (5 km)	0.55 mm	0.65 mm	0.80 mm

Table 7.1: Comparison between background and corrected radar hourly rainfall accumulations between 1950 and 1955 UTC on 28 September 2005 and gauge measured accumulation at Blackpitts, Upper Exe.

Gauge		Radar	Background	Back + Orog.	Corrected
Blackpitts	8.7 mm	Cobbacombe (1 km)	5.92 mm	6.95 mm	4.80 mm
		Cobbacombe (2 km)	5.13 mm	6.17 mm	4.26 mm
		Cobbacombe (5 km)	4.42 mm	5.27 mm	3.64 mm
		Crug-y-Gorllwyn (5km)	1.75 mm	2.54 mm	3.82 mm
		Clee Hill (5 km)	0.77 mm	1.65 mm	2.58 mm
		Predannack (5 km)	2.38 mm	3.22 mm	3.91 mm

Table 7.2: Comparison between background and corrected radar hourly rainfall accumulations between 1900 and 2000 UTC on 28 September 2005 and gauge measured hourly accumulation at Blackpitts, Upper Exe.

11 October 2005

October 2005 was a notably wet month across the UK. For example, 152% of the average monthly rainfall across Wales and 142% of the average rainfall across southern England were measured (Figure 3.1). These statistics are particularly remarkable given that the first ten days of October were very dry. The first significant rainfall of October 2005 arrived on 11 October and resulted in widespread flooding and disruption. For example, a total of 113.8 mm rain fell in Milford Haven during 24 hours, more than the average monthly value, while several roads and railway lines were closed in Cumbria and the Scottish Borders as a result of flooding.

8.1 Synoptic background

Figure 8.1 illustrates that this flooding resulted from a period of prolonged rainfall associated with a stationary front which extended across the UK for about 42 hours between 1800 UTC on 10 October and 1200 UTC on 13 October 2005. Rainfall over Scotland on 10 October was accompanied by very strong winds with a gust of 53 knots recorded at Sella Ness. Heavy rain spread slowly from the west during the night of 10-11 October 2005 bringing heavy bursts across Wales during the afternoon and evening. The frontal rainfall weakened during the morning of 12 October 2005 when occasionally heavy rain drifted north from France across much of southern England, Wales and the West Midlands.

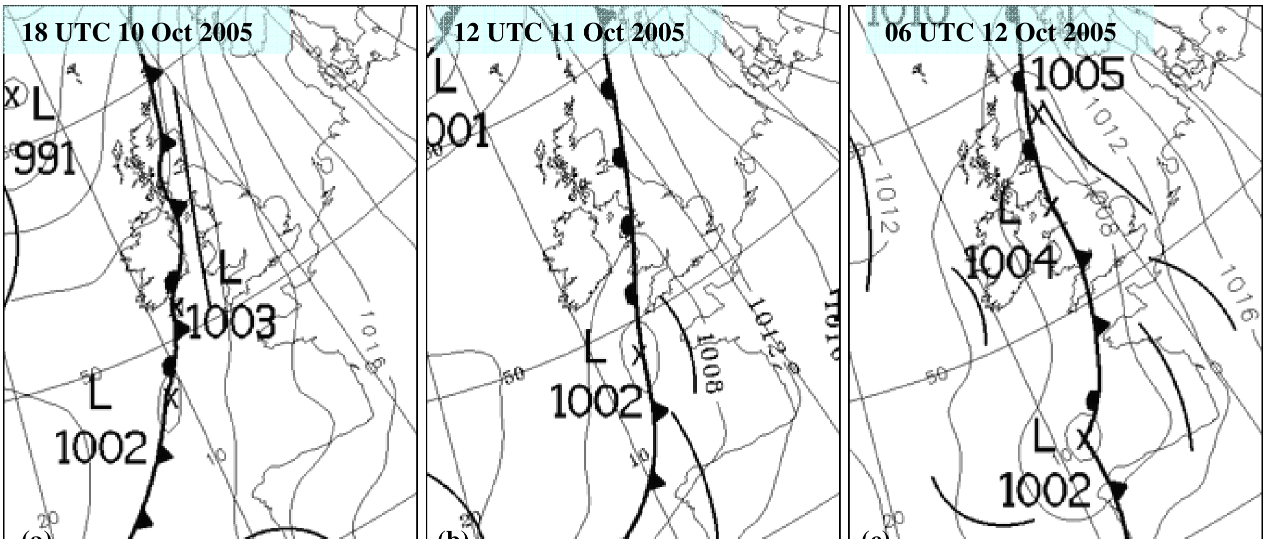


Figure 8.1: Surface pressure analysis chart for 1800 UTC on 10 October, 1200 UTC on 11 October and 0600 UTC on 12 October 2005 during a period of persistent rainfall across the UK.

Rain gauges in each of the three upland study areas measured significant daily accumulations on 11 October 2005. The highest daily accumulations measured at Capel Curig and Padog gauges in the Upper Conwy region during the entire study of 69.4 mm and 51.6 mm respectively occurred on this day while 87.4 mm was measured at Cwm Dyli. The highest hourly rainfall accumulations measured by the Betws-y-Coed and Ysbyty Ifan gauges in the Upper Conwy region of 7.6 mm and 9.2 mm also occurred on this day while an hourly accumulation of 15.6 mm fell between 1800 and 1900 UTC at Cwm Dyli. In the Upper Exe study area, the highest hourly accumulation measured by the Oareford gauge of 11.8 mm occurred between 1700 and 1800 UTC on this day, contributing over a third of the total daily accumulation measured at this site. The highest hourly accumulation measured at the Storey Arms gauge in the Upper Taff study area of 14.7 mm was also recorded between 1800 UTC and 1900 UTC on this day. A total of 74.0 mm fell at this site during the entire day while rainfall accumulations at other upland sites in the region all exceeded 30 mm.

8.2 Orographic correction

The mesoscale model output at the 800 m level which was used to determine the orographic correction field to be applied to radar data is shown in Figure 8.2. Relative humidities were in excess of 90% across each of the three study areas and winds were typically west-south-westerly with speeds in the range 12–14 ms^{-1}. This wind speed corresponds to the first non-zero correction wind speed category of the operational orographic enhancement correction scheme. The relatively slow moving nature of the front means that only a moderate correction of up to 2 mmh^{-1} was applied to the background radar data during this event.

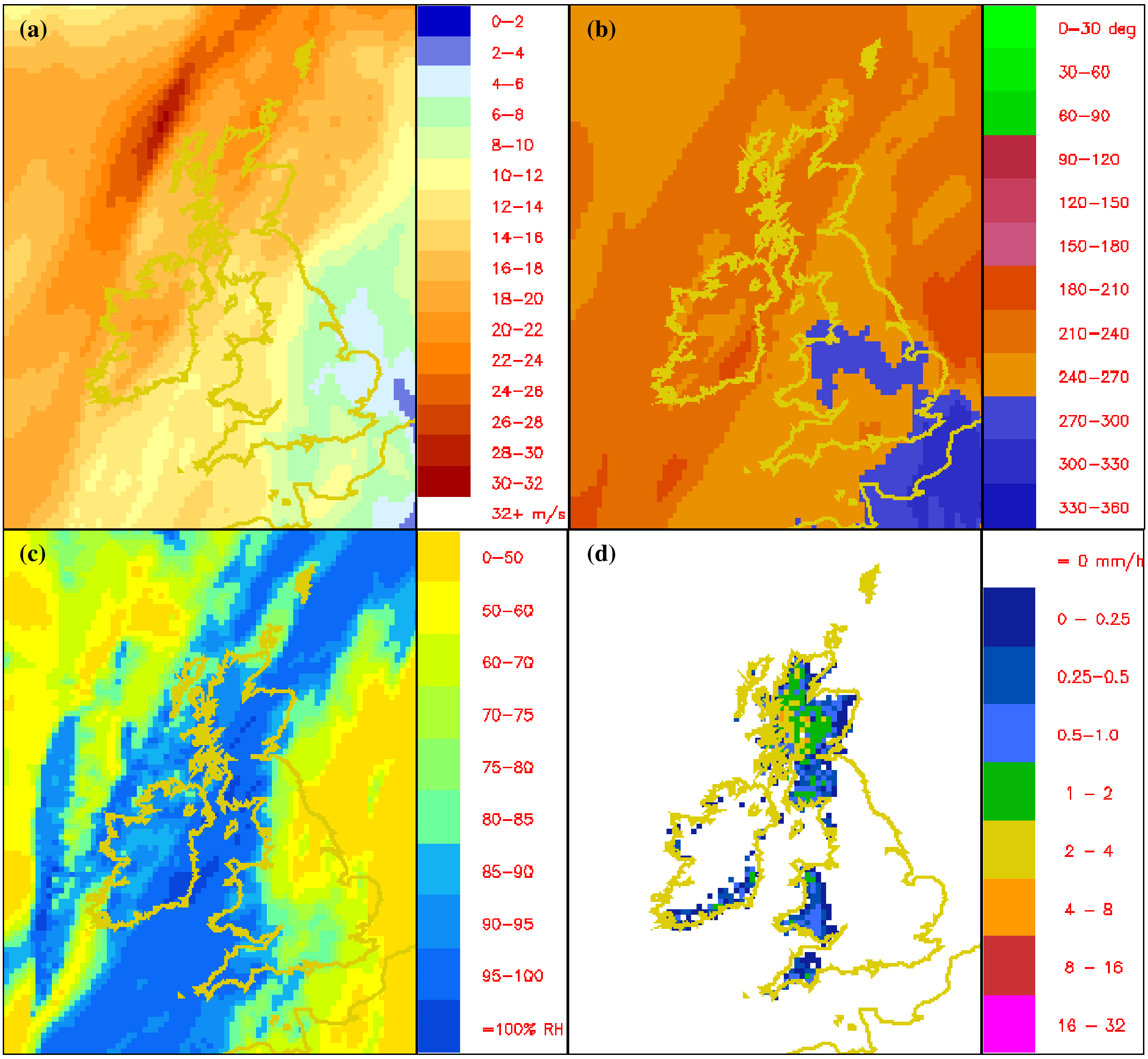


Figure 8.2: Met Office mesoscale model output for 0000 UTC on 11 October 2005 showing (a) wind speed, (b) wind direction and (c) relative humidity at the 800m level used to derive the orographic correction factors shown in (d).

8.3 Comparison between radar and gauge accumulations: Upper Conwy

Figure 8.3 shows the hourly rainfall time series between 0000 UTC on 10 October 2005 and 0000 UTC on 13 October 2005 at each gauge in the Upper Conwy study area. Also plotted are the background and corrected hourly rainfall accumulations derived from radar measurements at the closest pixel to each rain gauge. The gauge measurements at each site in the region are qualitatively similar, showing intermittently intense rainfall during the morning of 11 October and prolonged heavy rain during the afternoon, peaking between 1800 and 1900 UTC at most sites.

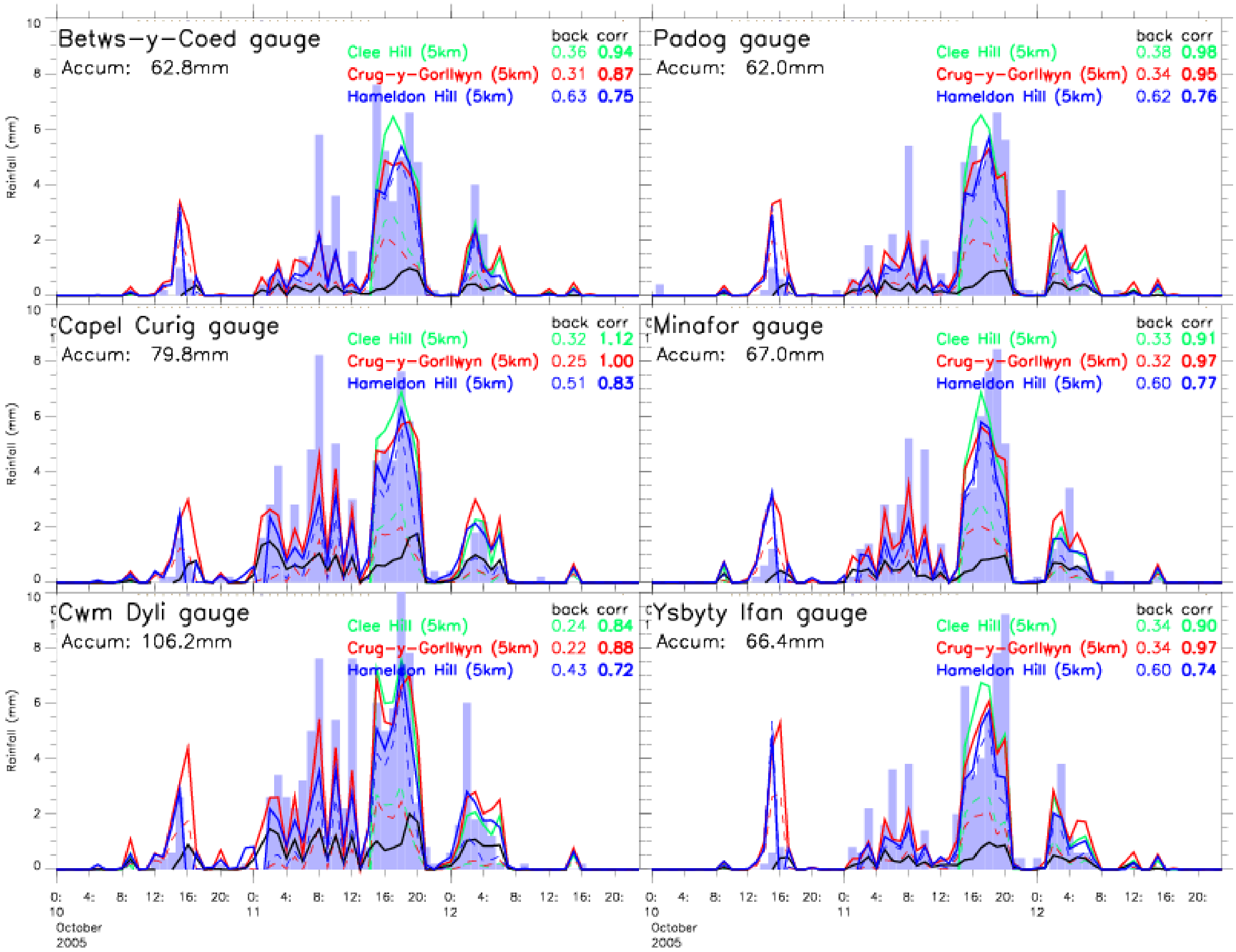


Figure 8.3: Time series of hourly rain gauge measurements (bars) and background (- - - -) and corrected (——) radar measurements for the closest pixel to each gauge site between 0000 UTC on 10 October and 0000 UTC on 13 October 2005. Note that Clee Hill radar was not working before 1400 UTC on 11 Oct. The total rainfall measured by each gauge during the event is listed along with the ratio of total radar to gauge accumulations for each radar (corrected values in bold). The orographic correction applied to the radar data is plotted in black.

A summary of the accuracy of the radar measurements during this event is provided by comparing the total rainfall accumulations for surface gauges with that for each radar when both gauge and radar measurements were available. The ratios of radar to gauge accumulations are listed in Figure 8.3. All ratios for this period show that

- Radars underestimate the measured surface rainfall by up to 25%.
- Orographic corrections improve the accuracy of radar measurements, typically halving the difference between background radar and gauge accumulations.
- Best agreement between radar and gauge measurements at each site is achieved using Crug-y-Gorllwyn data, worst quantitative agreement occurs with Hameldon Hill data.

Analysis of the time series in Figure 8.3 shows considerable variation in the level of agreement between radar and gauge measurements during the event. For example, the radars measured heavy rainfall during the afternoon of 10 October 2005 with values more than twice as large as those measured by the surface gauges. The addition of orographic enhancement to the background data was clearly detrimental to data quality at this time. In contrast, the radars underestimated the occasionally intensive rainfall measured during the morning of 11 October 2005 although there is good temporal correlation between the gauge and radar time series during this period. This is highlighted by the correlation plots between radar and gauge measurements during 11 October 2005 shown in Figure 8.4. All points measured during the morning (shown with dashed lines) consistently lie on a line corresponding to radar values being about 30% smaller than gauge measurements over the entire rainfall range. The degree of agreement clearly improves with the application of orographic corrections but the applied enhancement of up to 2 mm was insufficient to provide significantly better radar rainfall estimates. Figures 8.3 and 8.4 both indicate that the radars captured the high level spatial variability observed between gauge sites during the morning well, with no significant difference between the correlation of radar and gauge measurements between sites. Figure 8.3 shows radar measurements over Cwm Dyli to be typically three times greater than those over Ysbyty Ifan for example, which is reflected in the corresponding gauge rainfall values.

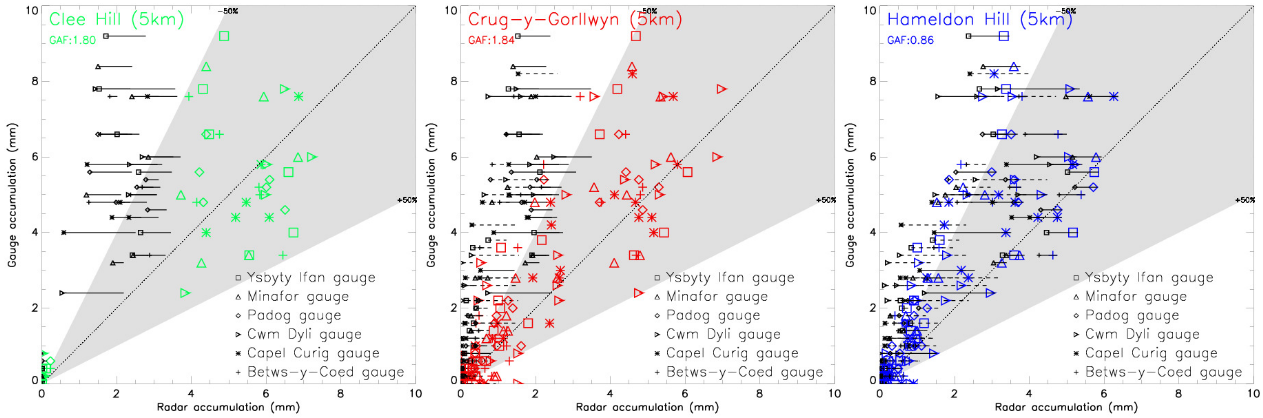


Figure 8.4: Correlation between hourly gauge measurements in the Upper Conwy study area and background (small points) and corrected (large points) radar data from (a) Clee Hill, (b) Crug-y-Gorllwyn and (c) Hameldon Hill during 11 October 2005. Horizontal lines show the magnitude of the orographic correction applied to the background data in each case.

Figure 8.3 shows that the corrected radar rainfall values are generally in good agreement with hourly gauge accumulations during the remainder of the event when the rainfall remained heavy for several hours. A more detailed time series plot showing 5 min rainfall accumulations during this period is shown in Figure 8.5. This highlights how the temporal structure of the rain measured at the surface was not captured particularly well by any of the available radars, each of which show reasonably constant rainfall values throughout. Figure 8.5 also shows the benefit of applying an increased orographic enhancement correction at Capel Curig and Cwm Dyli between 1830 and 2100 UTC when the background radar rainfall estimates began to decrease while the corrected radar and gauge measurements suggest that the high rainfall values persisted. The correction scheme was inadequate for identifying the locally intense rainfall recorded at Cwm Dyli between 1800 and 1830 UTC however. It is likely that this is a result of radar data being available at only 5 km horizontal resolution, over which distance considerable changes in rainfall totals may occur in the Upper Conwy region. Snapshot radar images from each of the three available radars across the study area are shown in Figure 8.6.

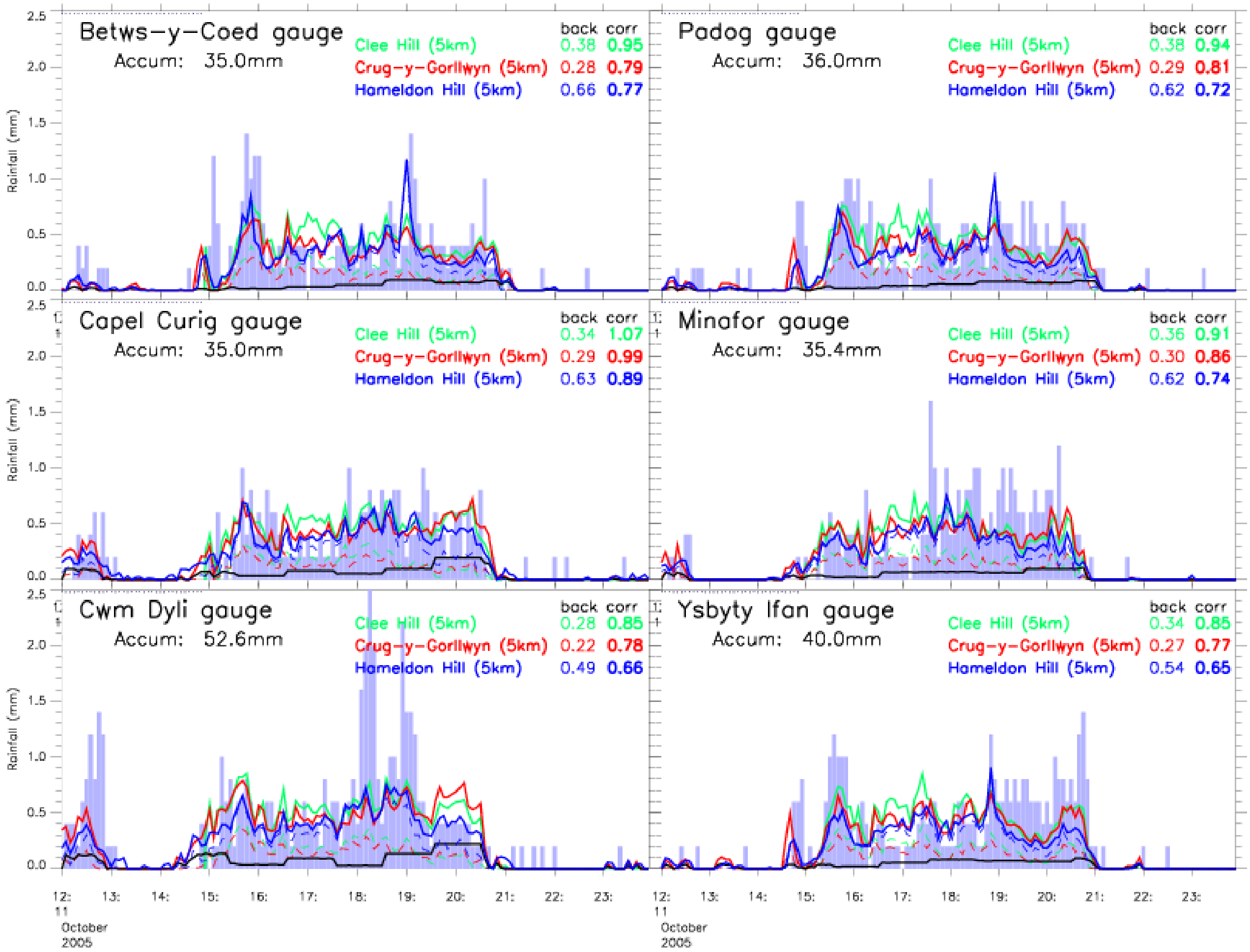


Figure 8.5: Time series of 5 min rainfall accumulation values measured by gauges and radar across the Upper Conwy study area during the afternoon of 11 October 2005. Other details are as in Figure 8.3.

The improved correlation between radar and gauge values during the afternoon is reflected in Figure 8.4. For hourly rainfall accumulations less than 6 mm the orographic correction of 2 mm is typically sufficient to give close agreement between gauge and radar values. In contrast to the results of Figure 8.3, best agreement at this time occurred with radar measurements at Hameldon Hill while values from Clee Hill tended to overestimate gauge values. Significant rainfall underestimation persisted during the afternoon for rainfall accumulations in excess of 6 mm however. The level of underestimation is similar to that found during the morning.

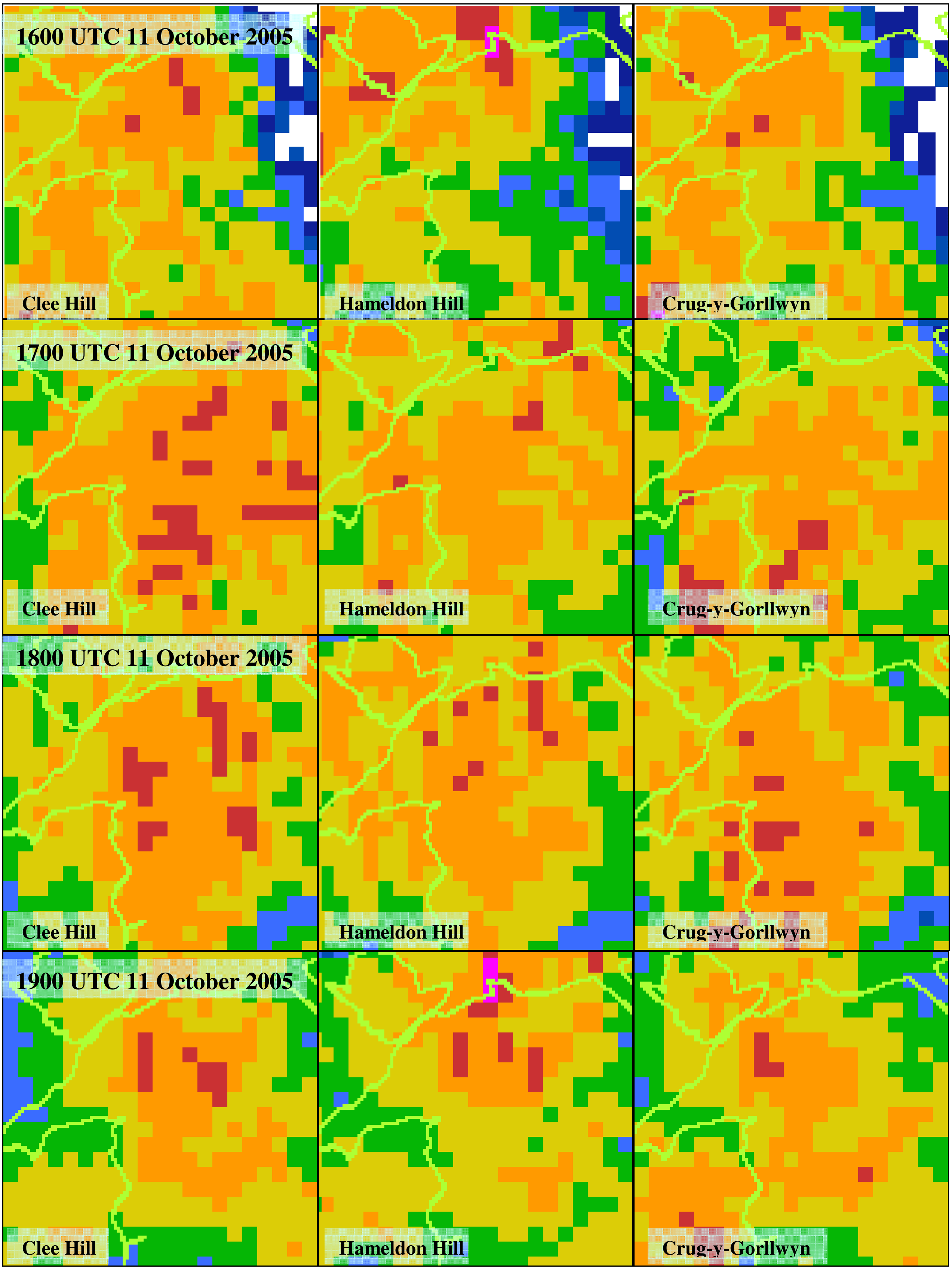


Figure 8.6: Comparison of 5 km radar data showing rainfall across the Upper Conwy catchment during the afternoon of 11 October 2005.

8.4 Comparison between radar and gauge accumulations: Upper Taff

Figure 8.7 shows time series comparing radar and gauge rainfall measurements across the Upper Taff study area during 11 October 2005. The correlation between radar and gauge hourly accumulations measured during this period are plotted in Figure 8.8.

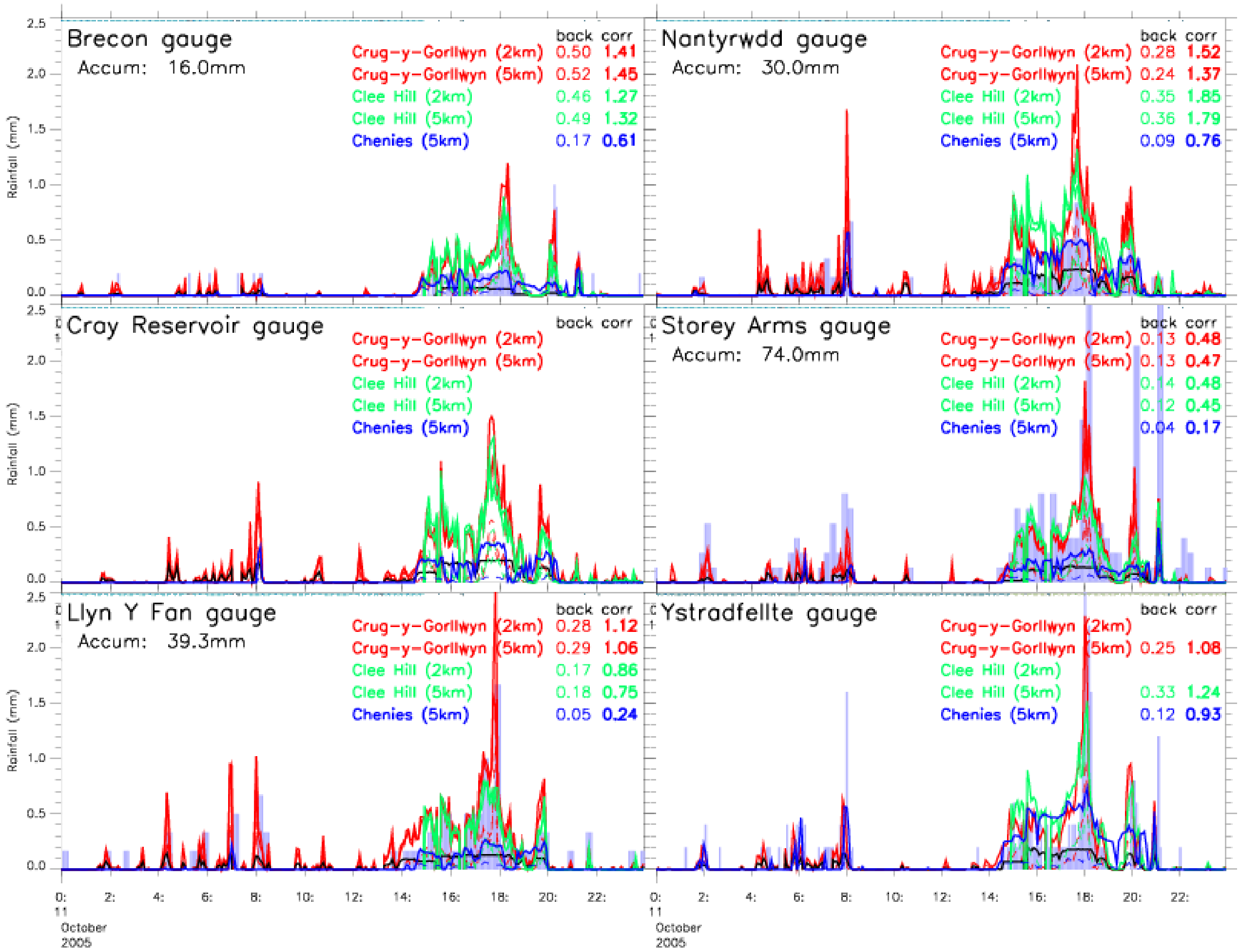


Figure 8.7: Time series of hourly rain gauge measurements (bars) and background (- - - -) and corrected (——) radar measurements for the closest pixel to each gauge site during 11 October 2005. The total rainfall measured by each gauge during the event is listed along with the ratio of total radar to gauge accumulations for each radar (corrected values in bold). The orographic correction applied to the radar data is plotted in black.

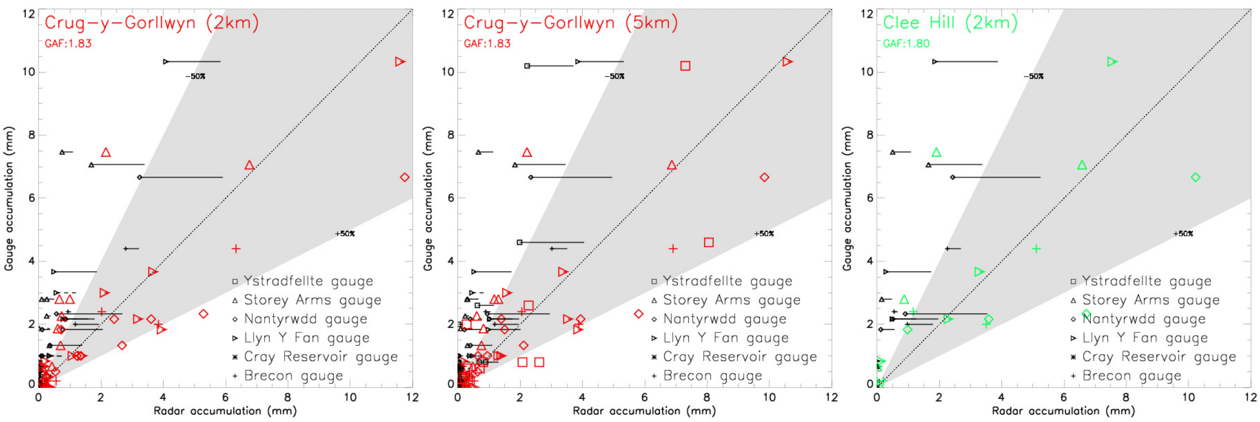


Figure 8.8: Correlation between hourly gauge measurements in the Upper Taff study area and background (small points) and corrected (large points) radar data during 11 October 2005. Horizontal lines show the magnitude of the orographic correction applied to the background data in each case.

Only corrected radar data for the Llyn Y Fan site displays reasonable agreement with the measured surface rainfall during 11 October 2005. Figure 8.7 shows that the Crug-y-Gorllwyn and Clee Hill radars consistently overestimated rainfall by between 30 and 40% at Brecon and by up to 85% at Nantyrwdd. In contrast, rainfall values at the Storey Arms gauge were underestimated by up to 50%. This leads to the generally poor level of agreement illustrated in Figure 8.8. Much of the rainfall underestimation identified for radar data at Storey Arms results from the radars missing the intensive bursts of rain at 1800 UTC, 2000 UTC and 2100 UTC. The hourly rainfall accumulations estimated by each available radar above Storey Arms between 1800 UTC and 1900 UTC are listed in Table 8.1. Sample radar images during this period are shown in Figure 8.9. Table 8.1 shows best agreement with the 2 km resolution Crug-y-Gorllwyn data, as might be anticipated, but the corrected radar derived accumulation is a factor of 1.6 smaller than the corresponding gauge value. It appears that an orographic correction of only 1 mmh^{-1} was insufficient to capture the enhancement observed at the surface. Interestingly, Figures 8.7 and 8.9 shows that stronger rainfall was measured by the Crug-y-Gorllwyn radar at 2 km resolution, but that the region of strongest rainfall at 1800 UTC was further west nearer the Llyn Y Fan gauge site. Comparison of the hourly rainfall accumulation for the Llyn y Fan gauge show both gauge and radar giving the same value of 3.67 mm (Figure 8.8).

Gauge		Radar	Background	Back + Orog.	Corrected
Storey Arms	14.7 mm	Crug-y-Gorllwyn (2km)	3.32 mm	4.49 mm	8.84 mm
		Crug-y-Gorllwyn (5km)	2.90 mm	4.11 mm	8.10 mm
		Clee Hill (2 km)	2.23 mm	3.31 mm	6.29 mm
		Clee Hill (5 km)	1.67 mm	2.88 mm	5.46 mm
		Chenies (5 km)	0.49 mm	1.08 mm	2.15 mm

Table 8.1: Comparison between background and corrected radar hourly rainfall accumulations between 1800 and 1900 UTC on 11 October 2005 and gauge measured hourly accumulation at Storey Arms, Upper Taff.

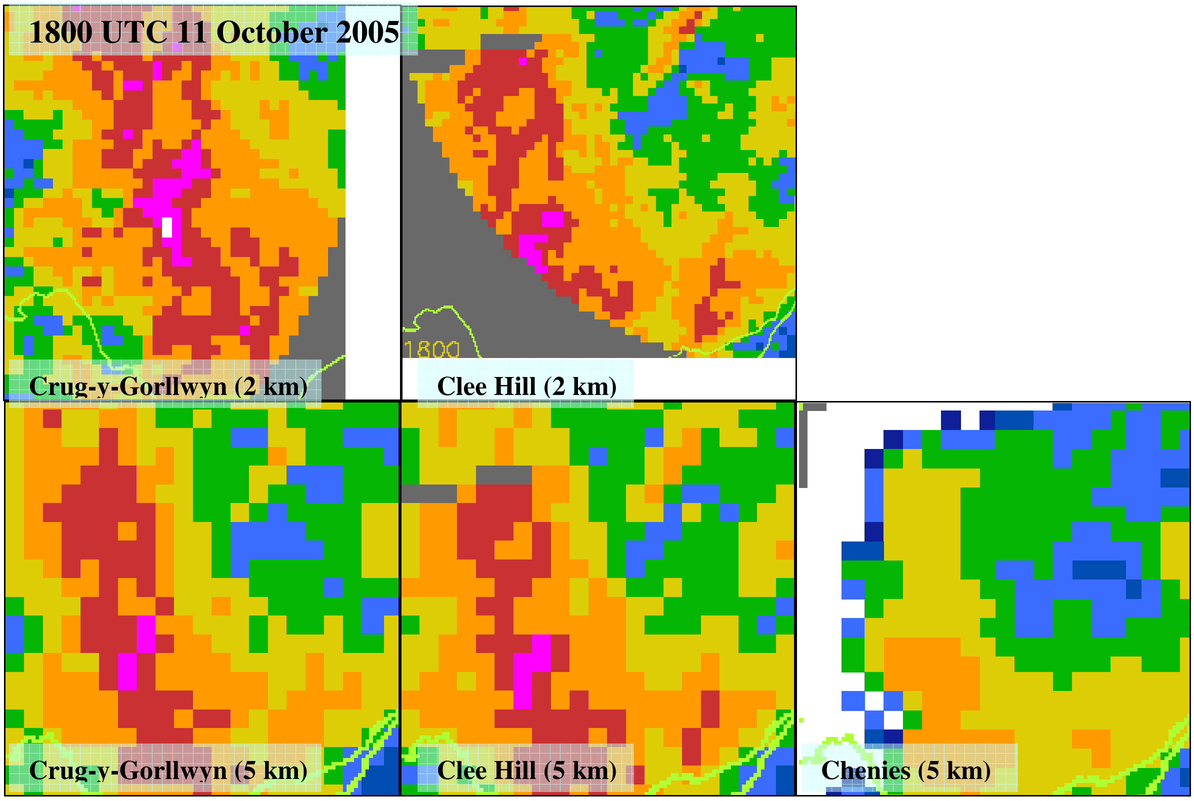


Figure 8.9: Comparison of radar data across the Upper Taff area at 1800 UTC on 11 October 2005.

8.5 Comparison between radar and gauge accumulations: Upper Exe

Figure 8.10 shows time series of radar and gauge measurements of the rainfall across the Upper Exe region during the afternoon of 11 October 2005. The gauge measurements clearly illustrate a strong orographic enhancement with accumulations at Oareford (343 m AOD) and Blackpitts (430 m AOD) gauges well over twice as high as those at Porlock (125 m AOD). Note that the Cobbacombe Cross data were not available at this time, such that radar data at longer range from Crug-y-Gorllwyn were likely to have been included in the UK national composite product during this period. Correlation plots of hourly accumulations measured by radars and gauges are shown in Figure 8.11.

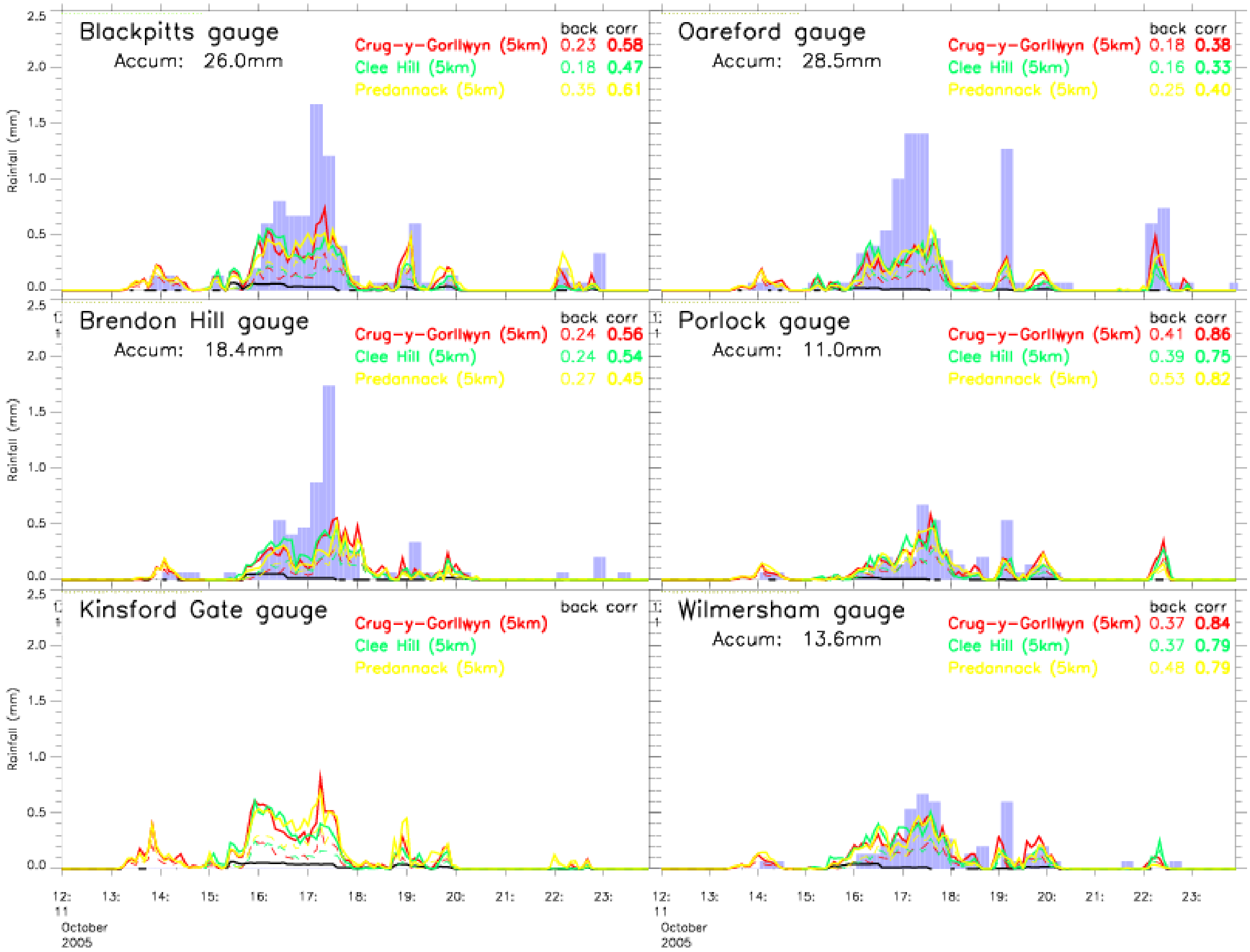


Figure 8.7: Time series of hourly rain gauge measurements (bars) and background (- - - -) and corrected (——) radar measurements for the closest pixel to each gauge site during 11 October 2005. The total rainfall measured by each gauge during the event is listed along with the ratio of total radar to gauge accumulations for each radar (corrected values in bold). The orographic correction applied to the radar data is plotted in black.

The bias values listed in Figure 8.7 summarise that all available radars underestimated the surface rainfall by between 14% (Crug-y-Gorllwyn radar, Porlock gauge) and 67% (Predannack radar, Oareford gauge). Figure 8.8 shows that the rainfall underestimation was a systematic feature over the entire rainfall accumulation range observed.

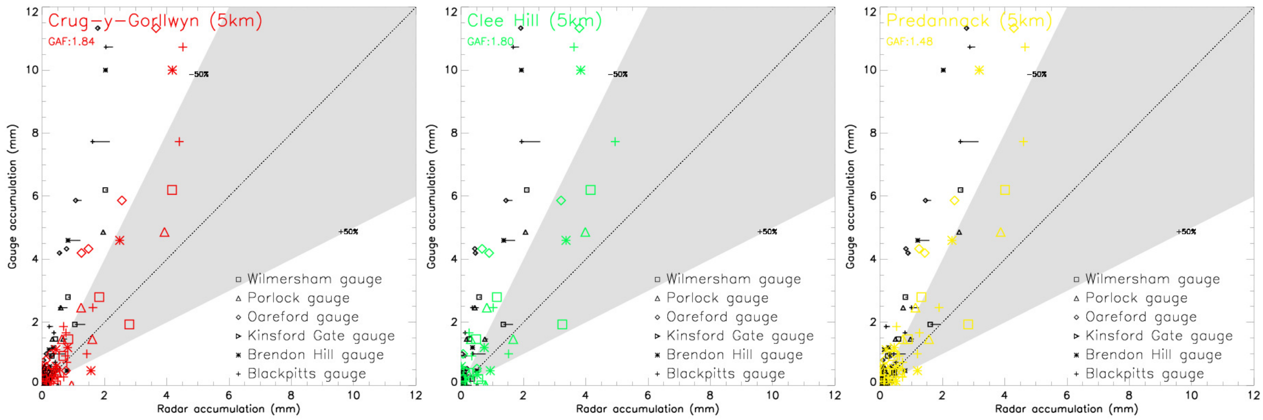


Figure 8.8: Correlation between hourly gauge measurements in the Upper Exe study area and background (small points) and corrected (large points) radar data during 11 October 2005. Horizontal lines show the magnitude of the orographic correction applied to the background data in each case.

It is evident from Figure 8.7 that best agreement between the radars and gauges occurred for low-lying gauge sites where only moderate rainfall was observed while considerable underestimation took place for upland gauges where the orographic enhancement was not correctly captured. While the orographic corrections applied clearly have a beneficial impact on data quality, the magnitude of the correction was insufficient to give better agreement between the radars and gauges. Figure 8.2 illustrates how only small corrections were derived from the model data across the Upper Exe region as a result of relative humidity values close to 85% and moderate wind strength. It is currently unclear as to why stronger enhancement was observed in reality.

Figure 8.9 shows rainfall measurements in the Upper Exe region during the afternoon of 21 October 2005 when even poorer radar data quality was observed. Although this was not a significant rainfall event in terms of the total rainfall accumulation, this provides an example of the limits to the success of any orographic correction scheme. As on 11 October 2005, the radar data at close range from Cobbacombe Cross were unavailable such that the closest available radar to the Upper Exe region was Crug-y-Gorllwyn at a range of about 100 km. Figure 8.9 shows a large variation between the different rain gauge measurements across the region, with almost no rainfall at Brendon Hill to the east of the study area and over 20 mm falling in 6 hours at Blackpitts in the west of the area. This rainfall distribution suggests that considerable orographic forcing occurred. Unfortunately, the rainfall on 21 October 2005 was largely missed by the available radars, with almost no rain measured across the region. This is most likely to be because the rainfall was limited to low-levels, below the height of the lowest available radar beam at about 1500 m. In this case, the orographic correction scheme made very little difference to particularly small background rainfall estimates.

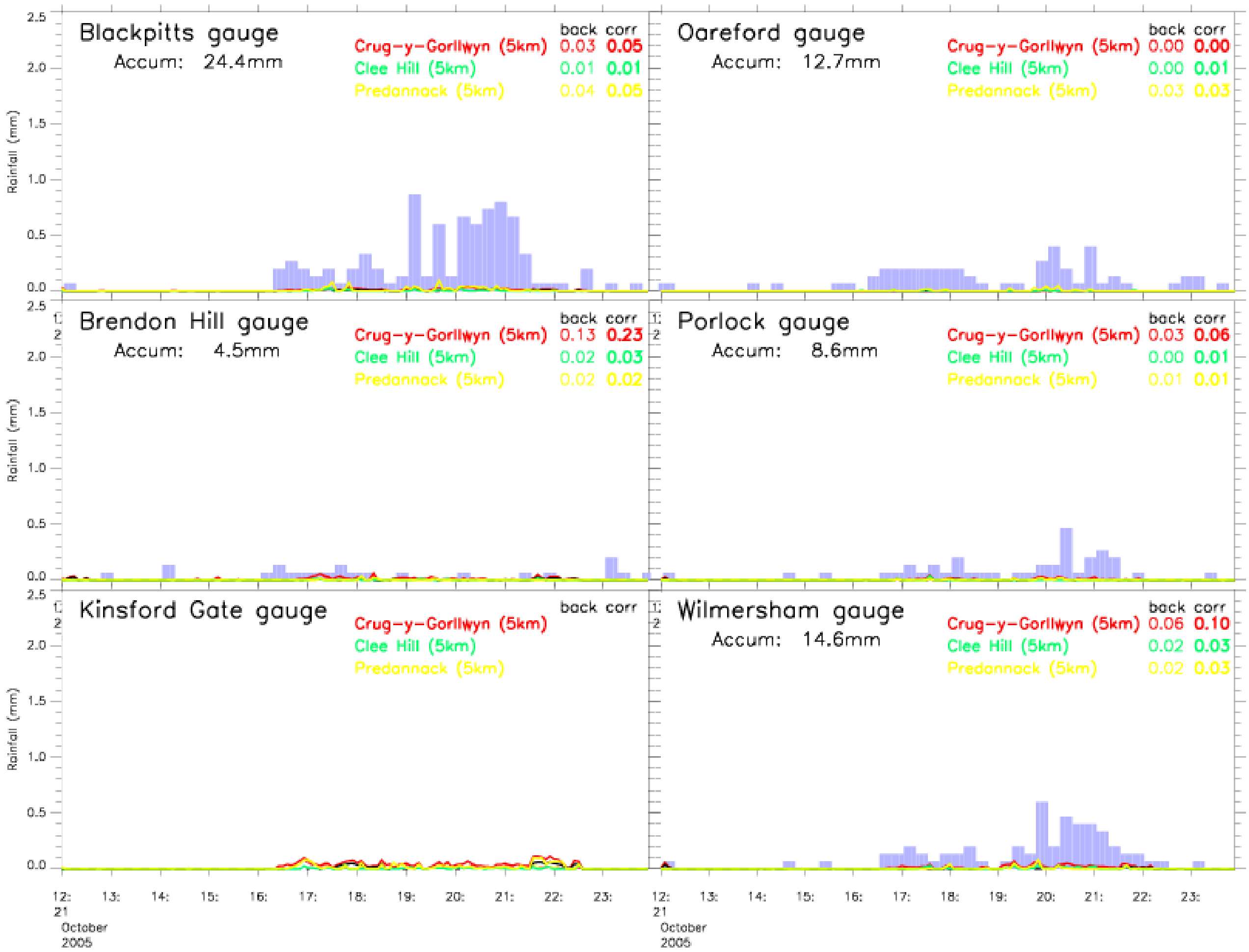


Figure 8.9: Time series of hourly rain gauge measurements (bars) and background (- - - -) and corrected (——) radar measurements for the closest pixel to each gauge site during 21 October 2005. The total rainfall measured by each gauge during the event is listed along with the ratio of total radar to gauge accumulations for each radar (corrected values in bold). The orographic correction applied to the radar data is plotted in black.

24 October 2005

Most of the highest daily rainfall accumulations measured during the entire study period in all three upland regions of interest occurred on 24 October 2005. These values are listed in Table 9.1. The lack of notably intense periods of rainfall during the event reflects how such large totals resulted from steady rainfall persisting for much of the day. Flood watches were issued by the Environment Agency in the Upper Exe and Upper Taff study areas on this day.

Upper Exe		Upper Conwy		Upper Taff	
Gauge	Accum.	Gauge	Accum.	Gauge	Accum.
Oareford	**52.7 mm**	Cwm Dyli	**99.0 mm**	Storey Arms	**145.9 mm**
Blackpitts	**42.9 mm**	Ysbyty Ifan	**71.6 mm**	Ystradfellte	**70.6 mm**
Brendon Hill	**37.9 mm**	Capel Curig	67.4 mm	Nantyrwdd	**64.2 mm**
Kinsford Gate	34.8 mm	Minafor	**65.8 mm**	Llyn-Y-Fan	55.0 mm
Wilmersham	**31.9 mm**	Betws-y-Coed	**57.6 mm**	Brecon	28.0 mm
Porlock	**26.6 mm**	Padog	51.0 mm	Cray Reservoir	-

Table 9.1: Daily rainfall accumulations at each gauge in the three upland study areas during 24 October 2005. Values listed in bold are maxima for that gauge measured during the entire July 2005-June 2006 study period.

9.1 Synoptic background

Figure 9.1 illustrates that the event was characterised by a series of fronts crossing the British Isles from the south-west. The first episode of persistent rainfall associated with an occluded front which was followed closely by a warm front began across south-west England during the evening of 23 October, spreading slowly north-eastwards into Wales and Northern Ireland by 2000 UTC. This heavy rain persisted until about noon on 24 October 2005 and was followed by outbreaks of rain and drizzle associated with the trailing cold front. The heaviest rain was over northern England and Scotland during the morning and over Wales and England in the evening. It was also notably windy, with a gust of 30 ms^{-1} recorded at Capel Curig in the Upper Conwy study area. The blustery showers, locally heavy and thundery in places, persisted across much of the UK during 25 October 2005 accompanied by gales in places over Wales and central and southern England. A gust of 28 ms^{-1} was recorded at Aberdaron on the Lleyn peninsula in north Wales for example.

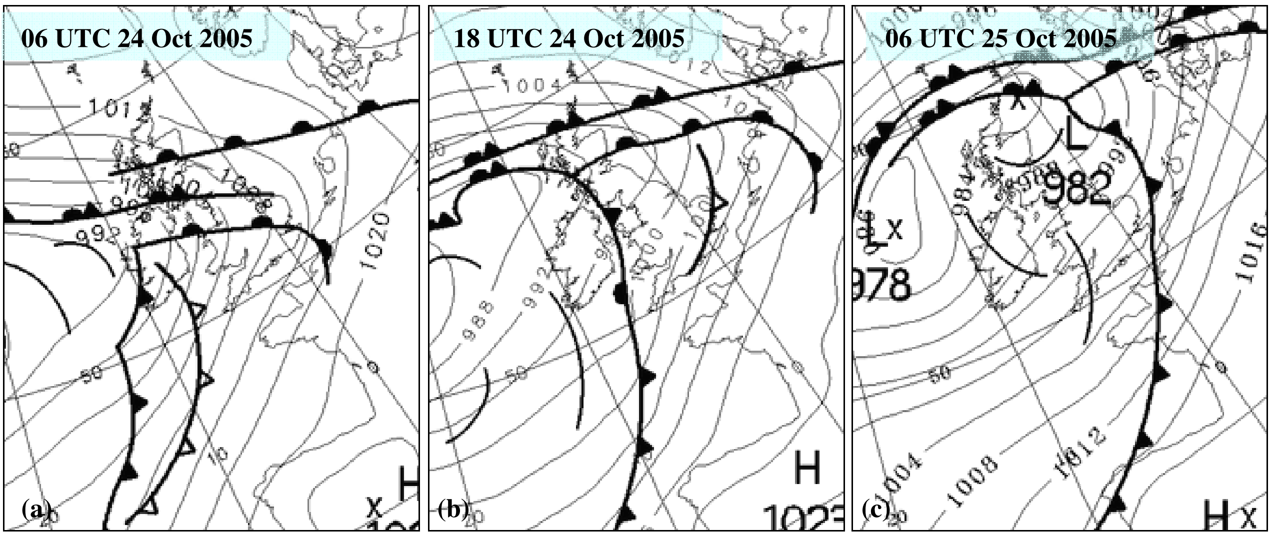


Figure 9.1: Surface pressure analysis chart for 0600 UTC and 1800 UTC on 24 October 2005 and 0600 UTC on 25 October 2005.

9.2 Orographic correction

Figure 9.2 shows samples of the mesoscale model output during the event. Strong wind speeds in excess of 32 ms^{-1} at the 800 m model level during the period across south-west England and Wales implies that large orographic corrections of up to 8 mmh^{-1} were applied to background radar data. The humidity fields plotted in Figure 9.2(b) show a strong spatial and temporal dependence on relative humidity however, periodically dropping below 85% in some areas.

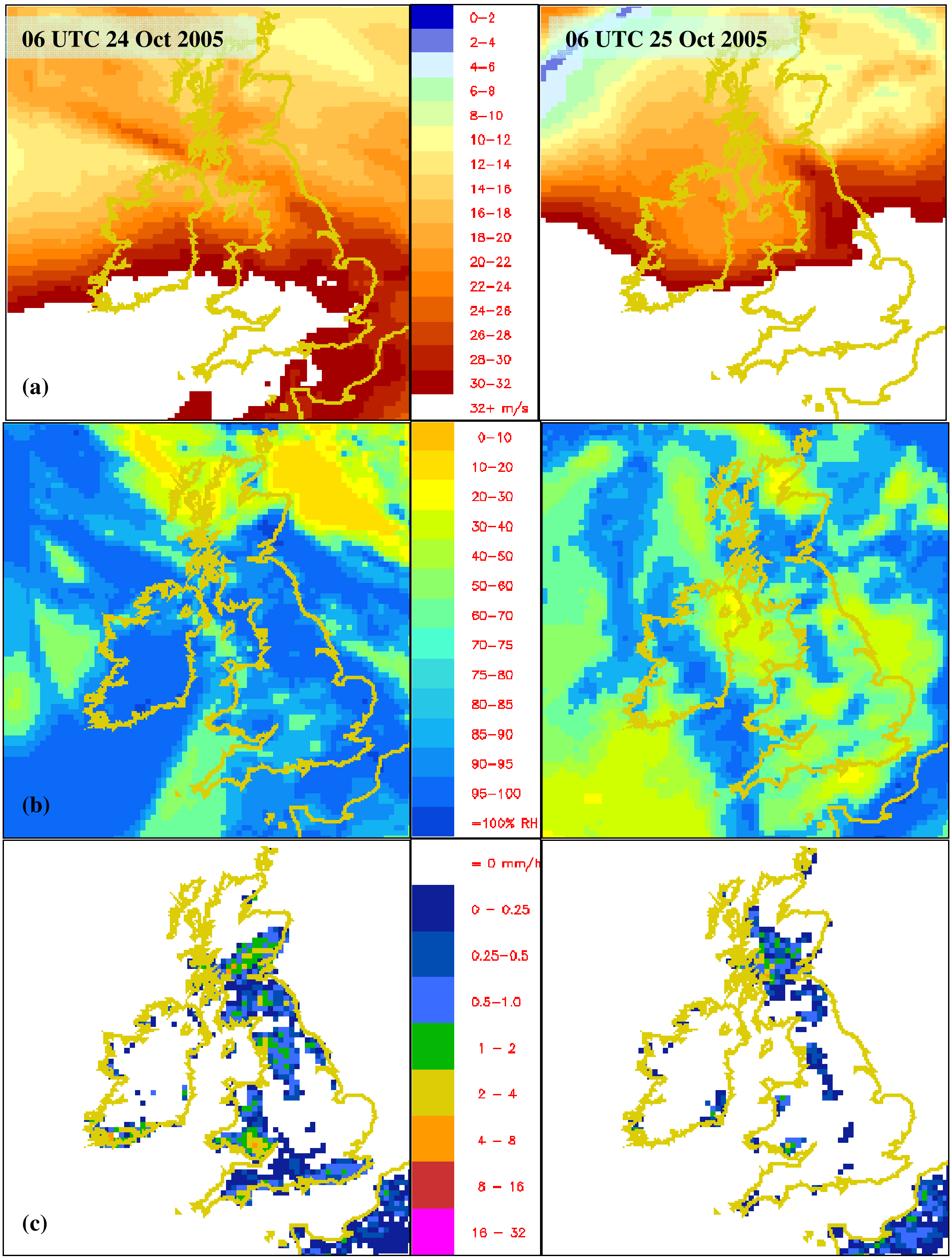


Figure 9.2: Met Office mesoscale model output for 0600 UTC on 24 and 25 August 2005 showing (a) wind speed and (b) relative humidity at the 800m level used to derive the orographic correction factors shown in (c). Winds were south-westerly throughout this period.

9.3 Comparison between radar and gauge accumulations: Upper Conwy

Figure 9.3 shows a time series of hourly rainfall accumulations for each gauge in the Upper Conwy study area and the corresponding background and corrected radar estimates from each available radar covering each site. The rain gauge data show broadly similar rainfall characteristics at all sites, particularly between about 2000 UTC on 23 October 2005 and 1200 UTC on 24 October 2005 when the series of fronts shown in Figure 9.1(a) crossed the region and in excess of 50 mm rainfall was recorded at all but the Padog gauge. A total of 80 mm rain fell at Cwm Dyli during a 12 hour period at this time. The gauge measurements show more variation in the structure and magnitude of measured rainfall during the second half of the event when showers associated with the trailing cold front were observed across the region.

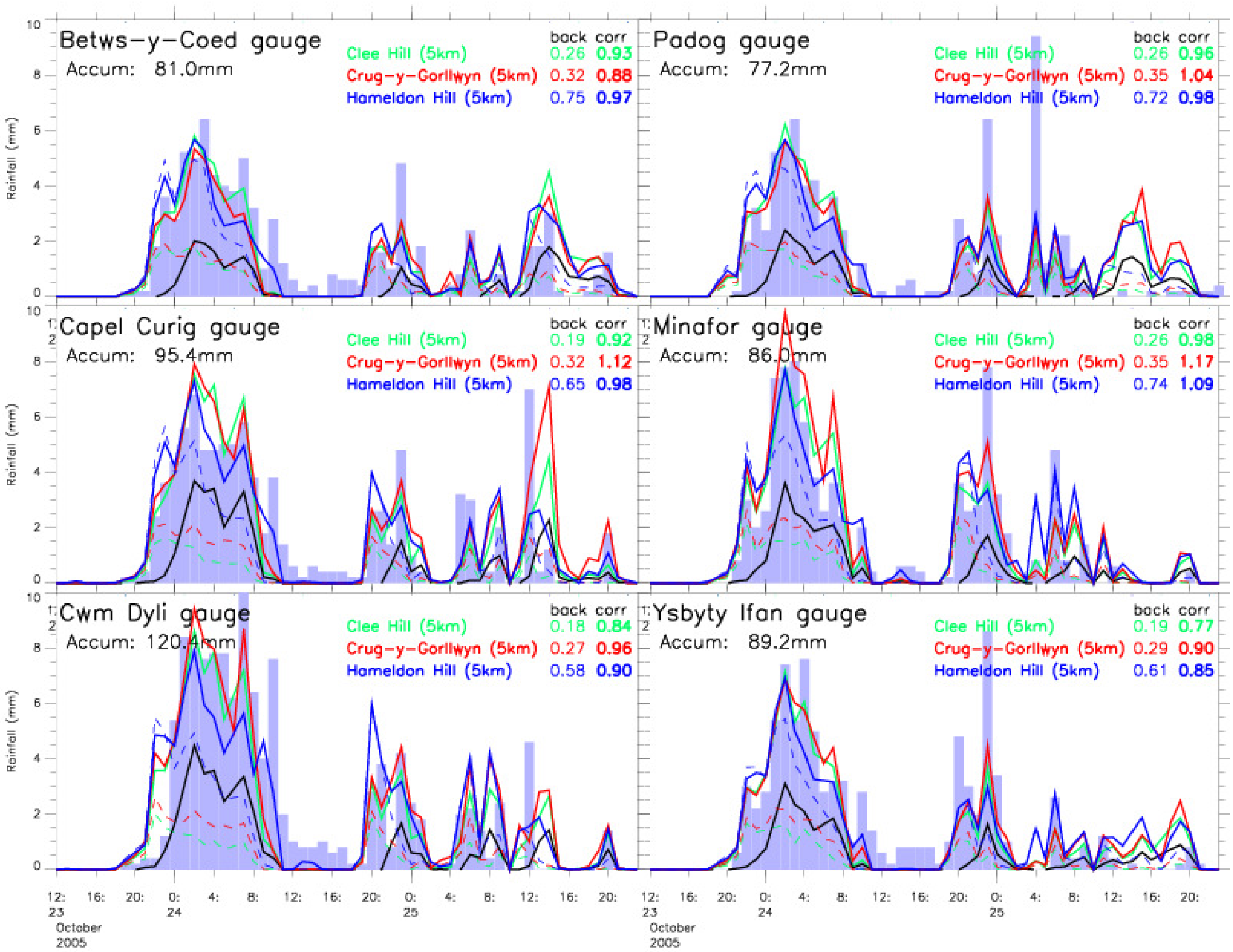


Figure 9.3: Time series of hourly rain gauge measurements (bars) and background (- - - -) and corrected (—) radar measurements for the closest pixel to each gauge site between 1200 UTC on 23 October 2005 and 0000 UTC on 16 October 2005. The total rainfall accumulation measured by each gauge during the event is listed along with the ratio of total radar to gauge accumulations for each radar (corrected values are shown in bold). The orographic correction applied to the radar data is plotted in black.

A general impression of radar data quality during the event can be quantified by the ratio of total radar to gauge accumulations, listed for each radar-gauge pair in Figure 9.3. These show that,

- Radars underestimate measured surface rainfall at most sites
- Orographic corrections improve the accuracy of radar measurements, typically reducing the error between background radar and gauge accumulations by at least 50%.

- The agreement between radars and gauges varies considerably for each radar between different gauge sites, with no radar performing clearly better over the entire region.

The improved agreement between gauge and radar measurements achieved by making orographic corrections is further illustrated by the sample contingency table listed in Table 9.2. While 46.5% of background radar data points are within a rainfall accumulation category lower than the corresponding gauge measurement, only 28% of corrected values are underestimated. The improvement between background and corrected radar data is particularly good at higher hourly rainfall accumulations in excess of 1 mm, which are of most relevance for the application of radar data to flood forecasting and warnings applications in upland areas.

		Background radar (Clee Hill)						Corrected radar (Clee Hill)						
	Hourly rain (mm)	0.0-0.2	0.2-0.4	0.4-1.0	1.0-4.0	4.0-8.0	>8.0	0.0-0.2	0.2-0.4	0.4-1.0	1.0-4.0	4.0-8.0	>8.0	
Rain gauge	0.0-0.2	**31.5**	0.0	1.9	0.0	0.0	0.0	**25.9**	1.9	1.9	3.7	0.0	0.0	33.3
	0.2-0.4	5.6	**1.9**	1.9	0.0	0.0	0.0	5.6	**1.9**	1.9	0.0	0.0	0.0	9.3
	0.4-1.0	5.6	1.9	**1.9**	3.7	0.0	0.0	5.6	0.0	**1.9**	5.6	0.0	0.0	13.0
	1.0-4.0	9.3	3.7	0.0	**11.1**	0.0	0.0	5.6	0.0	0.0	**18.5**	0.0	0.0	24.1
	4.0-8.0	3.7	0.0	5.6	7.4	**0.0**	0.0	0.0	0.0	1.9	7.4	**7.4**	0.0	16.7
	>8.0	0.0	0.0	0.0	3.7	0.0	**0.0**	0.0	0.0	0.0	0.0	1.9	**1.9**	3.7
		55.6	7.4	11.1	25.9	0.0	0.0	42.6	3.7	7.4	35.2	9.3	1.9	

Table 9.2: Contingency table showing percentage of (a) background and (b) corrected Clee Hill radar and Cwm Dyli gauge hourly rainfall values within each threshold accumulation group during period shown in Figure 1.3.

Analysis of the time series shown in Figure 9.3 highlights three main rainfall episodes based on the agreement between radar and gauge rainfall accumulations. The first episode of pre-frontal rain between 2000 UTC on 23 October 2005 and 0900 UTC on 24 October 2005 is characterised by particularly close agreement between corrected radar data and the corresponding gauge measurements. The second period between 0900 UTC and 2000 UTC on 24 October 2005 is characterised by the radars missing rainfall associated with the warm front. The third episode during the latter part of the study period is characterised by highly variable gauge and radar rainfall accumulations and a variety of agreement between measurements at different gauge sites. Figure 9.4 shows the radar-derived radar accumulations over the 24 hour period between 2000 UTC on 23 October 2005 and 2000 UTC on 24 October 2005, illustrating the spatial variability of rainfall during the first two episodes. As observed for the cases of 13 August 2005 (Figure 6.4) and 28 September 2005 (Figure 7.5), the spatial variability shown by the corrected radar data originates from the distribution of orographic corrections applied rather than directly from the background radar measurements.

9.3.1 Occluded front and pre-frontal rain period

Time series showing 5 minute temporal resolution data during the first band of persistent rain are plotted in Figure 9.5. The correlation between hourly rain gauge and radar rainfall accumulations during the period illustrated in Figure 9.5 is shown in Figure 9.6. Sample radar images during this period are shown in Figure 9.7. Figures 9.5 and 9.6 show similarly good agreement between gauge and corrected radar values for all available radars over the whole rainfall range. In this case the application of large orographic corrections to the background radar data significantly improves the correspondence between gauge and radar rainfall values. In particular, there is considerable skill

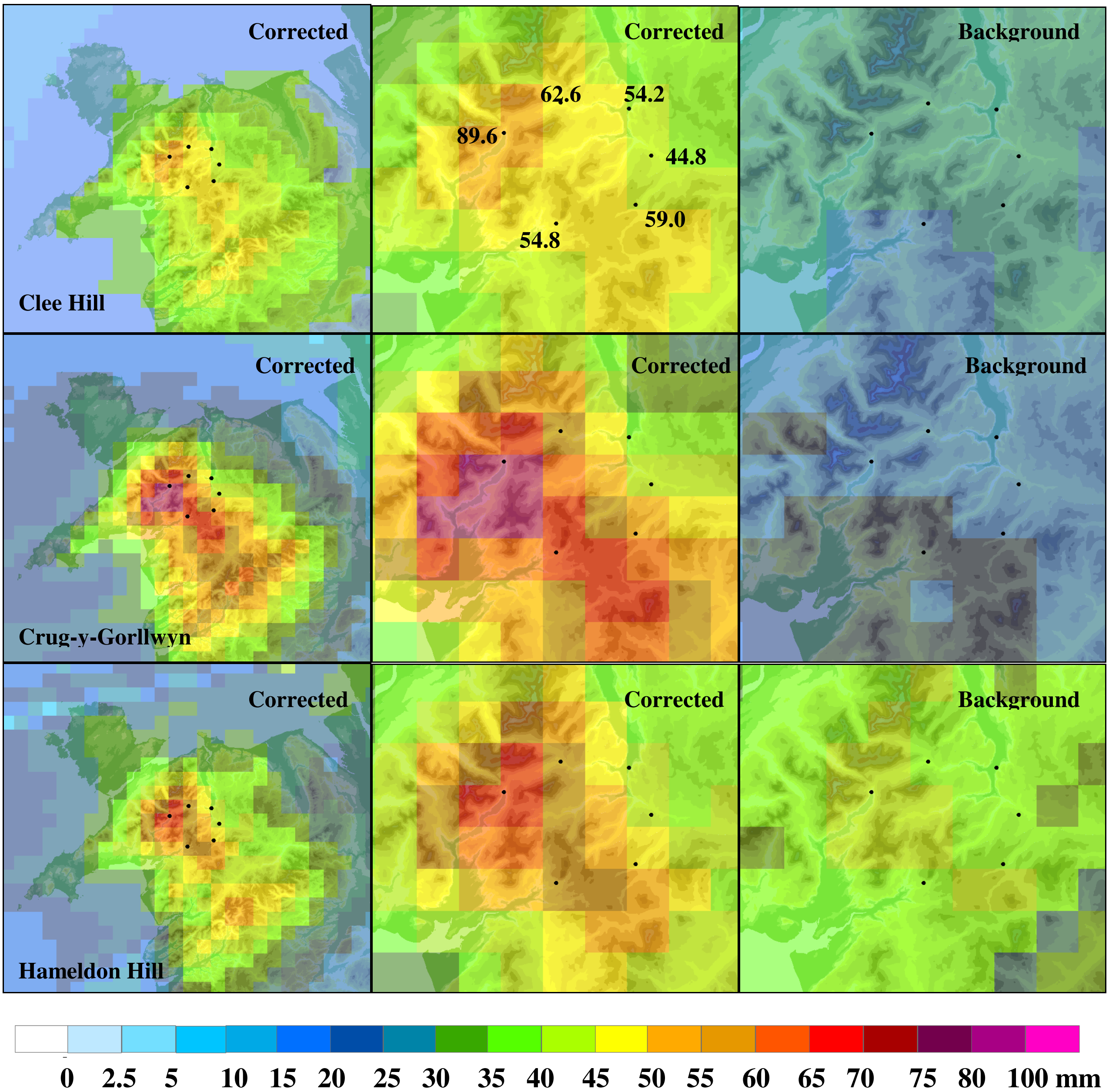


Figure 9.4: Comparison of 24 hour rainfall accumulations from a selection of available radars across the Upper Conwy region between 2000 UTC on 23 October 2005 and 2000 UTC on 24 October 2005. Black circles indicate rain gauge locations with labels showing the corresponding available rain gauge accumulation over the same period in mm.

demonstrated by the ability of the orographic correction scheme to capture the temporal variation of rainfall measured at each gauge site while the background radar time series shows slowly decreasing values throughout. The application of radar-dependent gauge adjustment factors also gave further improvements to radar data quality, shifting the orographic corrected radar rainfall estimates towards the surface gauge measurement in all cases.

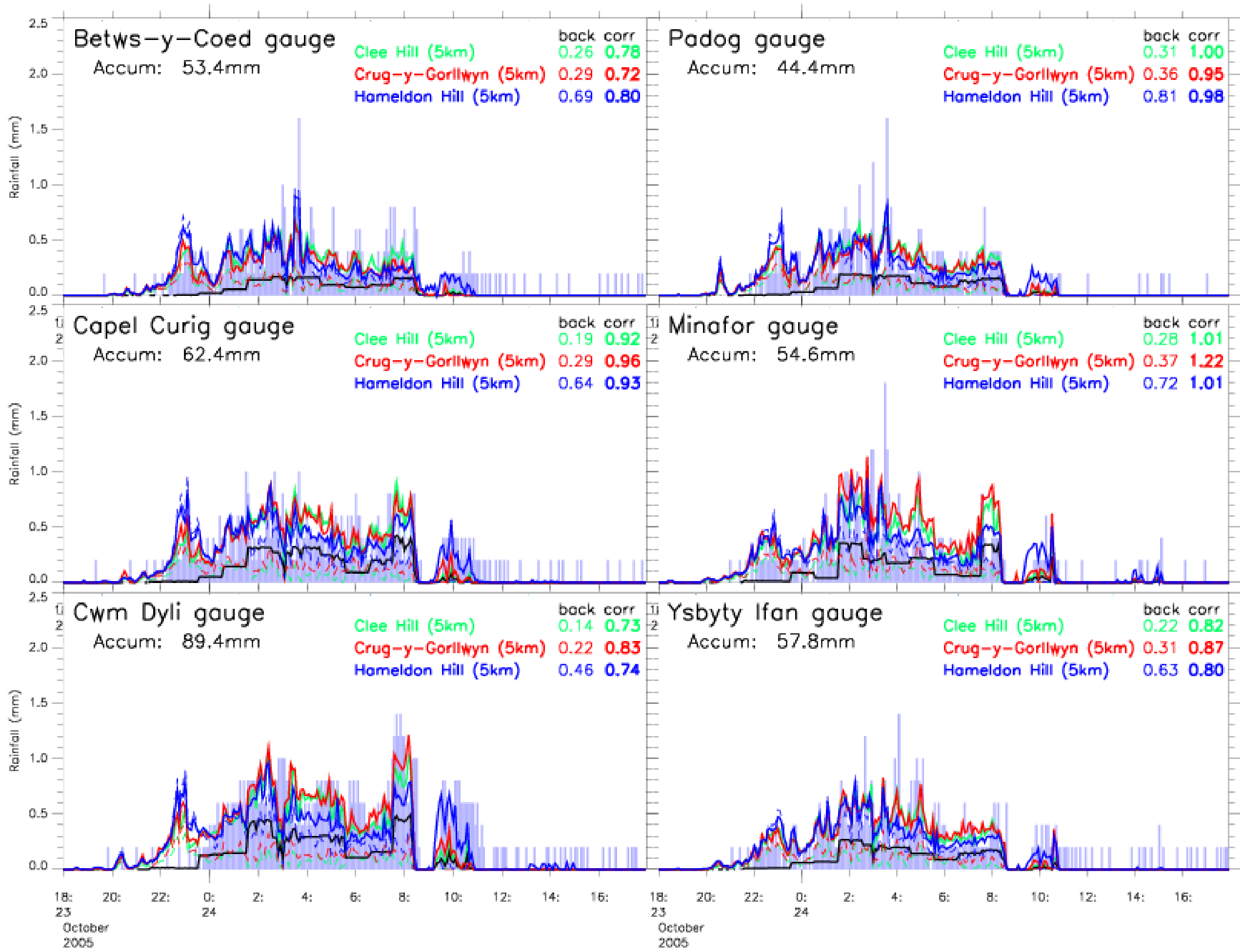


Figure 9.5: Time series of 5 minute rain gauge measurements (bars) and background (- - - -) and corrected (—) radar measurements for the closest pixel to each gauge site between 1800 UTC on 23 October and 1800 UTC on 24 October 2005. The total rainfall accumulation measured by each gauge during the event is listed along with the ratio of total radar to gauge accumulations for each radar (corrected values are shown in bold). The orographic correction applied to the radar data is plotted in black.

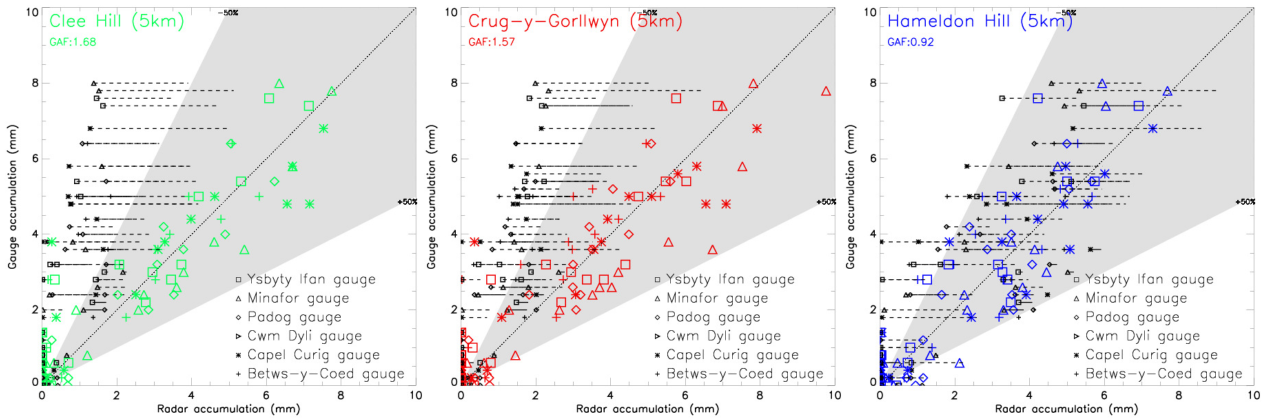


Figure 9.6: Correlation between hourly gauge measurements in the Upper Conwy study area and background (small points) and corrected (large points) radar data between 1800 UTC on 23 October and 24 October 2005. Horizontal lines show the magnitude of the orographic correction applied to the background data in each case.

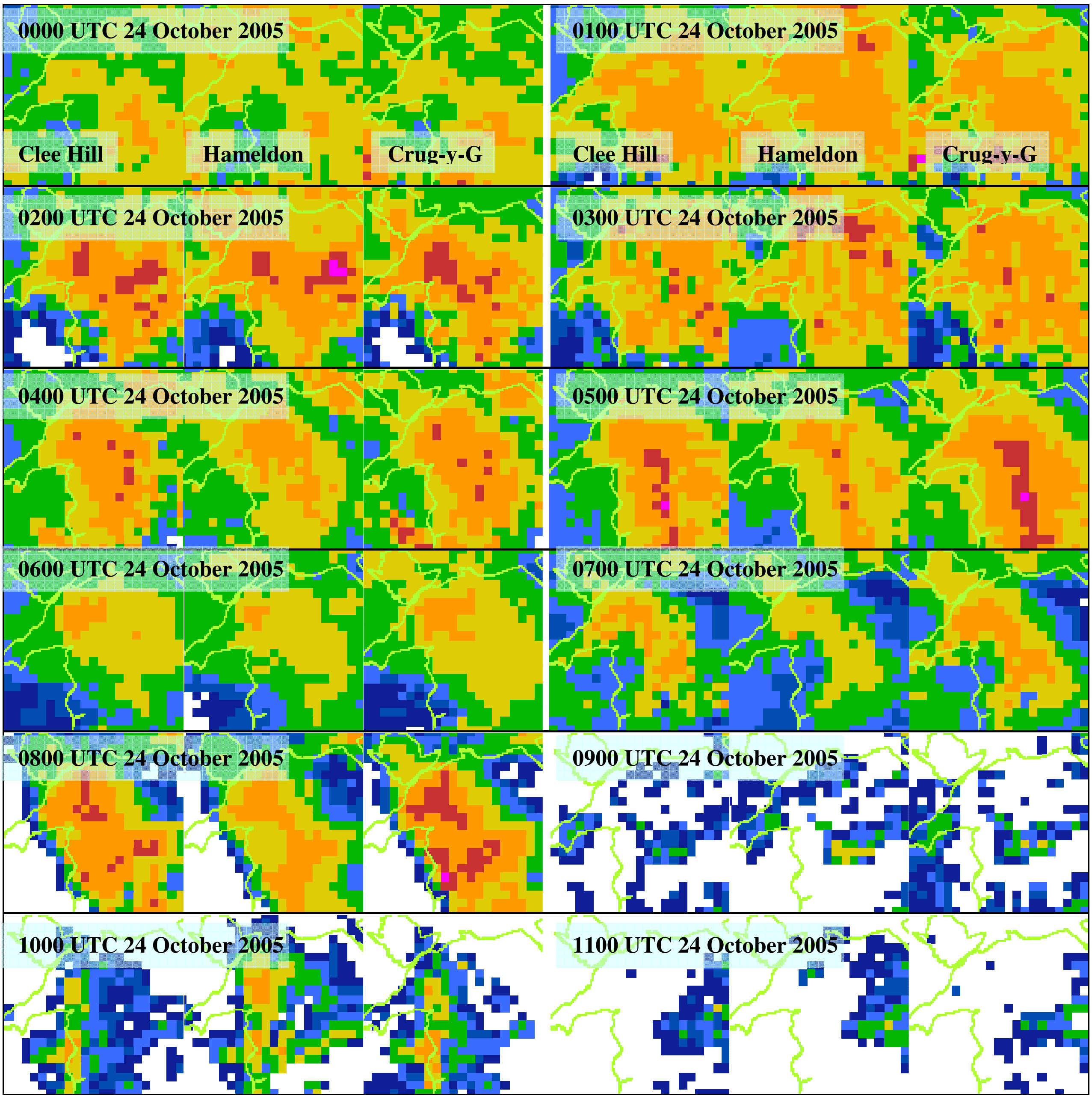


Figure 9.7: Comparison of 5 km radar data showing rainfall associated with the north-westerly passage of occluded and warm fronts across the Upper Conwy study area during the morning of 24 October 2005.

9.3.2 Warm front

Figure 9.5 highlights poorer agreement between the radar and gauge measurements after about 0900 UTC on 24 October 2005, shown in Figure 9.6 as radar accumulations of less than 1 mm in an hour. Rainfall estimates from Clee Hill and Crug-y-Gorllwyn, which were used in the national radar composite product, underestimated the rainfall associated with the warm front between 0900 UTC and 1000 UTC while all radars missed the subsequent showers which occurred intermittently during the rest of the day.

The most likely explanation for the poor agreement shown during the afternoon of 24 October 2005 is that the rainfall was a low-level feature, generally below the height of the radar beam at the range of interest. The lowest available radar beam above the Upper Conwy region is at a height of 1126 m above the surface at Ysbyty Ifan while the lowest available beam above Cwm Dyli is at 1716 m above the surface. The sample radar images shown in Figure 9.8 illustrate how Clee Hill, Crug-y-Gorllwyn and Hameldon Hill radars all identified patchy regions of light rain close to the radar site, with little correspondence between rainfall features at longer range in each image. It is likely that better identification of rainfall over the Upper Conwy region might have been achieved at this time were radar data available at shorter range.

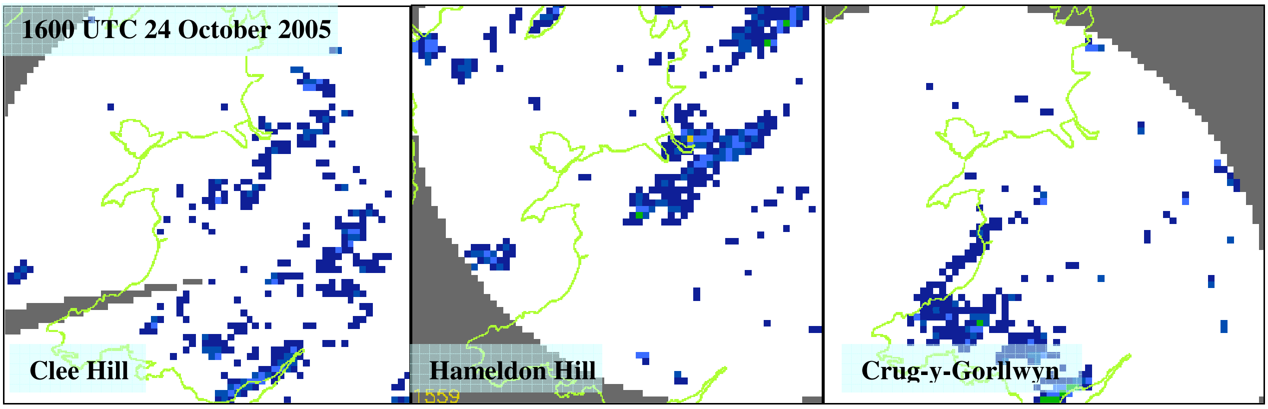


Figure 9.8: Comparison of 5 km resolution radar data at 1600 UTC on 24 October 2005.

9.3.3 Cold front

The second period of heavier rainfall occurred between 2000 UTC and 0000 UTC on 24 October, associated with the passage of the cold front across the Upper Conwy region. Figure 9.9 shows sample radar images and Figure 9.10 shows time series of 5 min resolution gauge and radar data during this period. Correlation plots of the available radar and gauge data are shown in Figure 9.11.

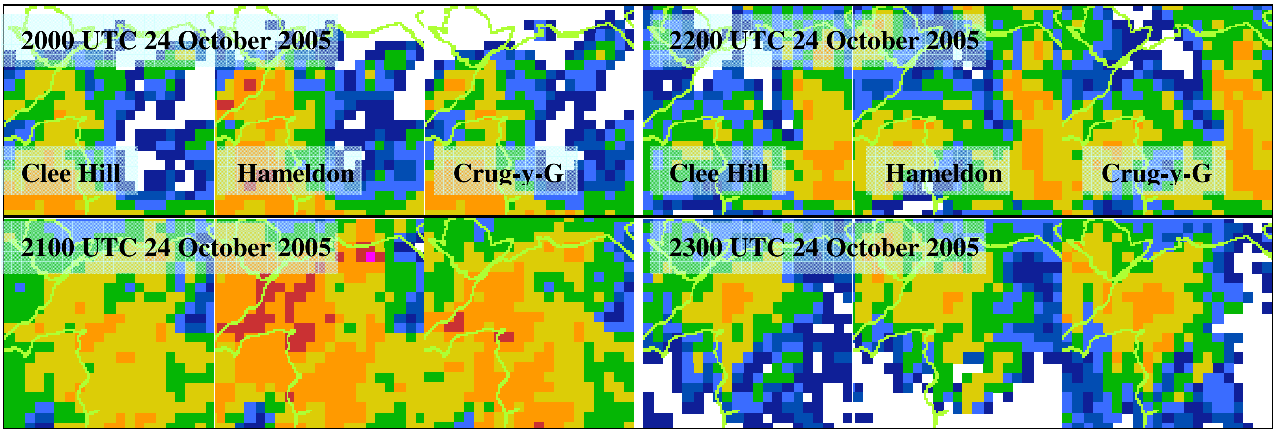


Figure 9.9: Comparison of 5 km radar data showing rainfall associated with the passage of a cold front across the Upper Conwy study area on 24 October 2005.

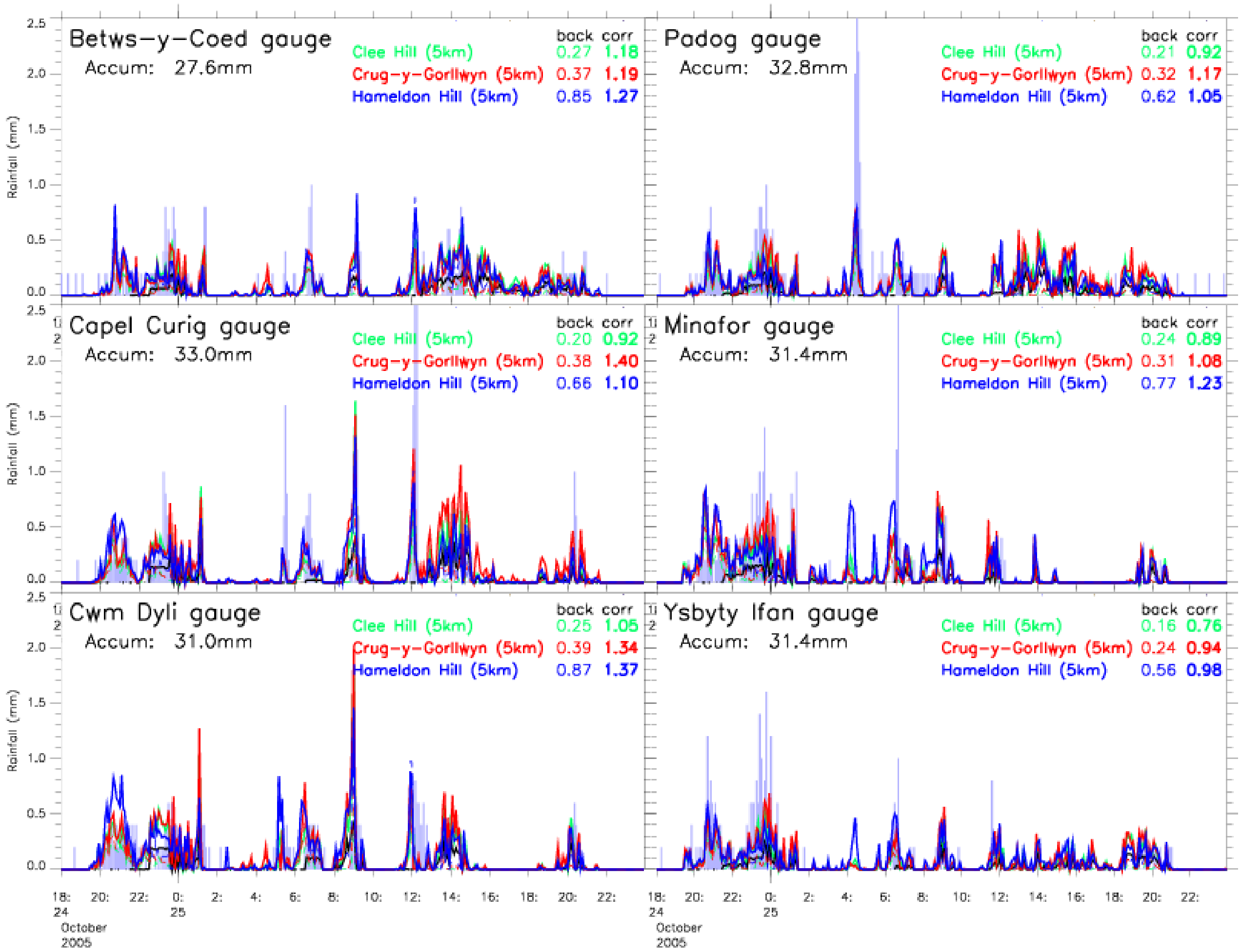


Figure 9.10: Time series of 5 minute rain gauge measurements (bars) and background (- - - -) and corrected (—) radar measurements for the closest pixel to each gauge site between 1900 UTC on 24 October and 0000 UTC on 26 October 2005. The total rainfall accumulation measured by each gauge during the event is listed along with the ratio of total radar to gauge accumulations for each radar (corrected values are shown in bold).

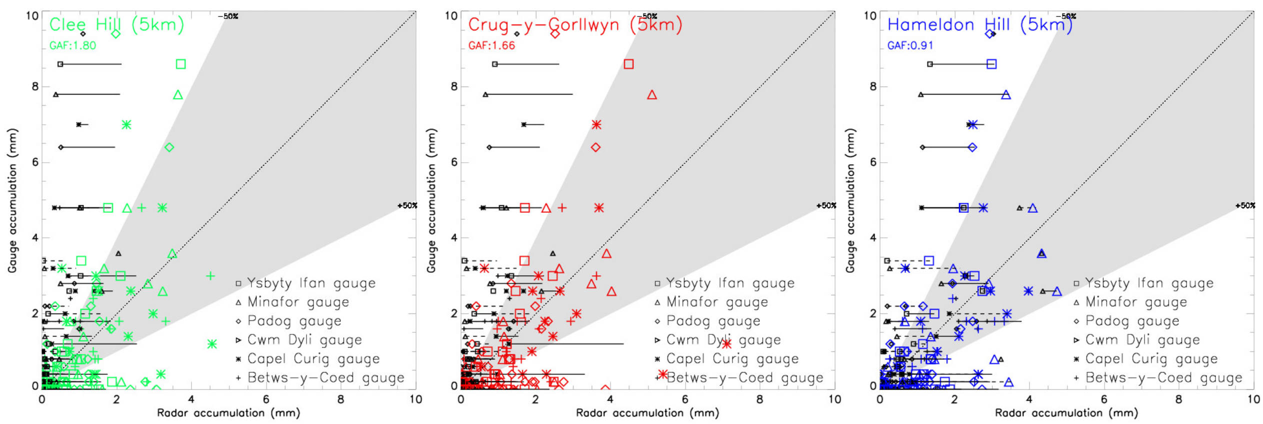


Figure 9.11: Correlation between hourly gauge measurements in the Upper Conwy study area and background (small points) and corrected (large points) radar data between 1900 UTC on 24 October and 000 UTC on 26 October 2005. Horizontal lines show the magnitude of the orographic correction applied in each case.

Figure 9.10 demonstrates particular benefit of applying the time-varying orographic corrections during the passage of the cold front. Examples of the corrections applied during this period are provided in Figure 9.12. While the radars all measured more intense background rainfall values during the first two hours between 2000 UTC and 2200 UTC, the gauge data show more intense rainfall associated with a second pulse between about 2300 UTC and 0100 UTC on 25 October 2005. The magnitude of the first pulse was captured reasonably well by the radars when no corrections were applied to the background data as a result of model relative humidity values across North Wales being less than 70%. As the second pulse of rain approached, the humidity increased above 85% and corrections were again applied to the background radar data, improving the agreement between radar rainfall estimates and the measured gauge values. The magnitude of the corrections applied was insufficient to match the locally intense rainfall measured at Betws-y-Coed, Padog, Minafor and Ysbyty Ifan gauges however. The large variation between rainfall measurements from each gauge at this time perhaps indicates that application of corrections and availability of radar data at higher spatial resolution would have improved the quantitative agreement observed.

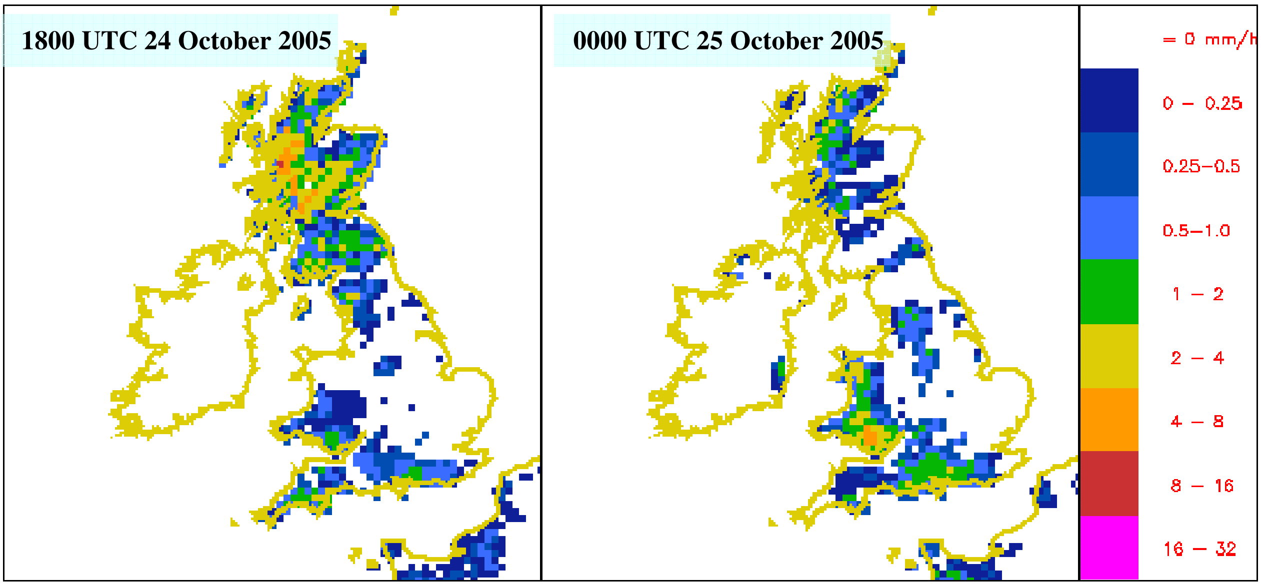


Figure 9.12: Orographic correction fields applied to background data during 24 and 25 October 2005.

9.4 Comparison between radar and gauge accumulations: Upper Taff

Figure 9.13 shows time series of hourly rainfall accumulations measured by the available radars and gauges across the Upper Taff study area between 1200 UTC 23 October 2005 and 0000 UTC 26 October 2005. The correlation between these measurements is plotted in Figure 9.14. A Flood Watch was issued by the Environment Agency for locations further downstream along the Taff River until 1409 UTC on 25 October 2005. The rain gauge measurements shown during this period demonstrate considerable orographic influence, with the total accumulation during the event at Storey Arms (530 m AOD) of 187.6 mm being over five times larger than that measured during the same period at Brecon (168 m AOD). Measurements by all gauges show rainfall associated with the three main frontal episodes identified in Section 9.3. The spatial distribution of radar-derived accumulations during 24 October 2005 is illustrated in Figure 9.15.

The comparison between total gauge and radar accumulations listed in Figure 9.13 shows corrected radar rainfall estimates to be typically within 25% of gauge measurements at the most gauge sites. Clearly, the data from all available radars failed to correctly capture the large orographic enhancement observed at Storey Arms, leading to underestimations of up to 70%. This is clearly shown in Figure 9.15. The correlation plots shown in Figure 9.14 demonstrate that this rainfall underestimation was a systematic feature over the entire range of rainfall accumulations measured at this site.

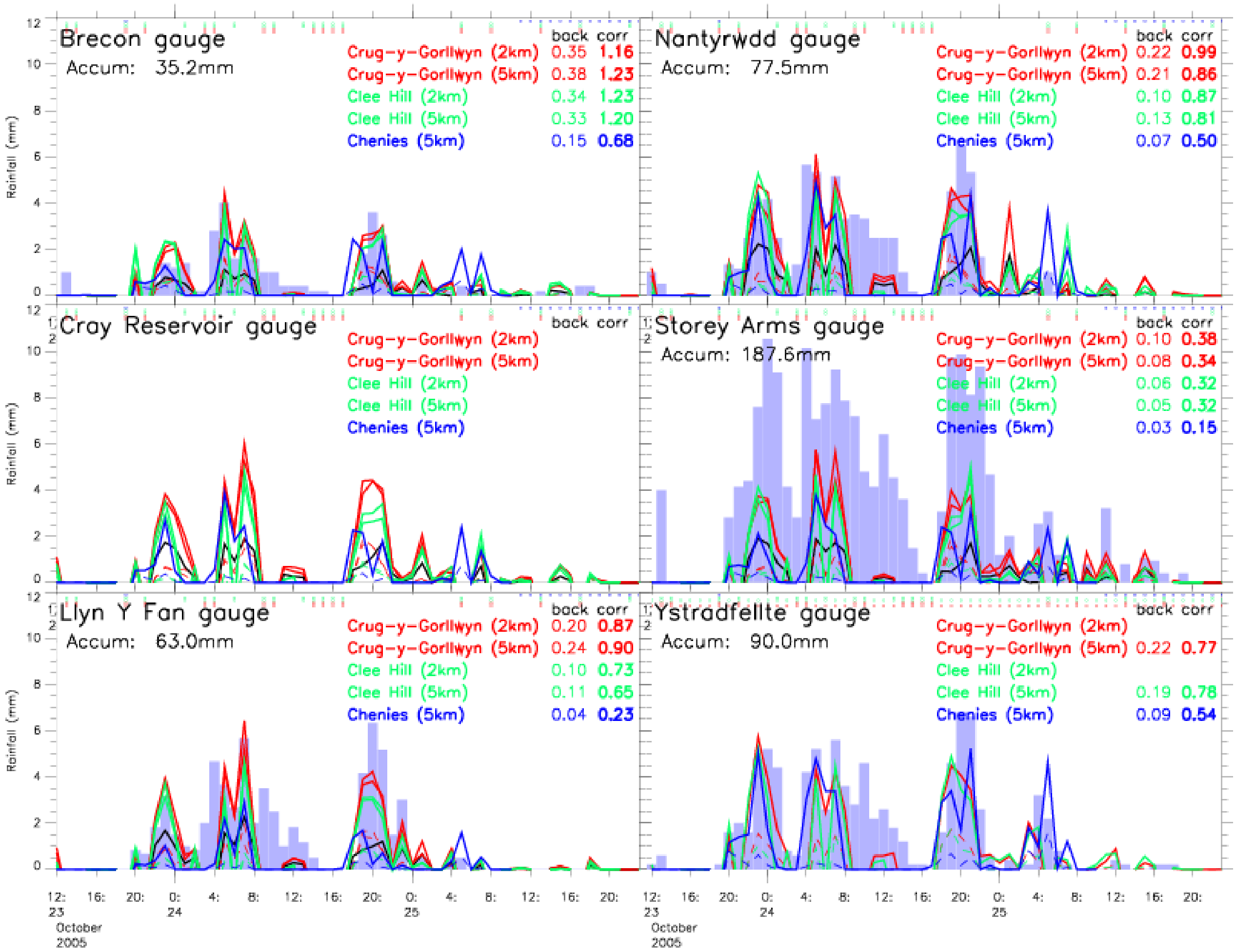


Figure 9.13: Time series of hourly rain gauge measurements (bars) and background (- - - -) and corrected (——) radar measurements for the closest pixel to each gauge site between 1200 UTC on 23 October and 0000 UTC on 26 October 2005. The total rainfall accumulation measured by each gauge during the event is listed along with the ratio of total radar to gauge accumulations for each radar (corrected values are shown in bold). The orographic correction applied to the radar data is plotted in black. Squares show missing periods of radar data.

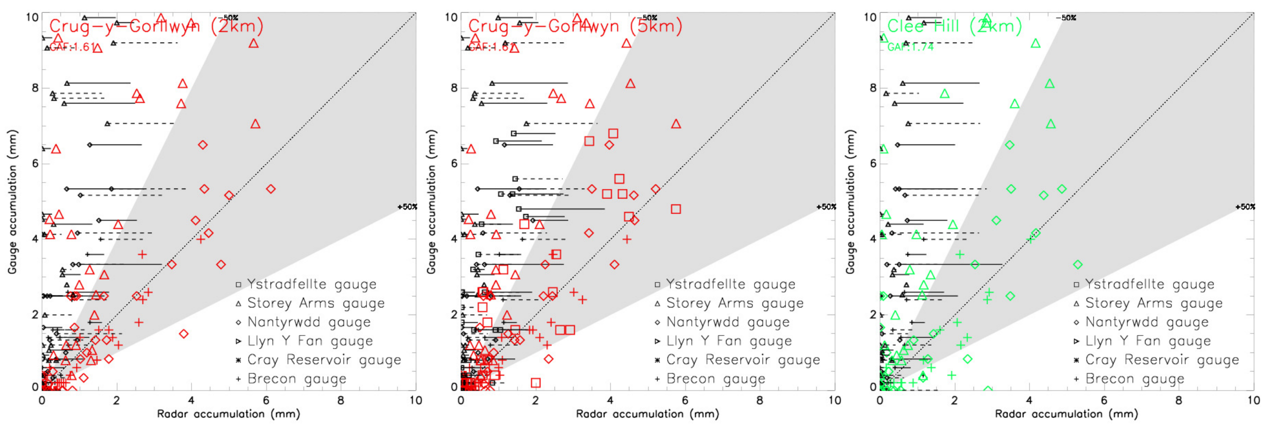


Figure 9.14: Correlation between hourly gauge measurements in the Upper Taff study area and background (small points) and corrected (large points) radar data between 1200 UTC on 23 October and 000 UTC on 26 October 2005. Horizontal lines show the magnitude of the orographic correction applied in each case.

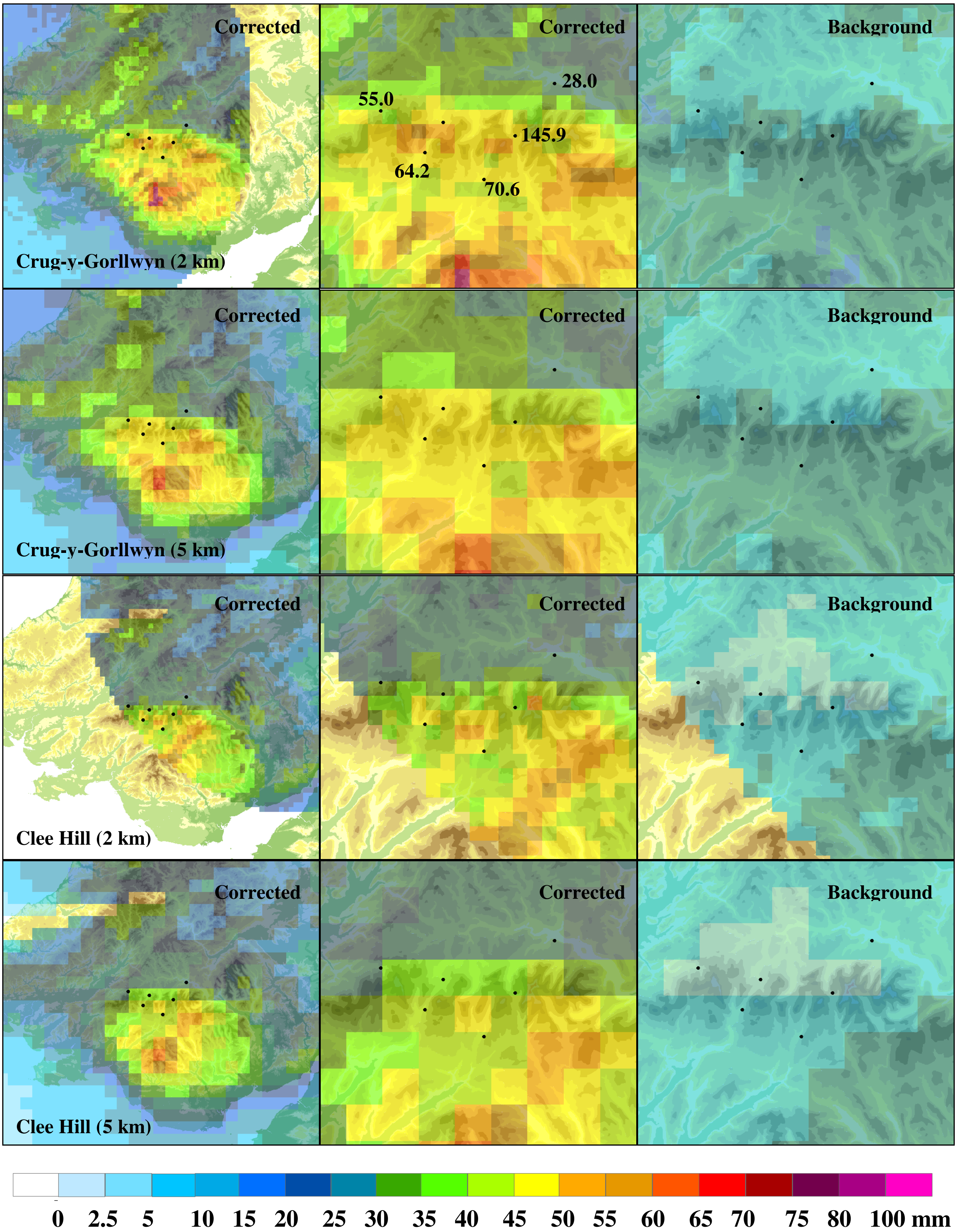


Figure 9.15: Comparison of 24 hour rainfall accumulations from a selection of available radars across the Upper Taff region during 24 October 2005. Black circles indicate rain gauge locations with labels showing the corresponding available rain gauge accumulation over the same period in mm.

Figure 9.14 shows slightly better agreement between the Storey Arms gauge and radar measurements from the nearest radar at Crug-y-Gorllwyn at the 2 km horizontal resolution than at 5 km resolution. The hourly accumulations listed in Table 9.3 illustrate this result, comparing the rainfall measured by each radar with that by the Storey Arms gauge between 0000 UTC and 0100 UTC on 24 October 2005 as the occluded front passed across the region. In this case a correction of about 1.7 mmh^{-1} was applied to the background data, clearly insufficient to account for the enhancement observed at the surface. Application of orographic correction fields at the same horizontal resolution as the available radar data may have provided improved agreement with the gauge data in this case.

Gauge		Radar	Background	Back + Orog.	Corrected
Storey Arms	10.5 mm	Crug-y-Gorllwyn (2km)	0.75 mm	2.43 mm	3.62 mm
		Crug-y-Gorllwyn (5km)	0.64 mm	2.37 mm	3.54 mm
		Clee Hill (2 km)	0.28 mm	1.72 mm	2.71 mm
		Clee Hill (5 km)	0.37 mm	2.01 mm	3.17 mm
		Chenies (5 km)	0.21 mm	0.72 mm	1.05 mm

Table 9.3: Comparison between background and corrected radar hourly rainfall accumulations between 0000 and 0100 UTC on 24 October 2005 and gauge measured hourly accumulation at Storey Arms, Upper Taff.

9.5 Comparison between radar and gauge accumulations: Upper Exe

Figure 9.16 shows time series of rainfall measurements across the Upper Exe region during the period shown in Figure 9.3. Five distinct rain bands can be identified during this event, each of which was measured with varying skill by the radars. The first period between 1800 UTC on 23 October 2005 and 0000 UTC on 24 October 2005 was associated with the passage of the occluded and warm fronts across the region. No data were available from Cobbacombe Cross at this time such that data from Crug-y-Gorllwyn would have been included in the national composite product. As observed in the Upper Conwy, all available radars were significantly better in capturing the magnitude of rainfall associated with the occluded front than with the warm front itself. Most of the daytime on 24 October 2005 was then characterised by persistent and generally light rain behind the warm front which lasted until the heavier rainfall associated with the cold front began at 1600 UTC. The spatial rainfall distribution measured by radars with coverage across the region during 24 October 2005 is illustrated in Figure 9.17. This period is shown in more detail in Figure 9.18.

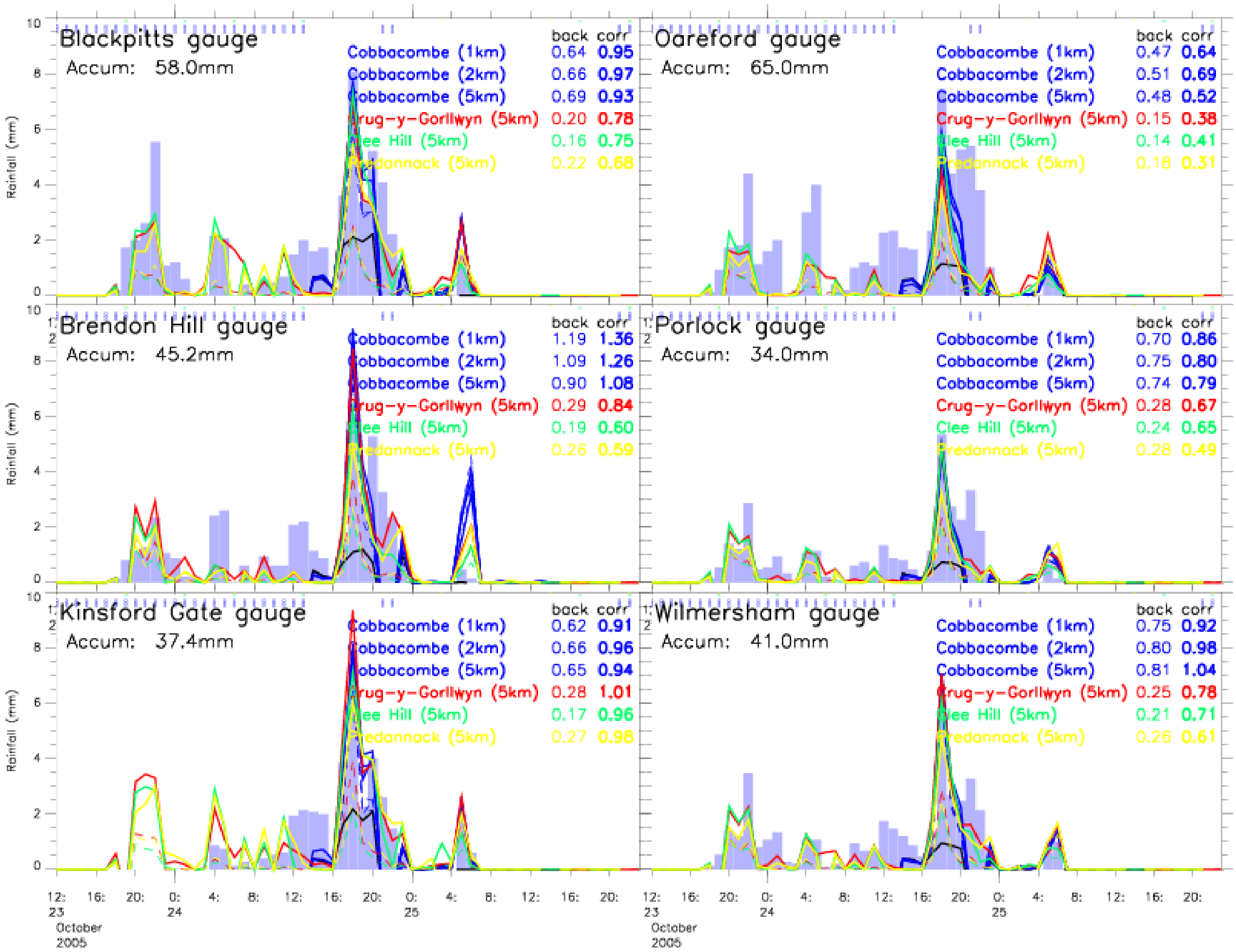


Figure 9.16: Time series of hourly rain gauge measurements (bars) and background (- - - -) and corrected (——) radar data for the closest pixel to each gauge site between 23 and 26 October 2005. The total rainfall accumulation measured by each gauge during the event is listed along with ratios of radar to gauge totals. The orographic correction applied to the radar data is plotted in black. Squares show missing periods of radar data.

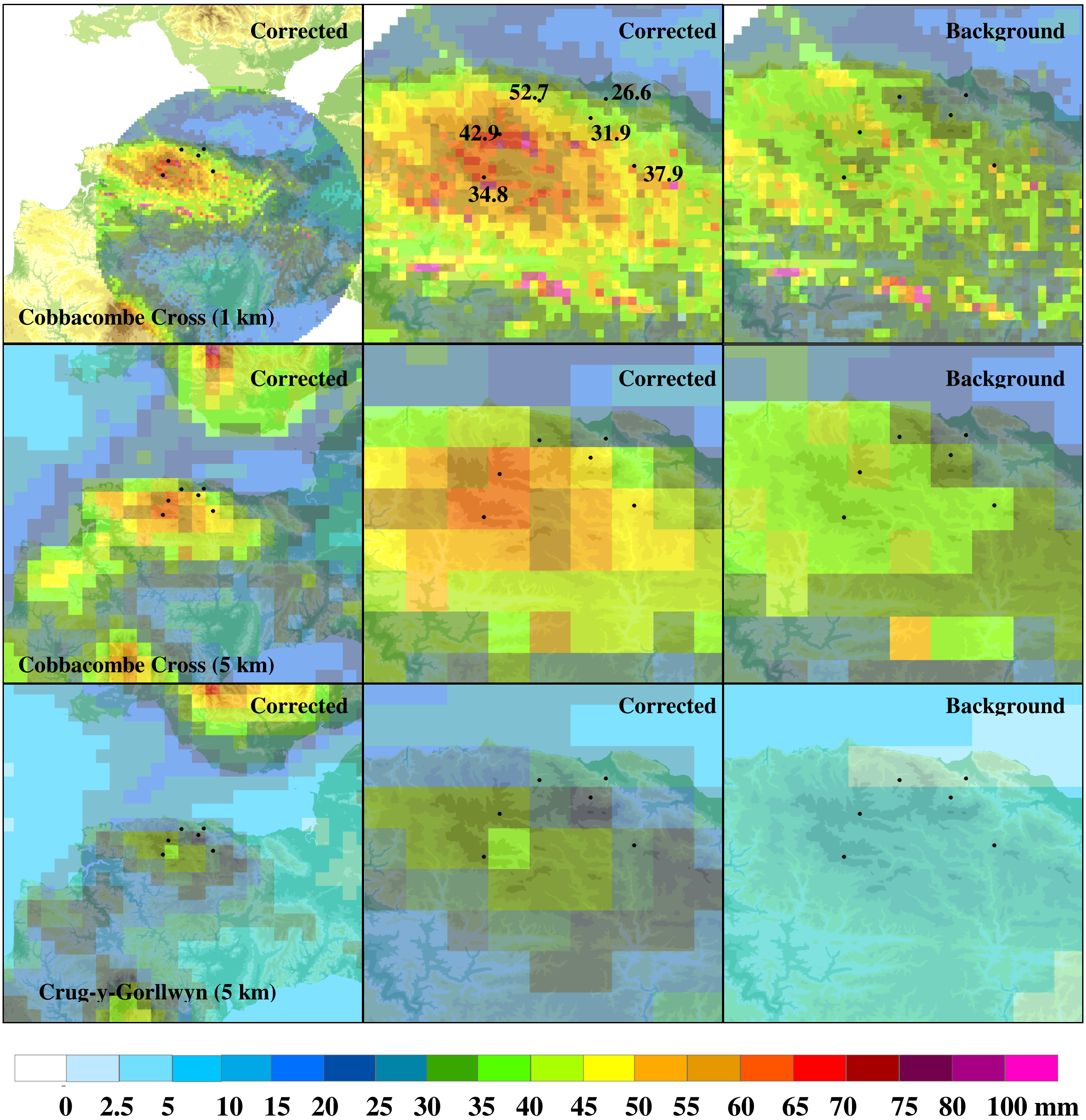


Figure 9.17: Comparison of 24 hour rainfall accumulations from a selection of available radars across the Upper Exe region during 24 October 2005. Black circles indicate rain gauge locations with labels showing the corresponding available rain gauge accumulation over the same period in mm.

Figure 9.18 shows poor agreement between gauge and radar measurements during the afternoon of 24 October 2005 when the gauges recorded continuous light rainfall across the Upper Exe region. Best agreement was achieved between gauge and radar data from Cobbacombe Cross, suggesting that the showers were confined to low levels and measurements from other radars at longer range were adversely affected by beam overshooting. Ratios of the total radar to gauge accumulations during this period listed in Figure 9.18 show that the Cobbacombe Cross radar data underestimated the gauge measured rainfall by up to 75%. The correlation plots shown in Figure 9.19 emphasise that even this level of agreement was only possible as a result of applying the orographic corrections to near-zero background rainfall values.

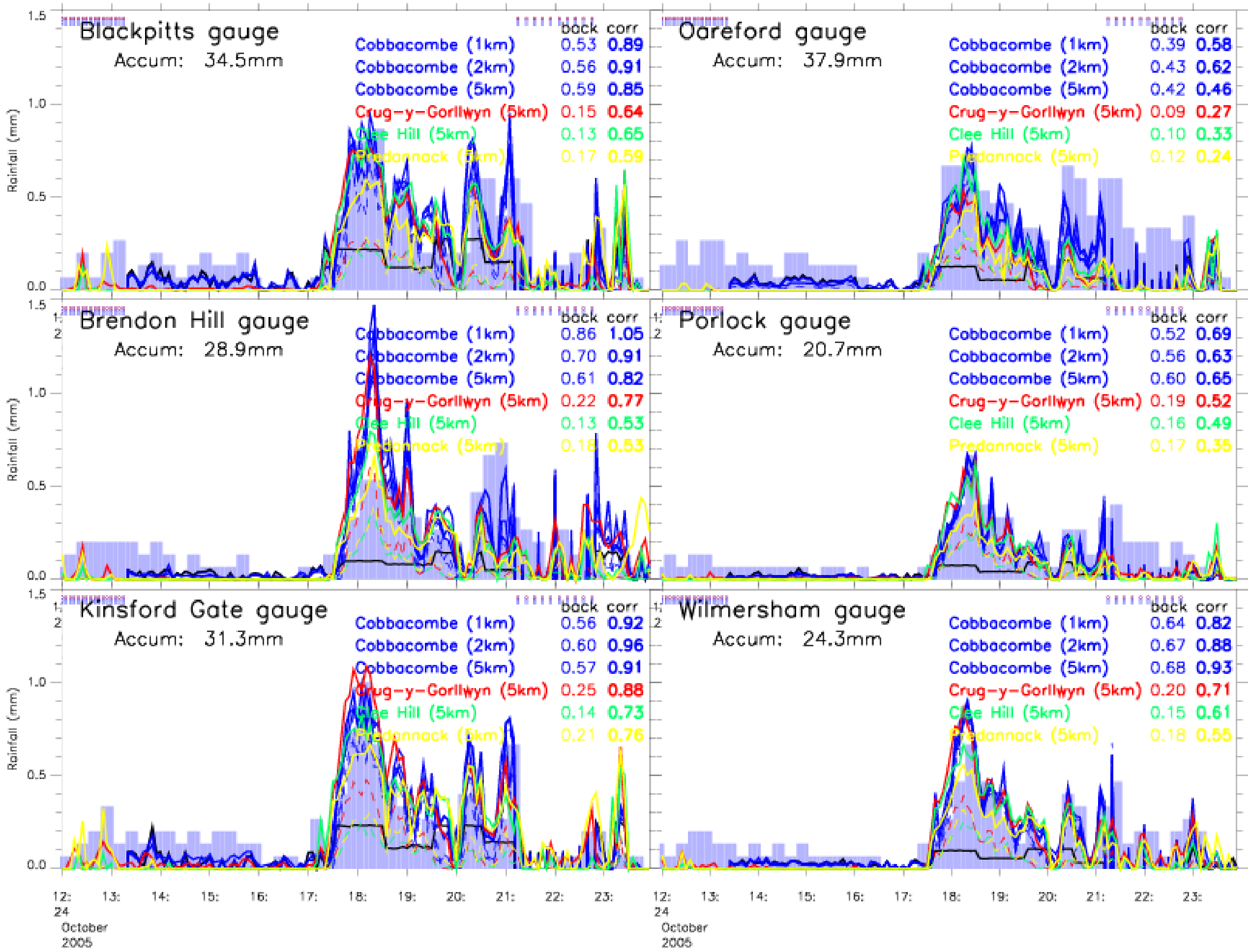


Figure 9.18: As in Figure 9.15 for 5 min rainfall measurements across the Upper Exe area on 24 October 2005.

Figure 9.19 shows generally good agreement between radar and gauge measurements for higher hourly rainfall accumulations, such as occurred between 1700 UTC and 2000 UTC on 24 October 2005 when the cold front crossed the Upper Exe region. The value of applying orographic corrections of up to 2 mmh^{-1} to the background radar data can be seen for all available radars. Figure 9.18 highlights a general failure of the radars to capture the magnitude of post-frontal rainfall between 2000 UTC and 2200 UTC however. Best agreement with the gauge measurements occurred with the 1 km resolution data from Cobbacombe Cross while the other available radar data underestimated this rainfall by as much as 50%. Particularly poor agreement occurred with gauge measurements at Porlock, Brendon Hill and Oareford.

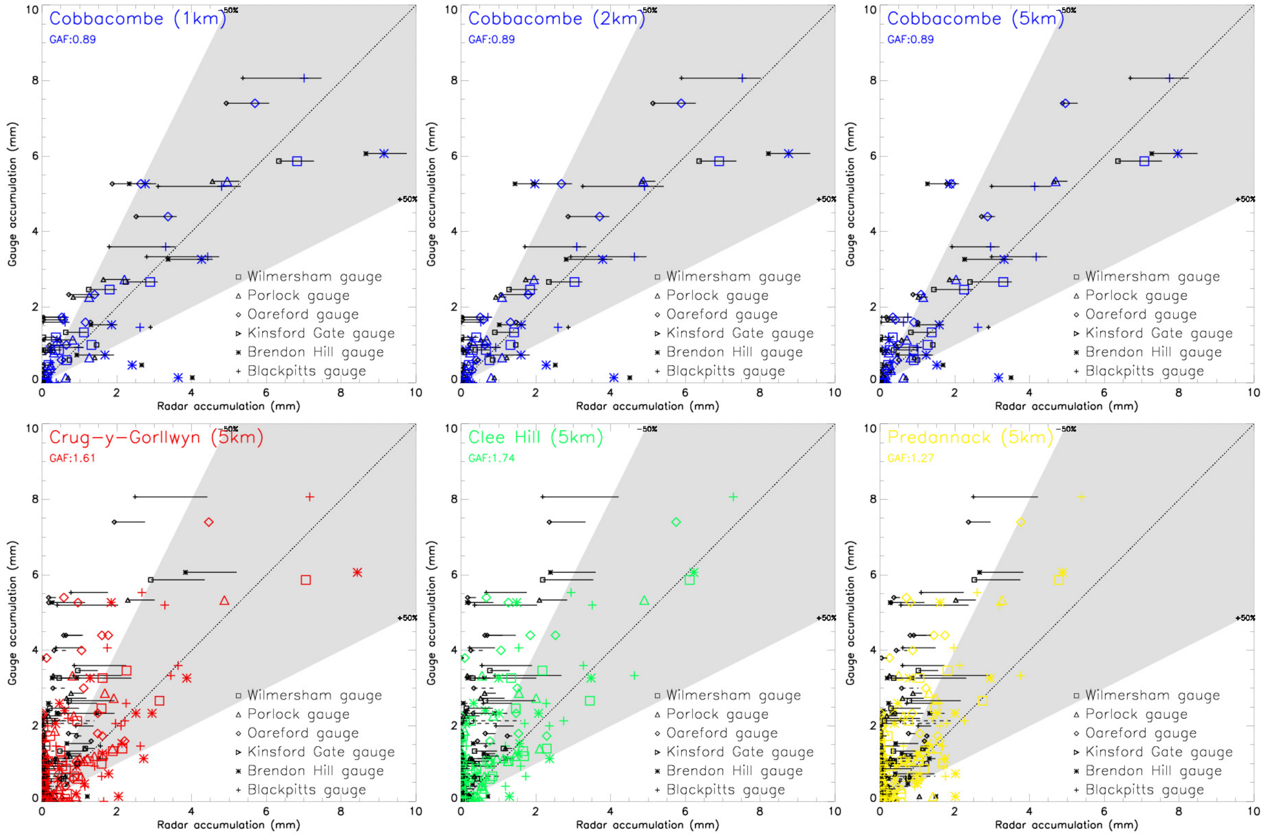


Figure 9.19: Correlation between hourly gauge measurements in the Upper Exe study area and background (small points) and corrected (large points) radar data from available radar across the region between 1200 UTC on 23 October 2005 and 0000 UTC 26 October 2005. Horizontal lines show the orographic correction.

November 2005

Substantial rainfall occurred across the British Isles during the first half of November 2005. Although high pressure then dominated for much of the rest of the month, 122% of the average monthly rain for November fell over Wales. A total of 290 mm rain was recorded in a week by the Cwm Dyli gauge in the Upper Conwy region, when 237 mm was measured by the Llyn Y Fan gauge in the Upper Taff region and 105 mm was measured at Oareford in the Upper Exe region. Time series showing the rainfall measured at these sites are plotted in Figure 10.1.

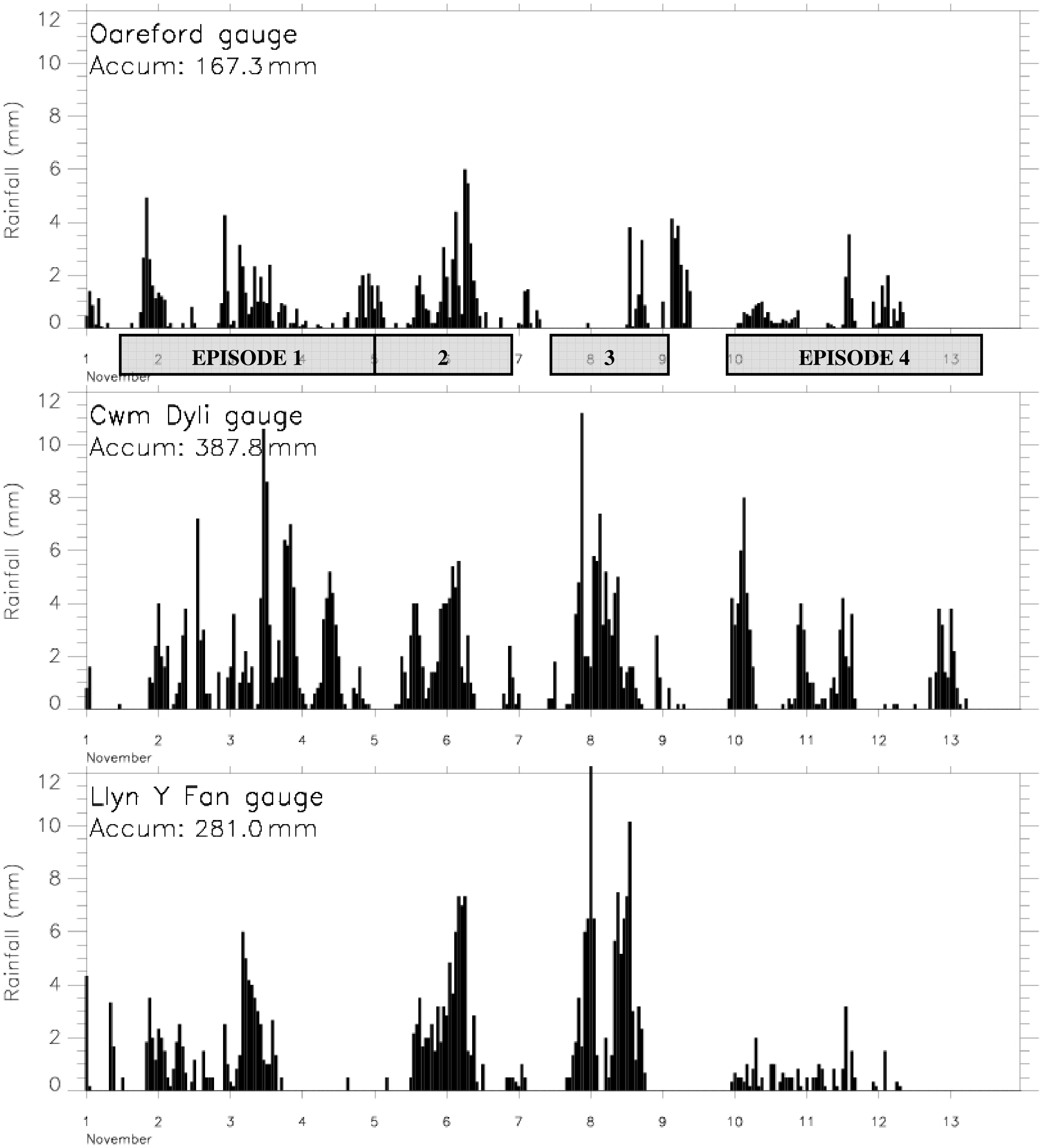


Figure 10.1: Time series of rain gauge measurements in the (a) Upper Exe, (b) Upper Conwy and (c) Upper Taff upland regions during the first thirteen days of November 2005.

The rainfall shown in Figure 10.1 is associated with the passage of a series of Atlantic frontal systems across the UK. Four primary systems tracked from the west during this time, which can be associated with rainfall on 2, 5-6, 7-8 and 10 November 2005.

Table 10.1 lists the total rainfall accumulation measured at each gauge during this period and Table 10.2 lists 24 hours accumulations associated with specific frontal systems. Both show considerable variation between rainfall accumulations within each region, demonstrating the significance of orographic factors on the local rainfall distribution in upland areas. The highest rainfall accumulations measured in the Upper Conwy and Upper Taff regions are typically at least twice as large as the smallest total in each region.

Upper Exe		Upper Conwy		Upper Taff	
Gauge	Accum.	Gauge	Accum.	Gauge	Accum.
Oareford	167.3 mm	Cwm Dyli	387.8 mm	Llyn-Y-Fan	281.0 mm
Blackpitts	162.9 mm	Ysbyty Ifan	320.6 mm	Ystradfellte	268.4 mm
Kinsford Gate*	133.6 mm	Capel Curig	279.2 mm	Storey Arms	262.8 mm
Brendon Hill	123.6 mm	Minafor	225.4 mm	Nantyrwdd	250.5 mm
Wilmersham	121.4 mm	Padog	162.4 mm	Brecon	126.4 mm
Porlock	98.4 mm	Betws-y-Coed	161.8 mm	Cray Reservoir	-

Table 10.1: Daily rainfall accumulations at each gauge in the three upland study areas between 0000 1 November 2005 and 0000 14 November 2005. (* missing gauge data during period at Kinsford Gate).

	Upper Exe				Upper Conwy				Upper Taff		
Event	1	2	3		1	2	3		1	2	3
OAR	22.0	**41.1**	10.4	CWM	72.2	60.0	**76.4**	LLY	38.5	71.5	**97.2**
BLA	10.2	**33.2**	14.4	YSB	**67.2**	46.0	62.2	STO	45.9	**74.9**	46.2
KIN	-	**34.5**	9.6	CAP	55.6	29.6	**72.4**	YST	36.2	**69.6**	44.8
BRE	9.4	**27.8**	13.0	MIN	**49.8**	21.8	49.4	NAN	27.5	**69.0**	55.0
WIL	10.2	**29.6**	9.0	BET	26.8	15.0	**55.8**	BRE	23.0	32.4	**33.8**
POR	9.8	**27.2**	8.4	PAD	25.4	14.4	**49.4**	CRA	-	-	-

Table 10.2: Sample 24 hour rainfall accumulations at each gauge in the three upland study areas during the period between 0000 UTC 1 November 2005 and 0000 UTC 14 November 2005. Values in bold show the largest 24 hour accumulation measured at each gauge during the period.
Event 1 = 0000 UTC 3 November 2005 - 0000 UTC 4 November 2005
Event 2 = 1100 UTC 5 November 2005 – 1100 UTC 6 November 2005
Event 3 = 1900 UTC 7 November 2005 – 1900 UTC 8 November 2005

Several flood watch alerts, listed in Table 10.3, were issued by the Environment Agency during the first part of the month as a result of rainfall in each of the three upland areas of interest.

Exe		Conwy		Taff	
0903 06/11/05 - 1333 06/11/05	Flood Watch	- 0909 09/11/05	Flood Watch	1122 03/11/05 - 1912 03/11/05	Flood Watch
1333 06/11/05 - 0625 07/11/05	Flood Warning			0708 06/11/05 - 1514 06/11/05	Flood Watch
0625 07/11/05 - 1652 07/11/05	Flood Watch				

Table 10.3: List of Environment Agency flood watch and flood warning alerts issued for the Exe, Conwy and Taff river catchments during November 2005.

1-5 November 2005

10.1.1 Synoptic background

Figure 10.2 shows that the period of prolonged rainfall between 1 and 5 November 2005 was associated with the passage of a frontal system and trailing occluded front and troughs from the south-west. This unsettled period was also associated with strong winds, with gusts of 24 ms^{-1} recorded at Aberporth in Ceredigion during the night of 1 November 2005 and 30 ms^{-1} at Mumbles, near Swansea, on 3 November 2005 for example.

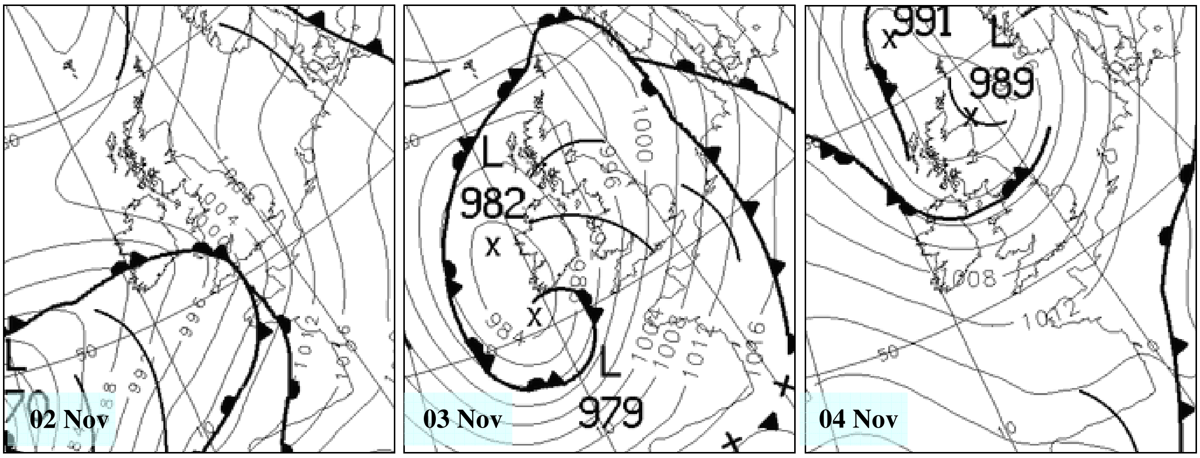


Figure 10.2: Surface pressure analysis charts for 0000 UTC between 2 and 4 November 2005.

10.1.2 Orographic correction

Sample mesoscale model output used to derive the orographic corrections applied to the background radar data during this period are shown in Figure 10.3. Winds were westerly or south-westerly throughout this period. At 1200 UTC on 2 November 2005 the occluded front shown in Figure 10.2 had already crossed Wales and south-west England. Largest orographic corrections of up to 4 mmh^{-1} are shown to be applied across the Upper Taff region at this time due to the moderate winds of up to 30 ms^{-1} predicted. Relative humidity values of up to only 80% imply that no corrections would be applied to any showers detected across the Upper Exe region. The wind strengthened by 1200 UTC on 3 November 2005 when the trailing occluded front brought substantial rainfall to south-west Britain. Figure 10.3 shows that this led to considerable orographic corrections being applied to radar data, particularly across the Upper Conwy region. The subsequent drop of wind speeds to less than 16 ms^{-1} by 1200 UTC on 4 November 2005 led to corrections of only up to 2 mmh^{-1} across western and northern parts of Wales where humidity values in excess of 85% were predicted.

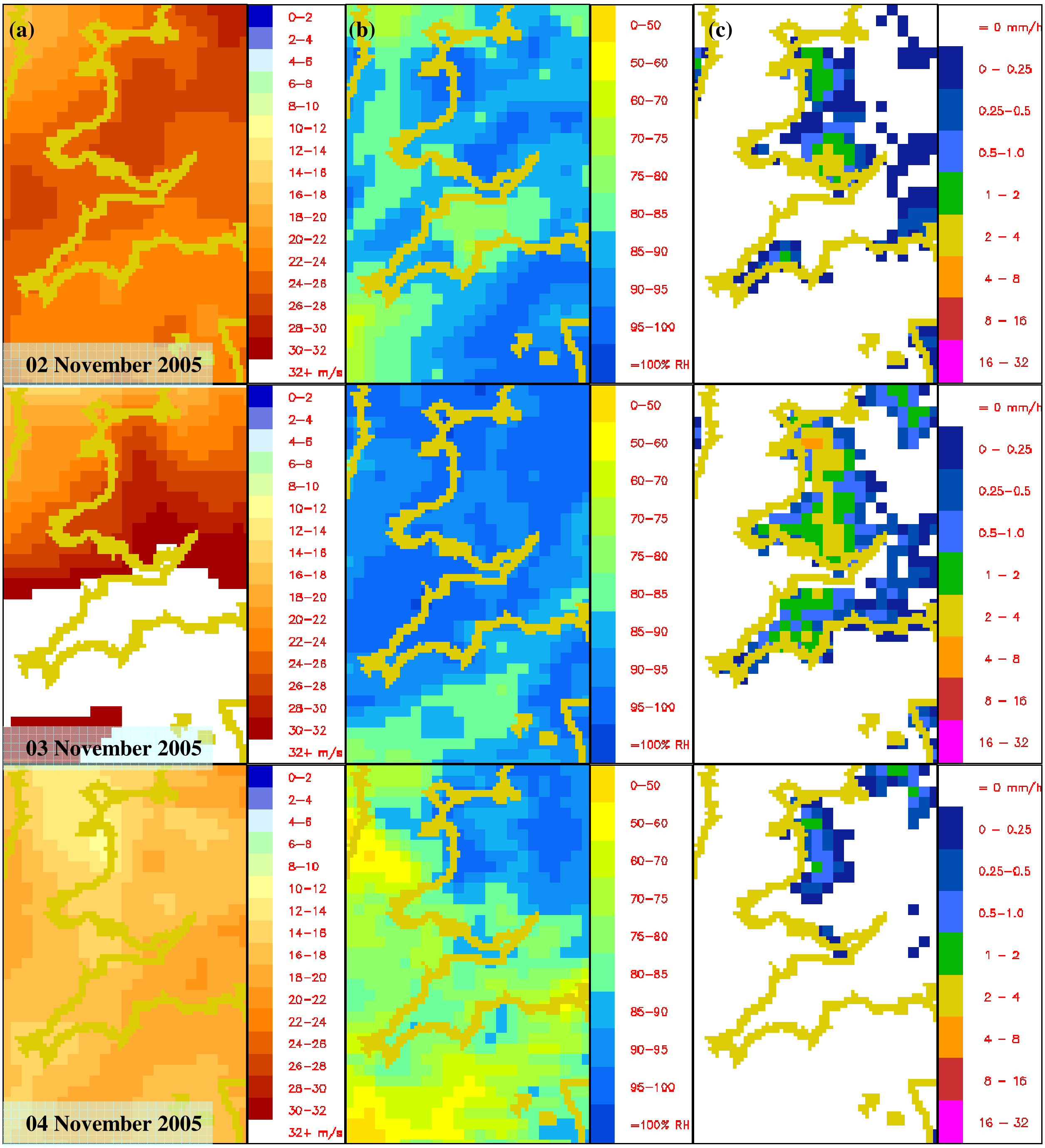


Figure 10.3: Met Office mesoscale model output for 1200 UTC on 2, 3 and 4 November 2005 showing (a) wind speed and (b) relative humidity at 800m used to derive the field of orographic correction factors in (c).

10.1.3 Comparison between radar and gauge accumulations: Upper Conwy

Figure 10.4 shows hourly rainfall accumulations measured by rain gauges across the Upper Conwy region and the corresponding radar data for each gauge location. There is good correspondence between gauge and radar derived rainfall episodes of rainfall during this period of generally intermittent rain. The agreement between radar and gauge measurements shown in Figure 10.4 is illustrated by the correlation plots shown in Figure 10.5.

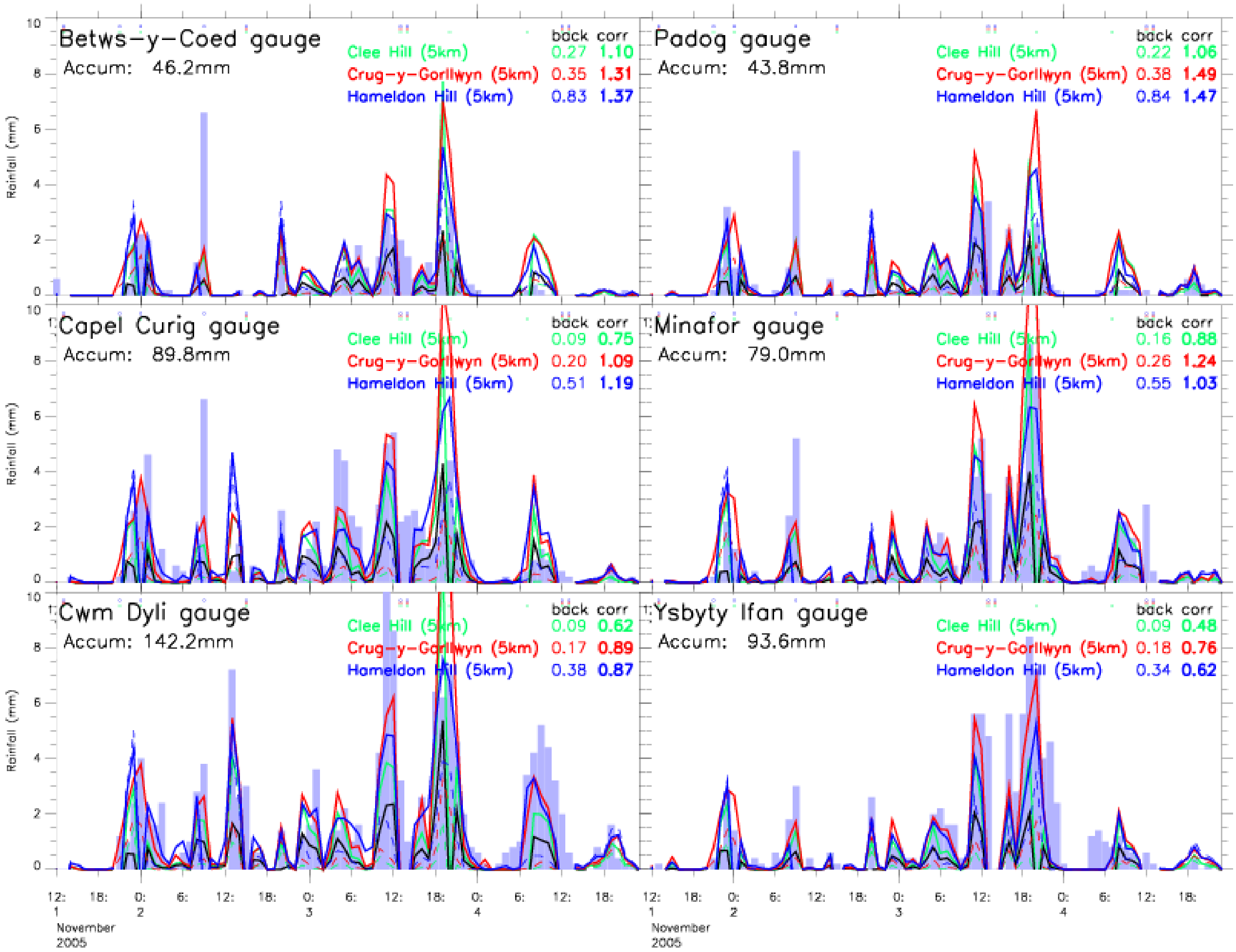


Figure 10.4: Time series of hourly rain gauge measurements (bars) and background (- - - -) and corrected (——) radar measurements for the closest pixel to each gauge site between 1200 UTC on 1 November and 0000 UTC on 5 November 2005. The total rainfall accumulation measured by each gauge during the event is listed along with the ratio of total radar to gauge accumulations for each radar (corrected values are shown in bold). The orographic correction applied to the radar data is plotted in black. Squares show missing periods of radar data.

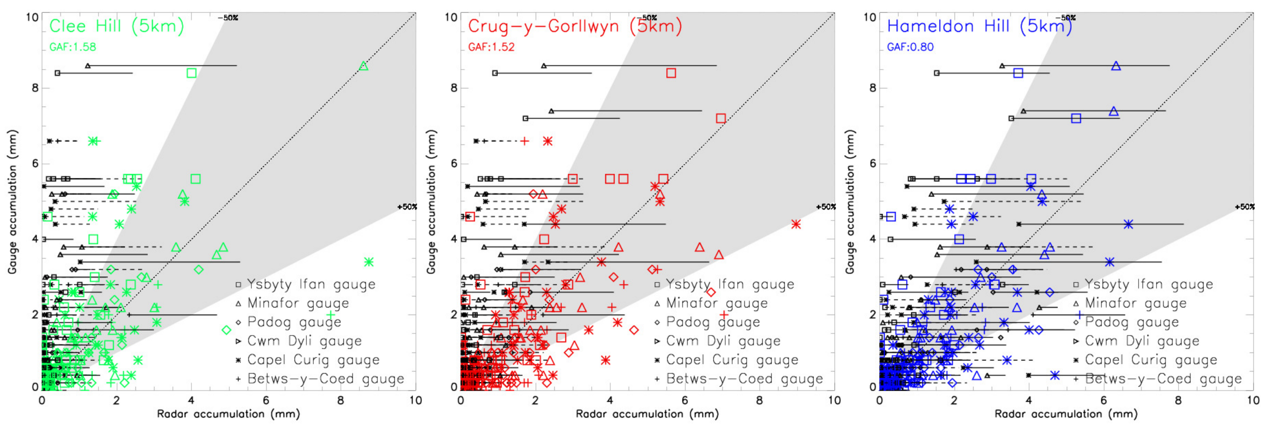


Figure 10.5: Correlation between hourly gauge measurements in the Upper Conwy study area and background (small points) and corrected (large points) radar data from (a) Clee Hill, (b) Crug-y-Gorllwyn and (c) Hameldon Hill between 1200 UTC on 1 November 2005 and 0000 UTC on 5 November 2005. Horizontal lines show the orographic correction.

Most gauge accumulations in excess of 5 mm were underestimated by the radars by typically up to

50% while the radars routinely overestimated gauge accumulations of less than 3 mm. In general, the application of orographic corrections had a beneficial impact of radar accuracy. Background radar rainfall accumulations from Clee Hill remained typically less than 0.5 mm over the entire range of gauge measurements shown.

Significant disagreements between radar and gauge measurements occurred during this period. This is illustrated by the spike in the timeseries in Figure 10.4 at 1900 UTC on 3 November 2005, when the second occluded front crossed the Upper Conwy region from the south-west. Sample radar images at this time are shown in Figure 10.6. Table 10.4 lists background and corrected radar data and the corresponding gauge accumulations at this time. Largest rainfall accumulations occurred towards the south of the study area, suggesting that greatest orographic enhancement took place due to the hills in the Minafor region. Figure 10.7 shows the distribution of rainfall accumulations measured by the Clee Hill and Crug-y-Gorllwyn radars during 3 November 2005, which illustrate how largest corrections were actually applied in the west of the region in the lee of Snowdon. Table 10.4 shows excellent agreement between the Clee Hill radar and Minafor gauge measurement after a correction of about 4 mmh^{-1} was applied. The larger corrections of over 5mmh^{-1} applied to data in the west of the region, combined with the influence of the gauge adjustment scaling, led to a large overestimate by a factor of over two of the surface measured rainfall at Cwm Dyli for example. The reason for the discrepancy between the distribution of orographic enhancement observed and that predicted by the operational correction scheme is currently unclear. This could possibly be related to the predicted model winds and relative humidity being unrealistically high at this time.

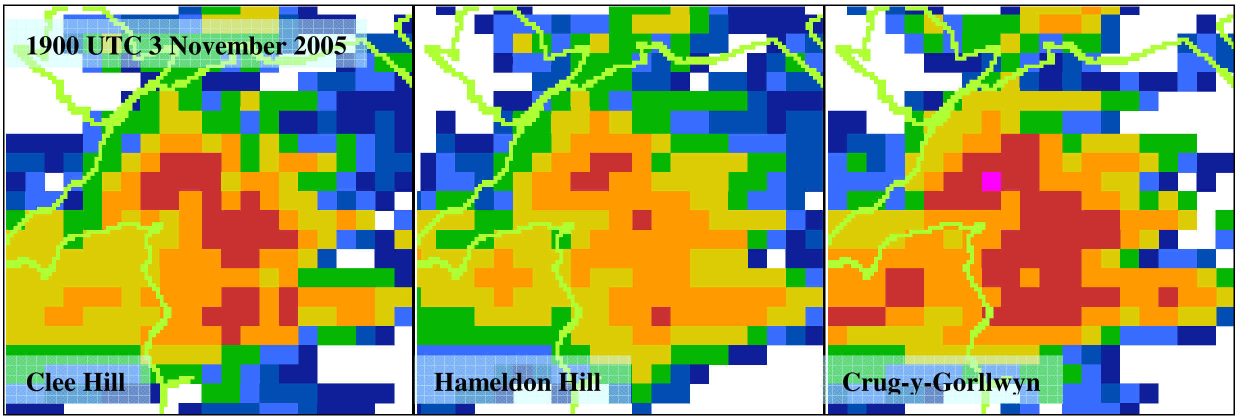


Figure 10.6: Comparison of 5 km radar images showing rainfall across the Upper Conwy study area at 1900 UTC on 3 November 2005.

Gauge		Clee Hill			Crug-y-Gorllwyn			Hameldon Hill		
		B	B+O	C	B	B+O	C	B	B+O	C
Minafor	8.6 mm	1.21	5.21	8.60	2.22	6.85	11.0	3.27	7.76	6.32
Ysbyty Ifan	8.4 mm	0.41	2.42	4.00	0.91	3.50	5.63	1.52	4.54	3.70
Cwm Dyli	6.2 mm	1.74	7.11	11.7	3.23	8.81	14.2	3.89	9.30	7.58
Capel Curig	3.4 mm	1.02	5.30	8.74	2.32	6.64	10.7	2.58	7.54	6.15
Betws-y-C	2.0 mm	2.33	4.68	7.72	2.19	4.38	7.04	4.10	6.56	5.35
Padog	1.6 mm	0.95	2.99	4.93	0.79	2.88	4.63	2.60	5.22	4.26

Table 10.4: Comparison between background (B), background+orog (B+O) and corrected (C) radar hourly rainfall accumulations between 1900 and 2000 UTC on 3 November 2005 and gauge measured hourly accumulations in the Upper Conwy region.

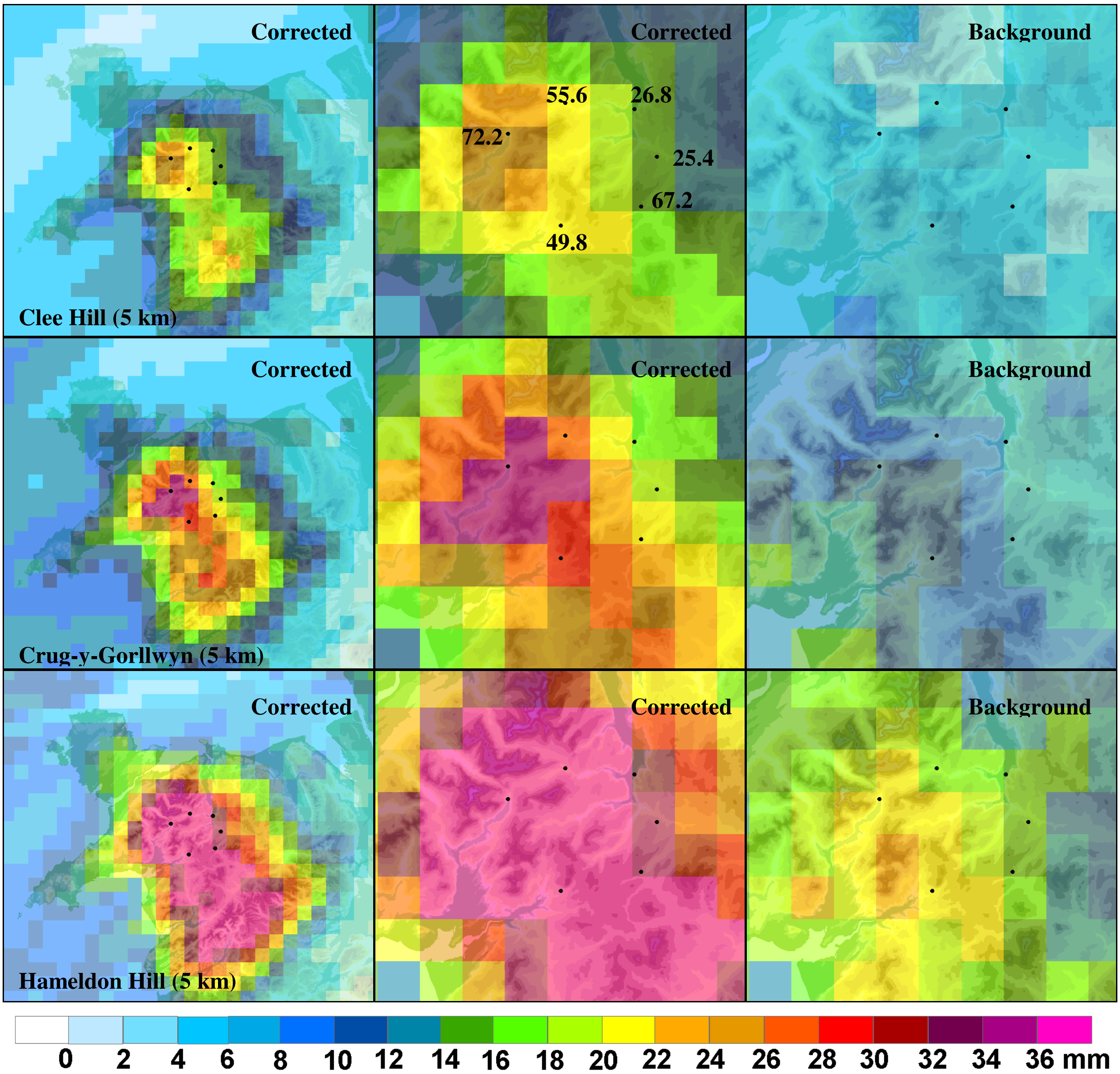


Figure 10.7: Comparison of 24 hour rainfall accumulations from each available radar across the Upper Conwy region on 3 November 2005. Black circles indicate rain gauge locations with labels showing the corresponding rain gauge accumulation over the same period in mm.

10.1.4 Comparison between radar and gauge accumulations: Upper Taff

Figures 10.8 and 10.9 illustrate the rainfall data measured across the Upper Taff region between 1200 UTC on 1 November 2005 and 0000 UTC on 5 November 2005. These show a systematic underestimation of the surface measured rainfall by up to 50% across the entire region. Best agreement between the radar and gauge rainfall values occurred between 0300 UTC and 0600 UTC on 3 November 2005 when the rain associated with the occluded front first arrived. Radar data quality sharply decreased following this period however, particularly at those sites most affected by orographic enhancement at Llyn Y Fan, Storey Arms and Ystradfellte. Figure 10.8 shows that the orographic correction applied to background radar data at this time was a factor of two smaller than that applied when the rain first arrived and radar data were in reasonable agreement with gauge measurements. This was clearly insufficient to account for the continued enhancement observed at the surface. Figure 10.8 also suggests that the contrast in data quality during this period may be associated with a change in the vertical structure of the rain band, since by 0600 UTC Figure 10.8 shows the radar data at long range from Chenies completely missed the rain. This implies that the rainfall was a low-level feature confined to below about 1500 m above the surface.

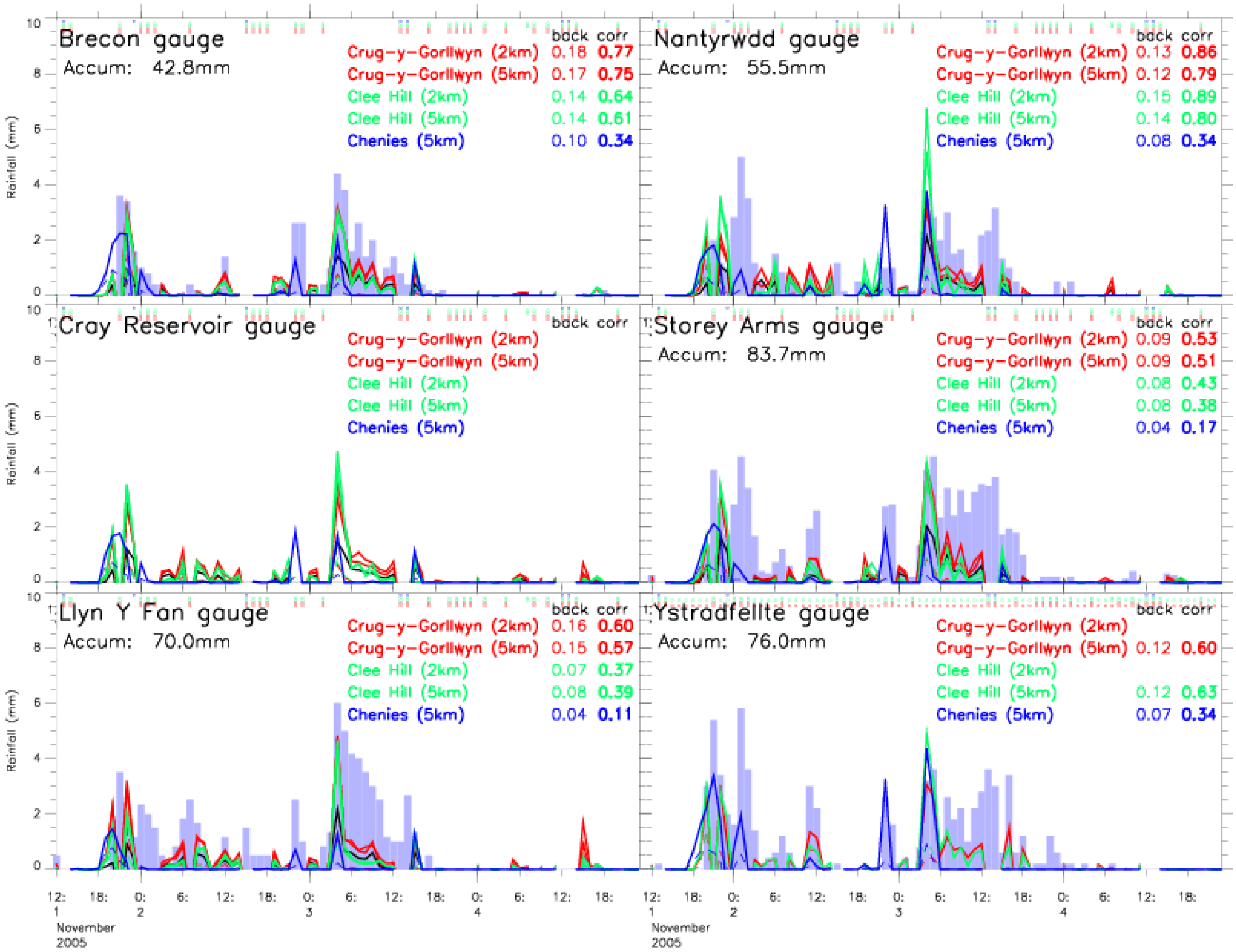


Figure 10.8: Time series of hourly rain gauge measurements (bars) and background (- - - -) and corrected (——) radar measurements for the closest pixel to each gauge site between 1200 UTC on 1 November and 0000 UTC on 5 November 2005. All other details are as in Figure 10.4.

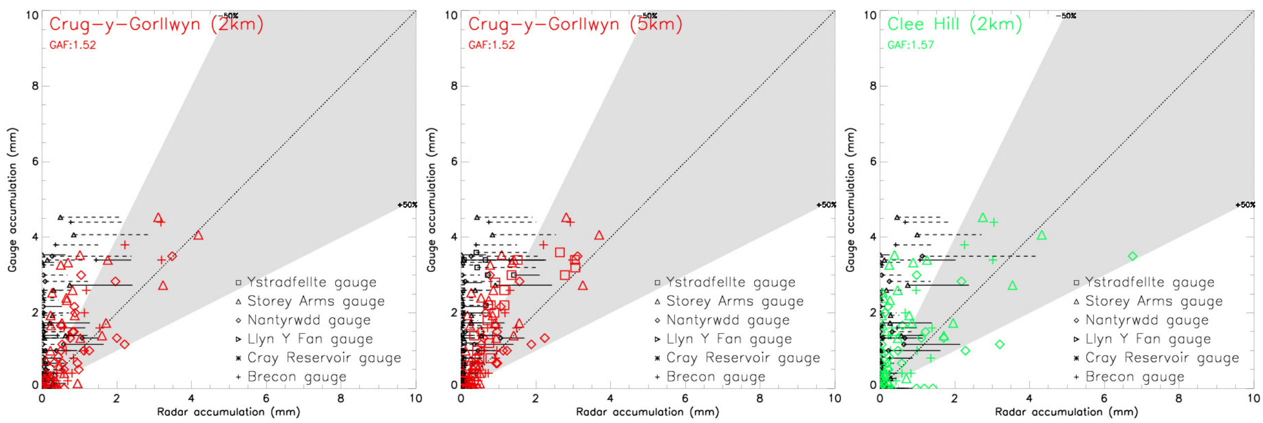


Figure 10.9: Correlation between hourly gauge measurements in the Upper Taff study area and background (small points) and corrected (large points) radar data between 1200 UTC on 1 November 2005 and 0000 UTC on 5 November 2005. Horizontal lines show the orographic correction applied to background radar data.

Figure 10.10 shows the distribution of radar-derived daily rainfall accumulations during 3 November 2005, illustrating that largest orographic corrections were applied to the south and east of the study area on this day.

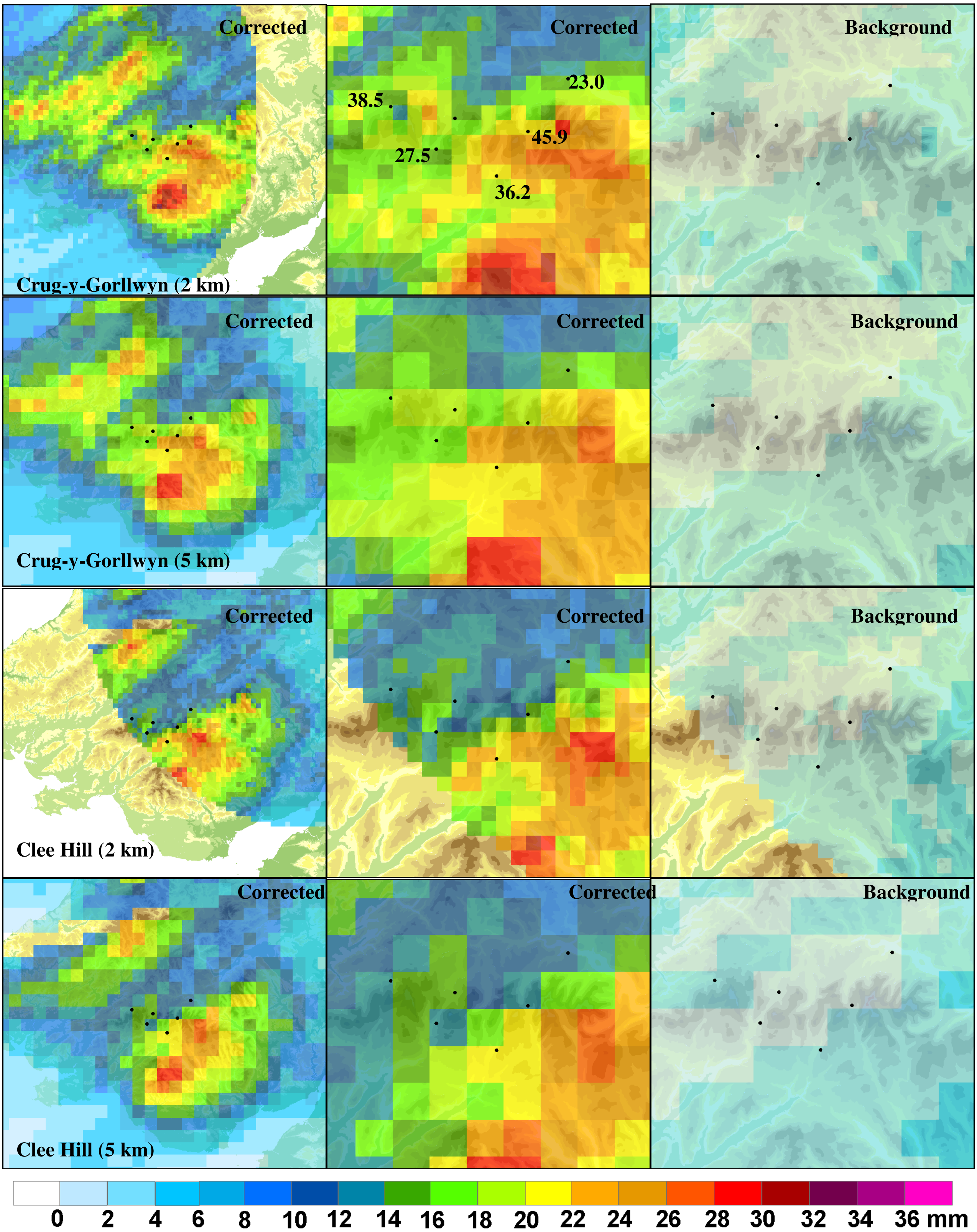


Figure 10.10: Comparison of 24 hour corrected rainfall accumulations from Crug-y-Gorllwyn and Clee Hill radars across the Upper Taff region on 3 November 2005. Black circles indicate rain gauge locations with labels showing the corresponding rain gauge accumulation over the same period in mm.

10.1.5 Comparison between radar and gauge accumulations: Upper Exe

Figure 10.11 shows timeseries of hourly gauge and radar rainfall accumulations at each gauge site across the Upper Exe study area between 1200 UTC 1 November 2005 and 0000 UTC 5 November 2005. Figure 10.12 shows the correlation between radar and gauge hourly rainfall accumulations during the period shown in Figure 10.11. The ratios of total radar to gauge rainfall accumulations listed in Figure 10.11 provide a summary of radar performance and show that,

- Radars generally underestimated the measured surface rainfall, by as much as 72% for Crug-y-Gorllwyn data at Oareford.
- Orographic corrections improved the agreement between gauge and radar accumulations, typically reducing the difference between background radar and gauge values by 20%.
- Best agreement between gauge and radar occurred for Cobbacombe Cross data, worst for Clee Hill radar data.

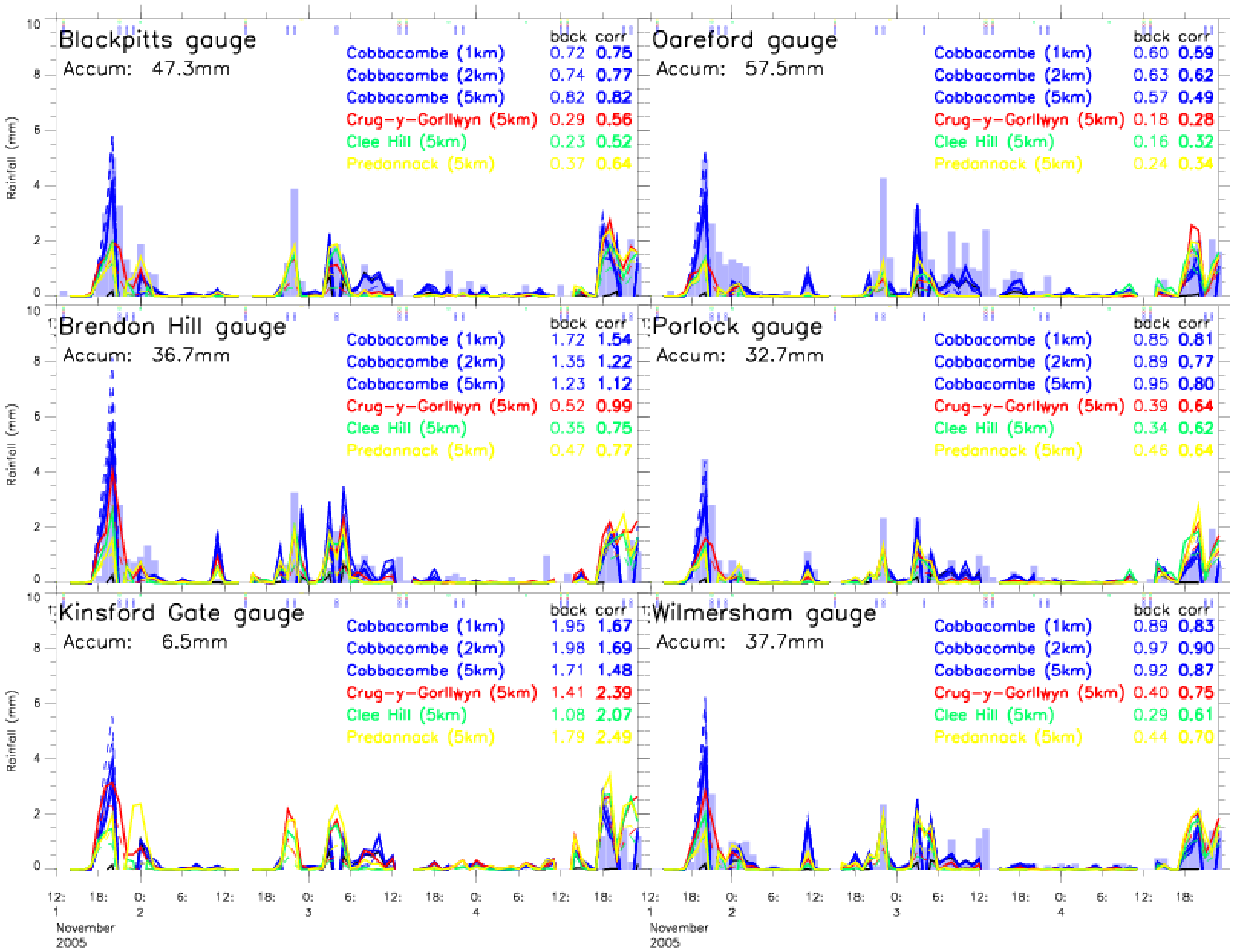


Figure 10.11: Time series of hourly rain gauge measurements (bars) and background (- - - -) and corrected (——) radar measurements for the closest pixel to each gauge site between 1200 UTC on 1 November and 0000 UTC on 5 November 2005. The total rainfall accumulation measured by each gauge during the event is listed along with the ratio of total radar to gauge accumulations for each radar (corrected values are shown in bold). The orographic correction applied to the radar data is plotted in black. Squares show missing periods of radar data.

The benefit of using radar data from close range is clearly illustrated in Figure 10.12 which shows good agreement between gauge and radar data from Cobbacombe Cross over the entire rainfall range. This is largely due to the lack of orographic corrections applied at times during this period.

In contrast, rainfall accumulations from Crug-y-Gorllwyn, Clee Hill and Predannack were up to 80% less than the corresponding gauge measurements. Figure 10.11 shows that this was a particular feature during the afternoon of 1 November 2005 when the first occluded front crossed the region. Sample radar images from Cobbacombe Cross at 1, 2 and 5 km horizontal resolution during this period are shown in Figure 10.13. There is little difference between the level of agreement between the gauges and radar data at each resolution. Images from all available radars across the region are shown in Figure 10.14. Table 10.5 lists the hourly radar and gauge rainfall at this time.

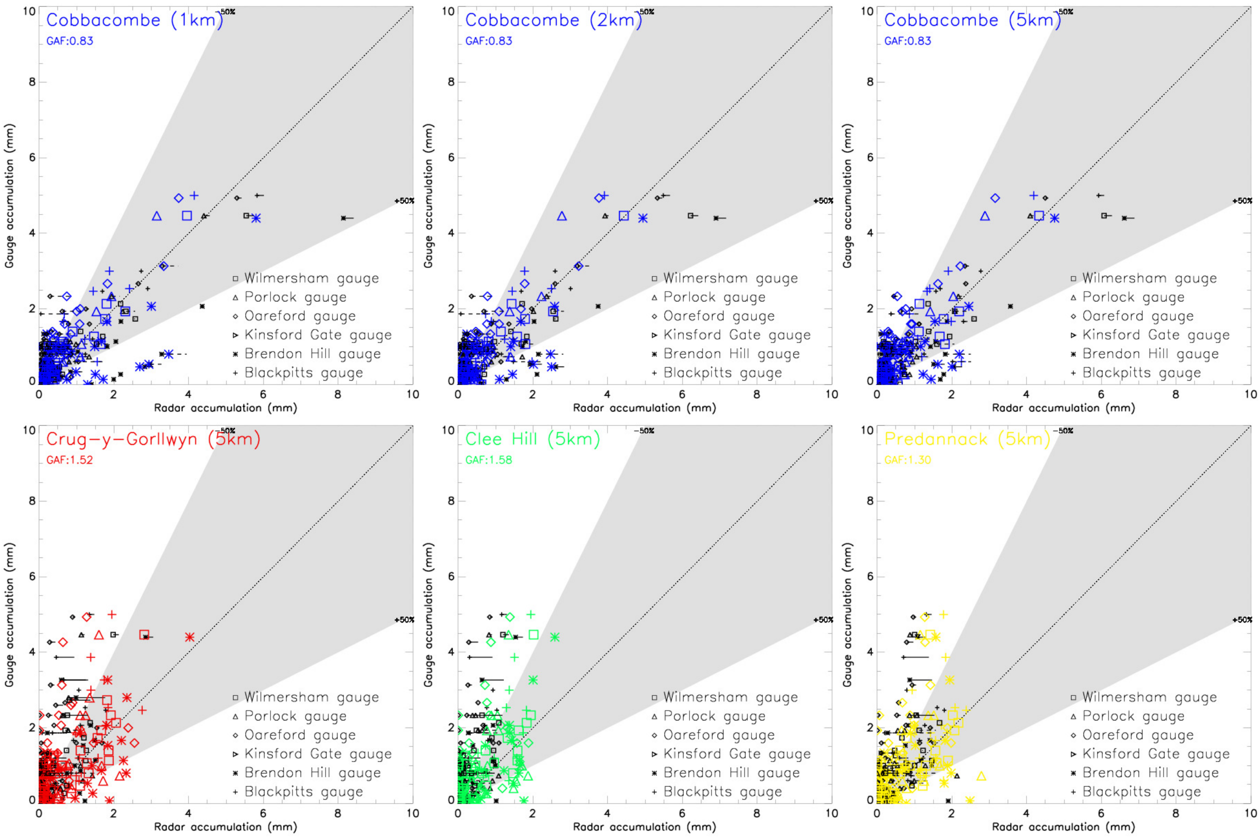


Figure 10.12: Correlation between hourly gauge measurements in the Upper Exe study area and background (small points) and corrected (large points) radar data between 1200 UTC on 1 November 2005 and 0000 UTC on 5 November 2005. Horizontal lines show the orographic correction applied to background radar data.

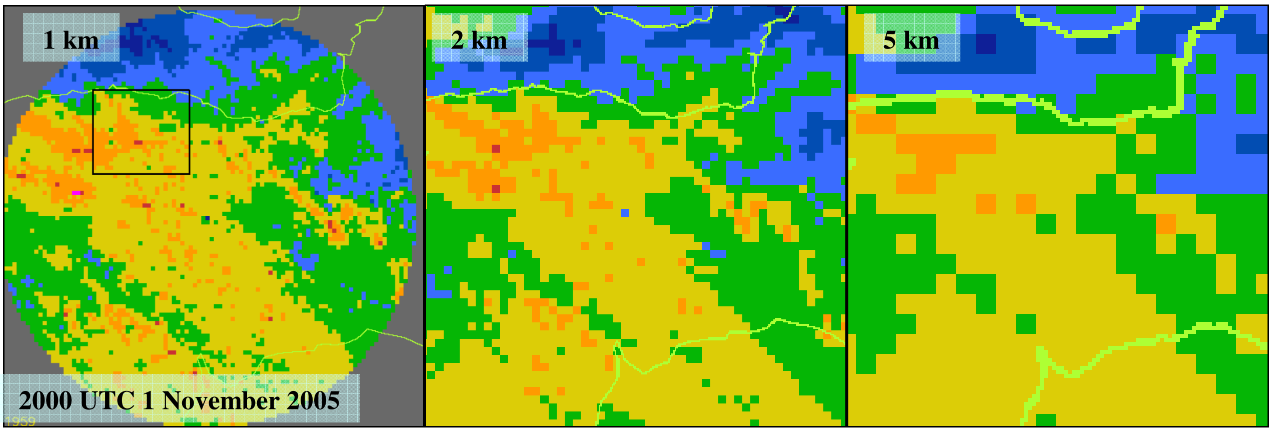


Figure 10.13: Comparison of 1, 2 and 5 km data from Cobbacombe Cross at 2000 UTC on 1 November 2005.

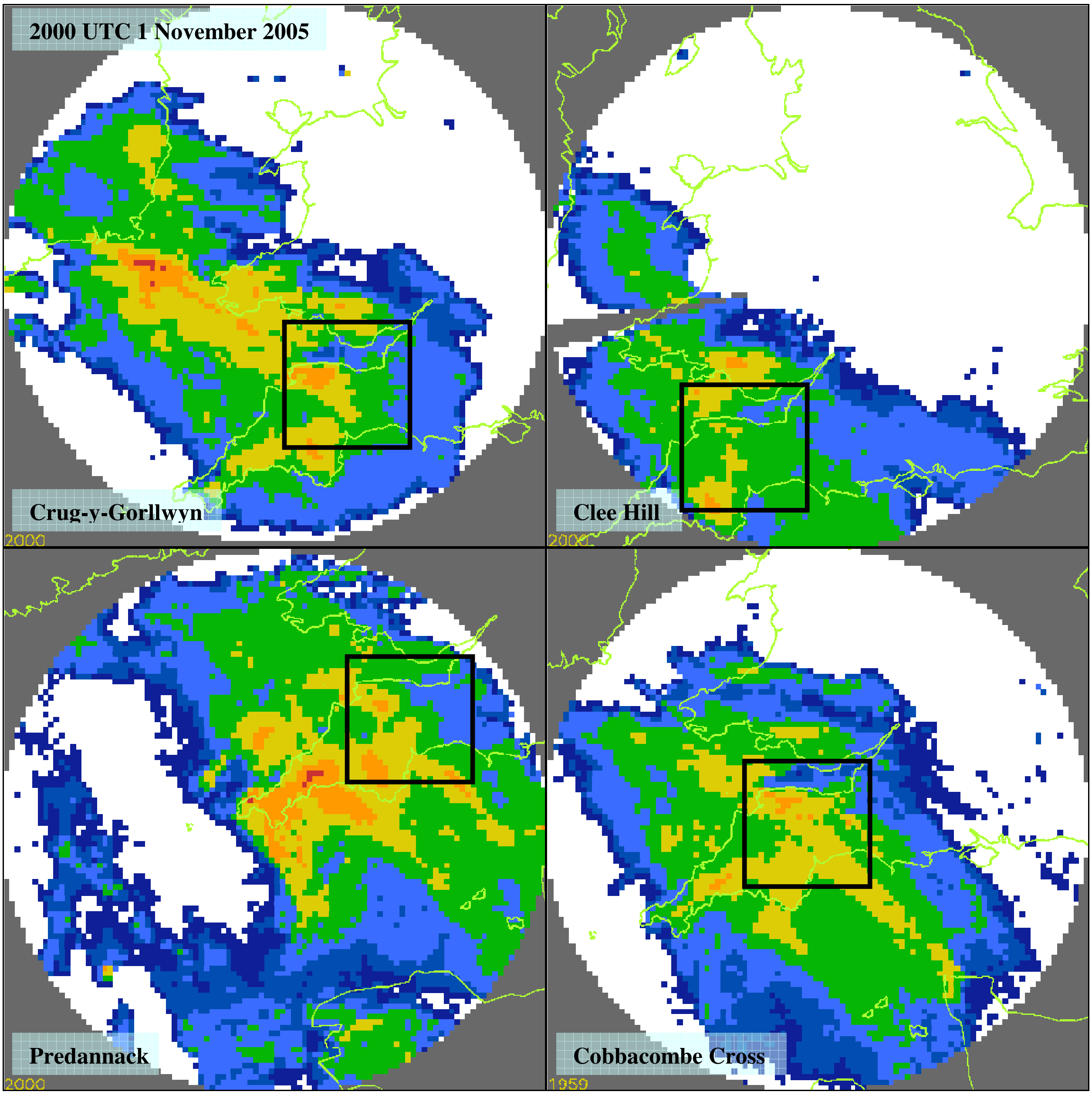


Figure 10.14: Comparison of 5 km radar data at 2000 UTC on 1 November 2005. The region of interest surrounding the Upper Exe area is highlighted by the black square in each image.

Gauge		CC (1 km)		CC (2 km)		CC (5 km)		Clee Hill		Crug-y-G		Pred.	
		back	corr	back	corr	back	corr	back	corr	back	corr	back	corr
BLA	5.00 mm	5.82	4.15	5.48	3.91	5.92	4.19	1.16	1.94	1.34	1.95	1.31	1.77
BRE	4.40 mm	8.14	5.80	6.90	4.94	6.61	4.75	1.53	2.59	2.85	4.03	1.08	1.57
KIN	-	4.13	2.95	4.73	3.38	5.52	3.91	0.88	1.46	2.27	3.12	1.50	1.98
OAR	4.93 mm	5.29	3.73	5.33	3.77	4.50	3.16	0.84	1.38	0.89	1.29	0.96	1.27
POR	4.47 mm	4.41	3.14	3.93	2.77	4.09	2.88	0.82	1.35	1.12	1.60	0.88	1.15
WIL	4.47 mm	5.54	3.95	6.22	4.43	6.07	4.34	1.19	2.02	1.98	2.81	1.00	1.42

Table 10.5: Comparison between background and corrected radar hourly rainfall accumulations between 2000 and 2100 UTC on 1 November 2005 and gauge measured hourly accumulations in the Upper Exe region.

Figure 10.11 also shows considerably better agreement between gauge data with Cobbacombe Cross radar data than with other available radars during the morning of 3 November 2005 when the trailing occluded front crossed the region. Sample radar images at this time are shown in Figure 10.15. The corresponding radar and gauge accumulations are listed in Table 10.6. While the Cobbacombe Cross radar data showed reasonable agreement with gauge measurements at most sites, but underestimated values at Oareford by up to 50%, the other available radars all detected very light or no rainfall. This is thought to be because the rainfall was a low-level feature below the beam height at the range of the other radars.

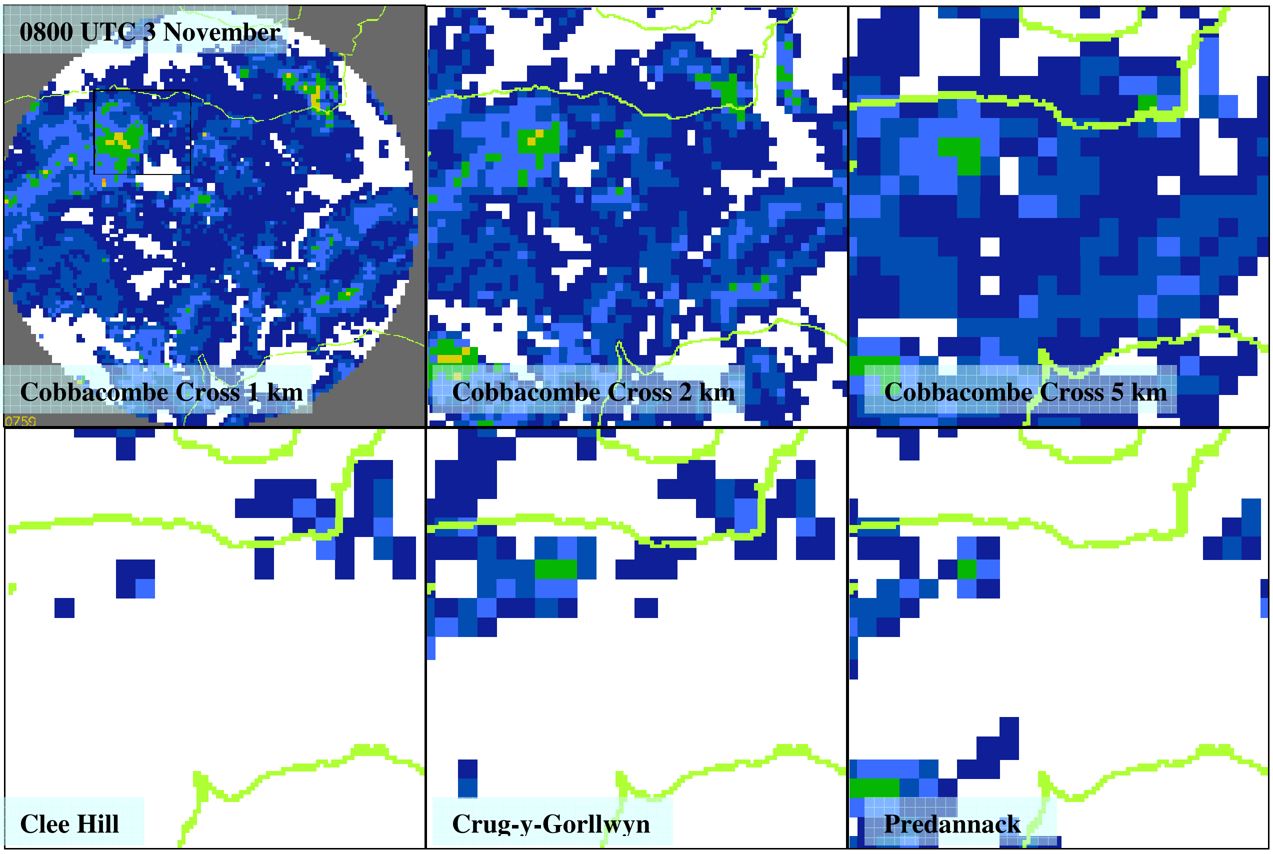


Figure 10.15: Comparison of radar data across the Upper Exe region at 0800 UTC on 3 November 2005.

Gauge		CC (1 km)		CC (2 km)		CC (5 km)		Clee Hill		Crug-y-G		Pred.	
		back	corr	back	corr	back	corr	back	corr	back	corr	back	corr
BLA	1.13 mm	0.10	0.77	0.15	0.77	0.22	0.77	0.00	0.05	0.02	0.21	0.03	0.22
BRE	1.00 mm	0.50	0.77	0.19	0.50	0.11	0.42	0.00	0.00	0.00	0.23	0.00	0.00
KIN	-	0.06	0.52	0.11	0.58	0.15	0.73	0.00	0.09	0.04	0.68	0.03	0.35
OAR	2.33 mm	0.29	0.73	0.36	0.78	0.44	0.54	0.00	0.00	0.00	0.01	0.02	0.05
POR	0.80 mm	0.31	0.56	0.35	0.44	0.38	0.44	0.00	0.04	0.02	0.15	0.00	0.01
WIL	1.07 mm	0.26	0.57	0.22	0.53	0.18	0.56	0.00	0.01	0.00	0.26	0.00	0.01

Table 10.6: Comparison between background and corrected radar hourly rainfall accumulations between 0800 and 0900 UTC on 3 November 2005 and gauge measured hourly accumulations in the Upper Exe region.

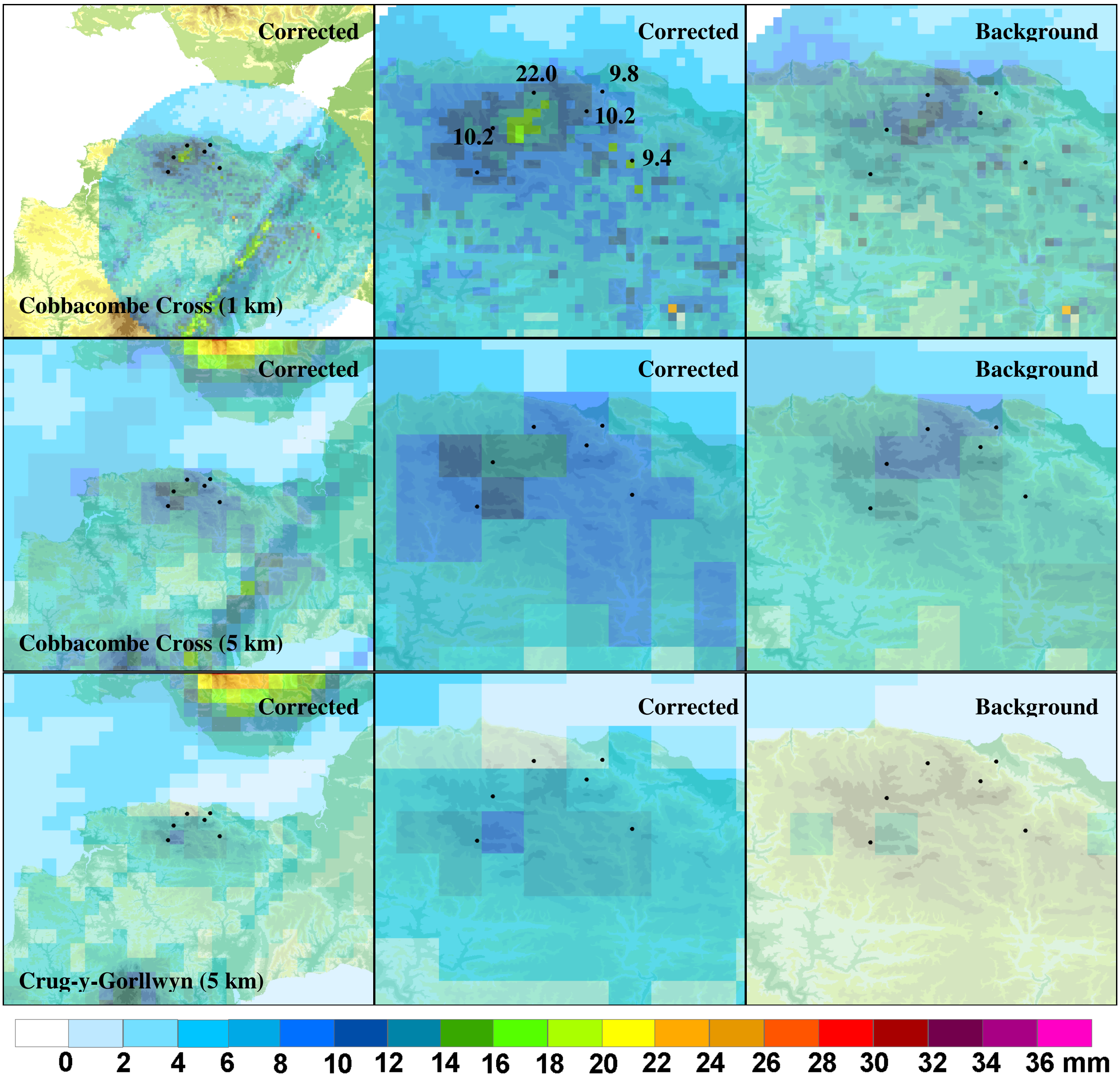


Figure 10.16: Comparison of 24 hour corrected rainfall accumulations from a selection of available radars across the Upper Exe region on 3 November 2005. Black circles indicate rain gauge locations with labels showing the corresponding rain gauge accumulation over the same period in mm.

5-7 November 2005

10.2.1 Synoptic background

Figure 10.16 shows how the rainfall measured in each of the three upland regions of interest between about 1200 UTC on 5 November 2005 and 1200 UTC on 6 November 2005 was associated with the passage of a warm front and very slowly moving cold front which was closely followed by a second frontal system in a region of deepening pressure. The second system became occluded by the time it reaches the British Isles. This period was notably windy, with gusts of up to 26 ms^{-1} recorded at Capel Curig in the Upper Conwy region.

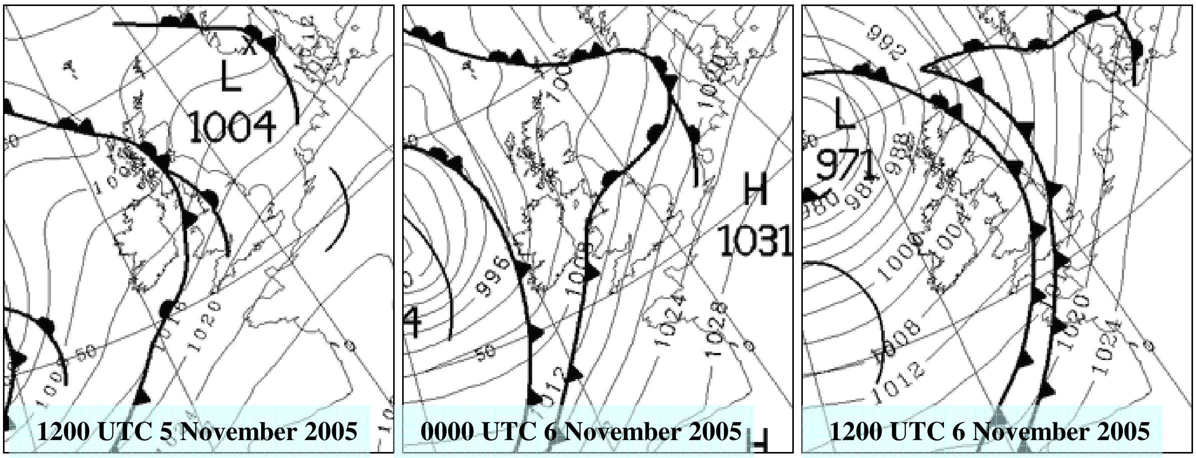


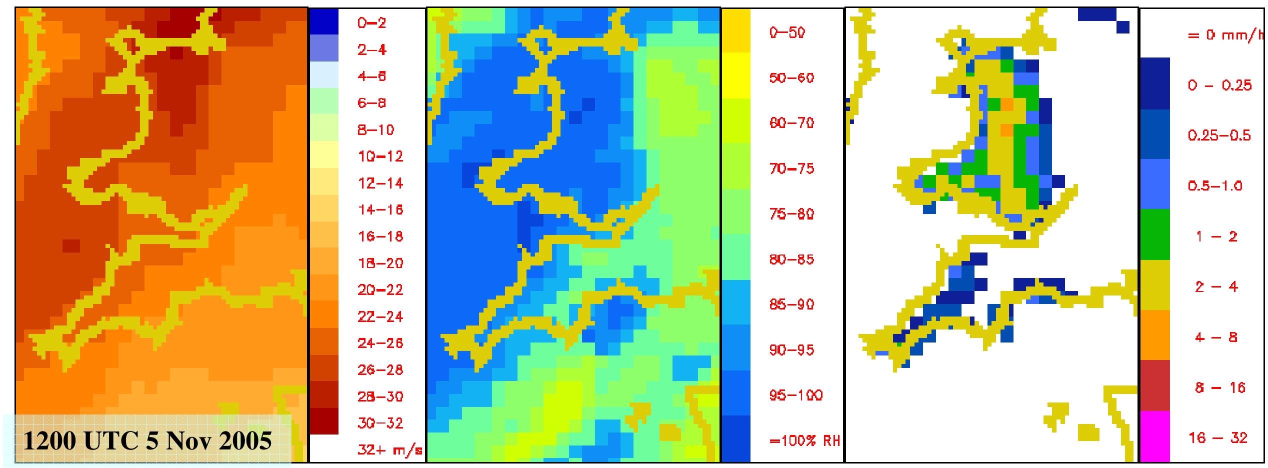
Figure 10.16: Surface pressure analysis charts on 5 and 6 November 2005.

10.2.2 Orographic correction

The orographic correction fields shown in Figure 10.17 remain reasonably steady across Wales over a 12 hour period during the period of rainfall. Corrections typically of up to 4 mmh^{-1} would be applied to the background radar data as a result of south-westerly winds of moderate strength and relative humidity values remaining in excess of 95%. By 1200 UTC on 6 November 2005 the model output showed relative humidity values of less than 80% across all of Wales and south-west England, implying that no orographic corrections would be applied to any radar-derived rainfall data at this time.

10.2.3 Data availability

Unfortunately, no radar data could be archived between 1400 UTC 5 November 2005 and 1100 UTC 7 November 2005 as a result of a data overload on the Radarnet operational processing system. Although radar products continued to be output on an operational basis as normal, no subsequent analysis of archived data from this period is possible.



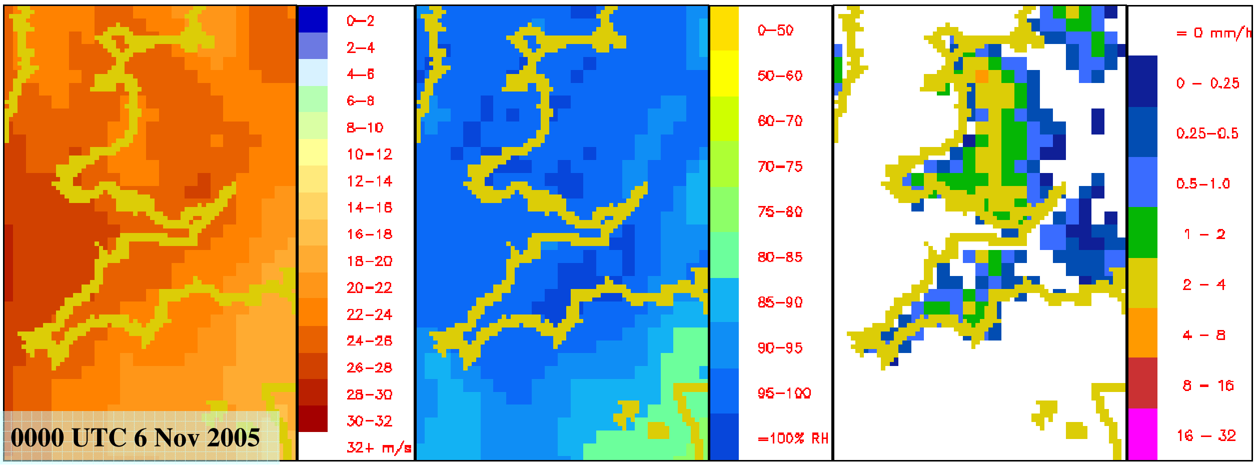


Figure 1.17: Met Office mesoscale model output for 1200 UTC on 5 November 2005 and 0000 UTC on 6 November 2005 showing (a) wind speed and (b) relative humidity at 800m used to derive the field of orographic correction factors in (c).

7-8 November 2005

10.3.1 Synoptic background

The rainfall on 8 November 2005 was brought by an Atlantic frontal system associated with a particularly intense region of low pressure to the north west of Scotland, illustrated in Figure 10.18.

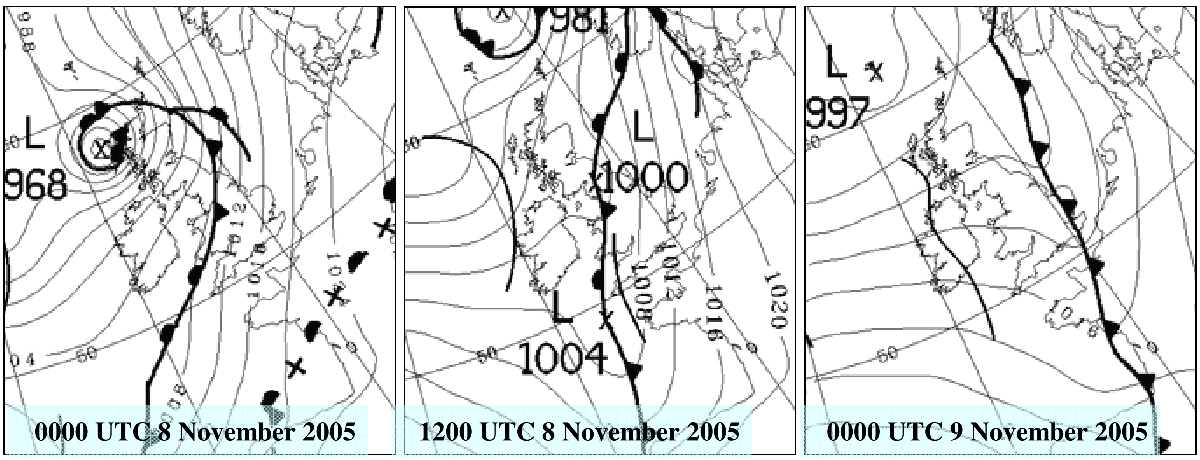


Figure 10.18: Surface pressure analysis charts during 8 November 2005.

Violent storm force winds were measured in the region. As the centre of the low pressure region tracked north-eastwards during 8 November 2005 the trailing front remained approximately stationary across Wales and northern England to bring persistent, sometimes heavy and thundery rain to these parts.

10.3.2 Orographic corrections

Figure 10.19 shows sample mesoscale model output during 8 November 2005. These illustrate weakening wind strength, and correspondingly weakening orographic corrections across each of the upland regions of interest during the event. Winds remained south-westerly during this period.

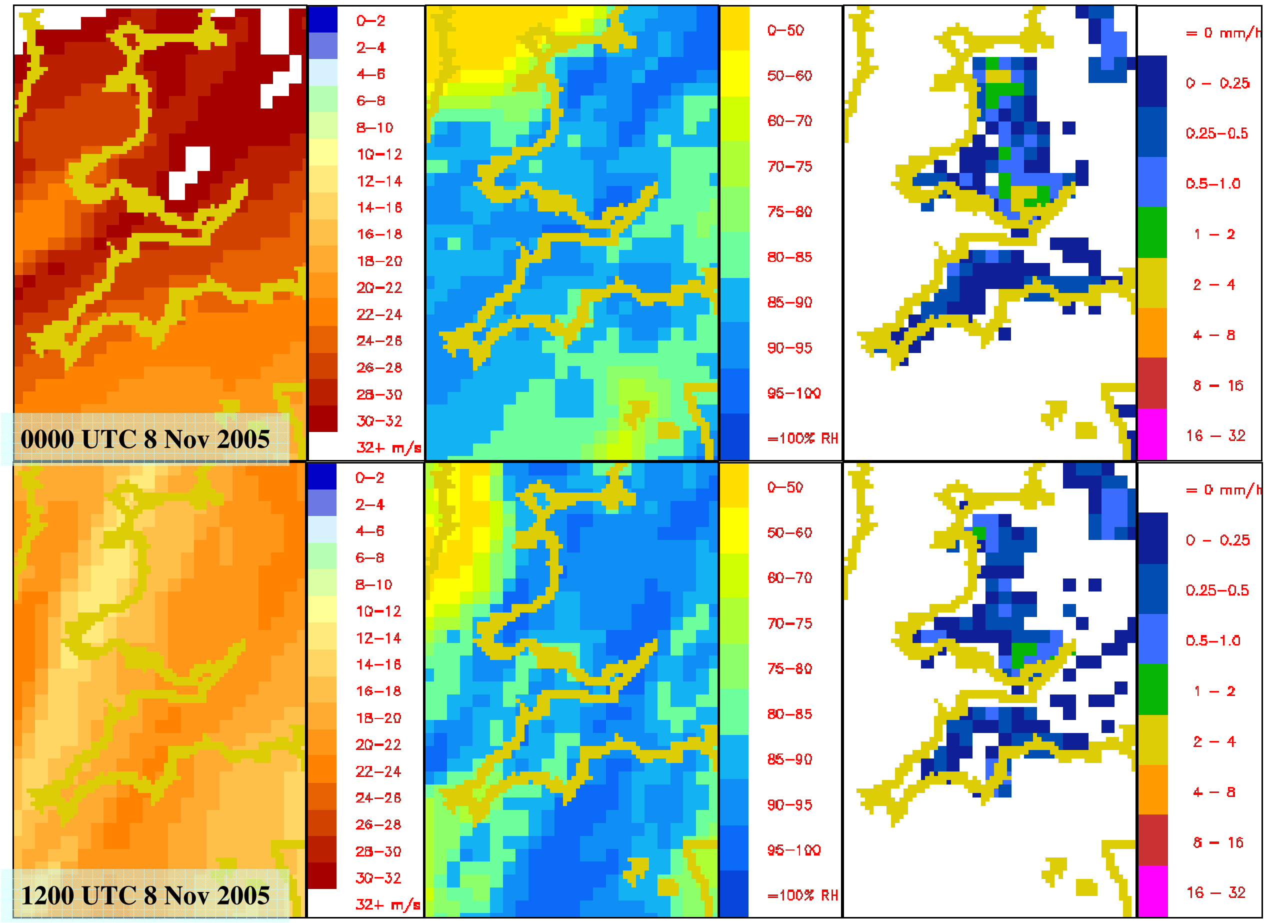


Figure 1.19: Met Office mesoscale model output for 0000 UTC and 1200 UTC on 8 November 2005 showing (a) wind speed and (b) relative humidity at 800m used to derive the field of orographic correction factors in (c).

10.3.3 Comparison between radar and gauge accumulations: Upper Conwy

Figure 10.20 shows timeseries of gauge and radar rainfall measurements across the Upper Conwy study area between 1200 UTC 7 November 2005 and 0000 9 November 2005. The gauge and radar timeseries at Padog, Minafor and Ysbyty Ifan are qualitatively similar during the event, characterised by persistent but generally light rain. In contrast, the timeseries at Betws-y-Coed, Capel Curig and Cwm Dyli display much greater temporal variation with intense rainfall spikes occurring intermittently. The rain gauge measurements are consistent with lighter more persistent rain to the south of the region where the orography is most uniform and heavier more intensive rainfall to the north and west of the region where the terrain is steepest. The high rainfall accumulation characterised by intense periods of rain measured at Cwm Dyli and Capel Curig sites are perhaps a result of low-level clouds developing within the deep valleys in the lee of Snowdon and the Glyder range which facilitate considerable intensification of the upper-level frontal rain, which itself may have been enhanced by clouds forming over the mountains themselves.

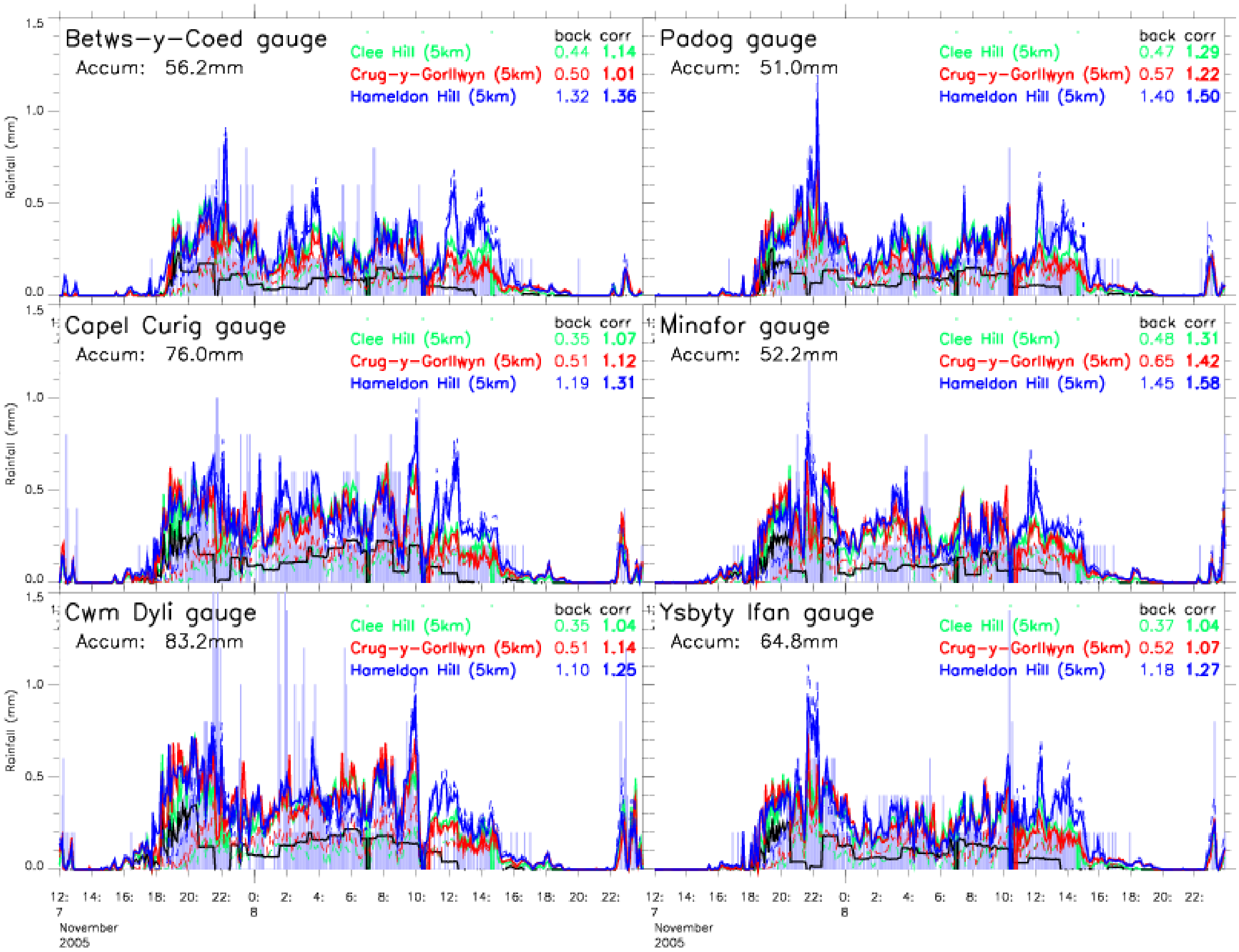


Figure 10.20: Time series of 5 minute rain gauge measurements (bars) and background (- - - -) and corrected (—) radar data for the closest pixel to each gauge site on 7 and 8 November 2005. The total rainfall accumulation measured by each gauge during the event is listed along with ratios of radar to gauge accumulations. The orographic correction applied to the radar data is plotted in black.

The ratios of total radar to gauge rainfall accumulation during this event, listed in Figure 10.20, show that,

- Corrected radar estimates slightly overestimated the gauge measured rainfall at all sites except Minafor where an overestimation of up to 50% occurred.
- Orographic corrections improved the accuracy of radar measurements, removing the initial underestimate of rainfall totals by background radar data.
- Best quantitative agreement with gauge measurements generally occurred with Clee Hill radar data and worst agreement was consistently with Hameldon Hill data.

This simple measure clearly does not reflect the overall radar performance. In particular, the radars failed to capture the intensive periods of rainfall measured at Cwm Dyli, Capel Curig and Betws-y-Coed sites, perhaps because the 5 km horizontal resolution was insufficient to detect small-scale rainfall or terrain features. This failing is reflected by the comparison between radar and gauge hourly accumulations plotted in Figure 10.21. The generally good agreement between the radar and gauge total rainfall for this event is a result of a systematic overestimate of the lighter rainfall combined with a similar underestimate during periods of intensive rain. Figure 10.20 shows particular benefit of applying the orographic corrections to provide closer agreement with gauge measurements during the afternoon of 7 November when the rain first arrived across the region.

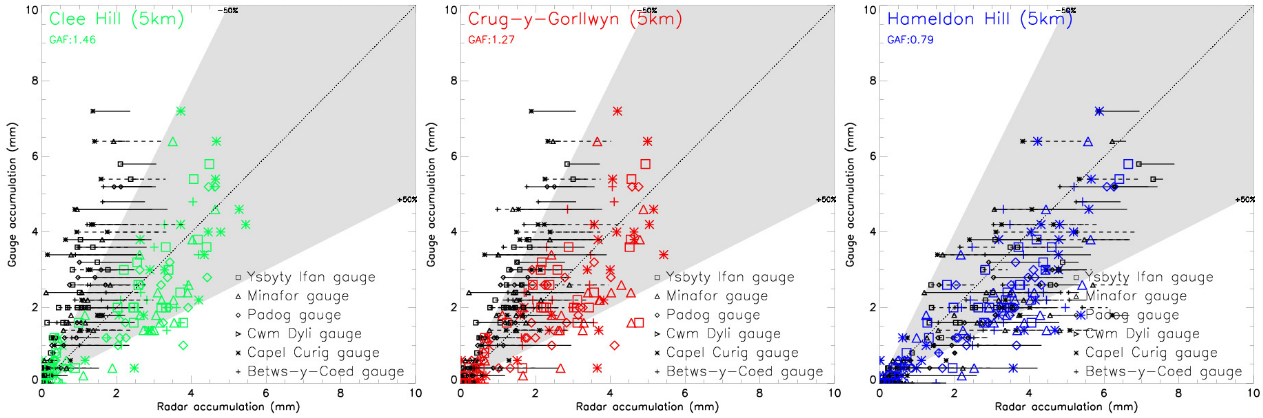


Figure 10.21: Correlation between hourly gauge measurements in the Upper Conwy area and background (small points) and corrected (large points) radar data from (a) Clee Hill, (b) Crug-y-Gorllwyn and (c) Hameldon Hill during 7 and 8 November 2005. Horizontal lines show the orographic correction applied to background radar data. Data measured during morning are connected with dashed lines.

The variation of background radar rainfall estimates plotted in Figure 10.21 is particularly interesting. Relatively poor radar performance by Hameldon Hill can be partly attributed to background rainfall values in excess of gauge measured rainfall during periods of lighter rain, which were increased further by the application of orographic corrections. The variation of background values for this radar is also considerably greater than that found for measurements from Clee Hill and Crug-y-Gorllwyn. In these cases background rainfall values show very little variation over the range of gauge measurements. As such, the orographic corrections applied to these data proved sufficient to overestimate lighter rainfall measurements while insufficient to completely correct rainfall estimates for heavier rain.

10.3.4 Comparison between radar and gauge accumulations: Upper Taff

Figure 10.22 shows timeseries of rainfall measurements across the Upper Taff region between 1200 UTC 7 November 2005 and 0000 UTC 9 November 2005. In contrast to the Upper Conwy data, Figure 10.22 shows two distinct rainfall episodes associated with the same stationary front.

Correlation plots comparing hourly rainfall accumulations measured by the radars and gauges during this period are shown in Figure 10.23. This highlights particularly poor radar performance observed across the Upper Taff region at this time. Largest corrected rainfall estimates at most gauges occurred during the first episode of rain on 7 November 2005, when available rain gauges measured generally low hourly rainfall accumulations of less that 2 mm. Figure 10.22 shows particularly poor radar performance by Clee Hill at Nantyrwdd at this time. It is thought that this rainfall was mostly confined to lower levels, since the rain band was completely missed by Chenies radar and background rainfall values from Crug-y-Gorllwyn and Clee Hill were almost zero at this time. The corrected radar rainfall data were therefore highly sensitive to the magnitude of the orographic correction applied, which varied on a 5 minute timescale. This was clearly inappropriate in this case.

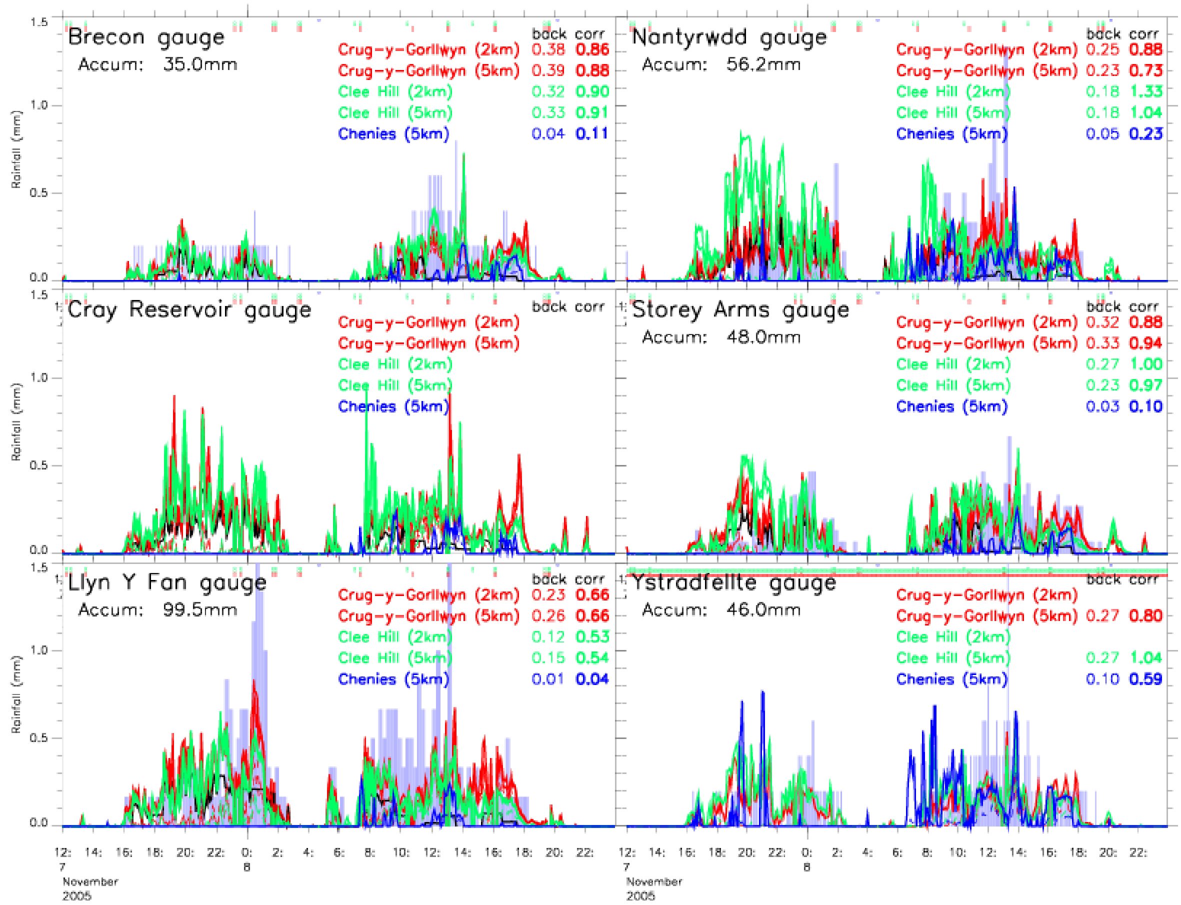
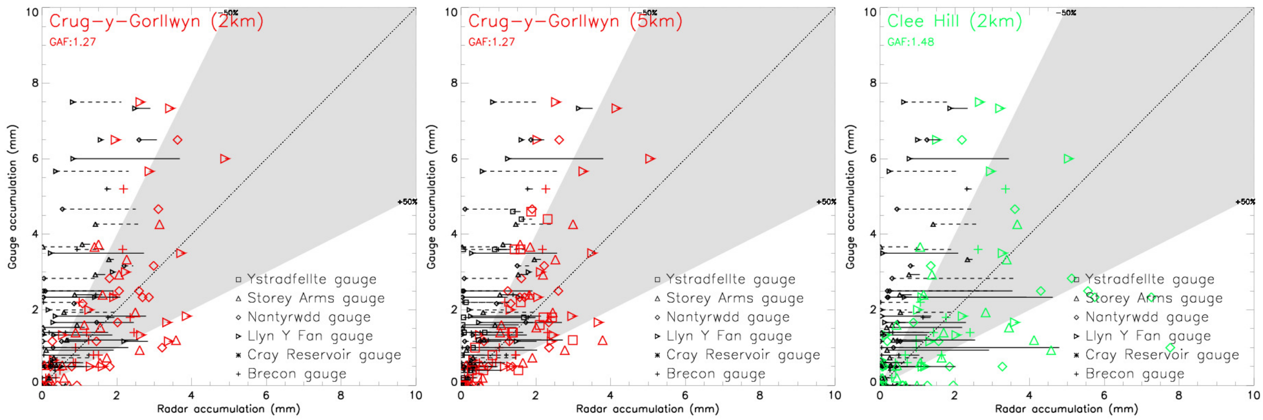


Figure 10.22: Time series of 5 minute rain gauge measurements (bars) and background (- - - -) and corrected (──) radar data for the closest pixel to each gauge site on 7 and 8 November 2005. The total rainfall measured by each gauge during the event is listed along with ratios of radar to gauge accumulations. The orographic correction applied to the radar data is plotted in black. Squares show missing periods of radar data.



10.23: Correlation between hourly gauge measurements in the Upper Taff area and background (small points) and corrected (large points) radar data during 7 and 8 November 2005. Horizontal lines show the orographic correction applied to background radar data. Data measured during morning are connected with dashed lines.

In contrast, largest gauge measured rainfall totals occurred during the second episode of rain on 8 November 2005. Figure 10.22 shows that most intense rainfall occurred at Llyn Y Fan and Nantyrwdd gauges to the west of the region at this time. Unfortunately, the available radars significantly underestimated this rainfall by as much as 60%. In this case, the orographic correction applied was apparently too small to account for the observed enhancement. Figure 10.22 shows better agreement with gauge measurements at Brecon and Storey Arms in the east of the region.

10-13 November 2005

10.4.1 Synoptic background

Figure 10.24 shows a further two weather systems crossing the British Isles on 10 and 12 November 2005 which brought generally light rain and drizzle to southern England and Wales and heavier intervals of rain to northern areas.

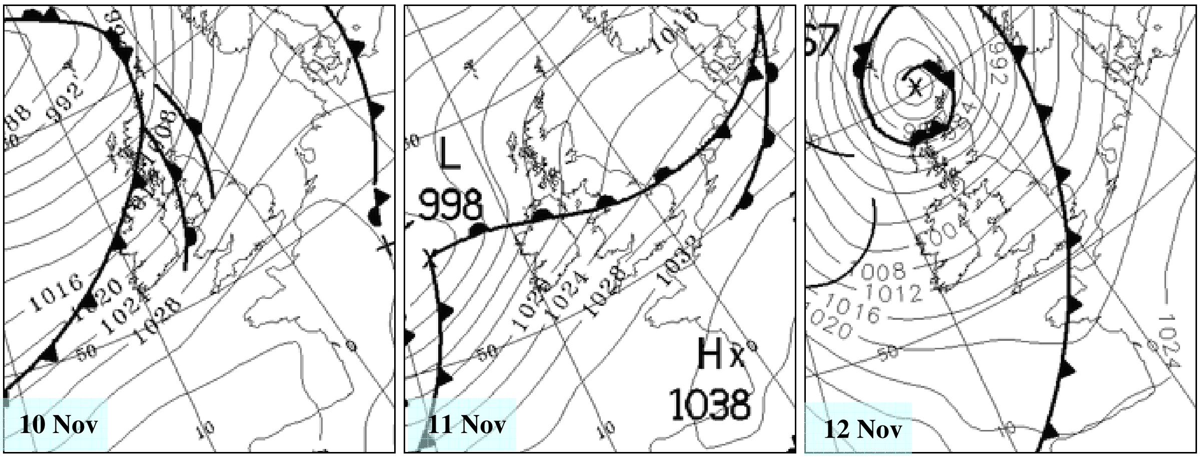


Figure 10.24: Surface pressure analysis charts at 0000 UTC between 10 and 12 November 2005.

10.4.2 Orographic corrections

The sample mesoscale model results shown in Figure 10.25 show strengthening wind speed between 0000 UTC on 10 and 11 November 2005, which led to increasing orographic corrections of up to 8 mmh^{-1} being applied to background radar data across the Upper Conwy region on 11 November 2005. No corrections were applied to data across south-west England at this time when relative humidity values of less than 75% were predicted by the model.

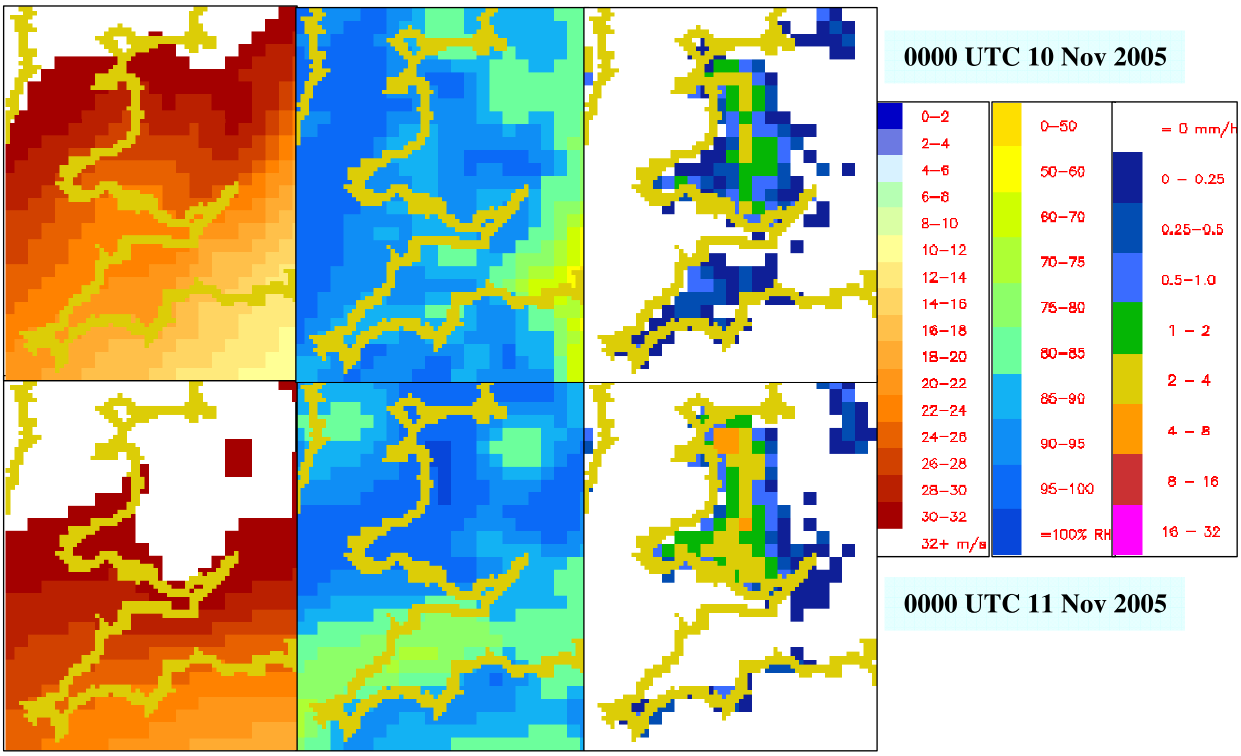


Figure 10.25: Met Office mesoscale model output for 0000 UTC on 10 and 11 November 2005 showing (a) wind speed and (b) relative humidity at 800m used to derive the field of orographic correction factors in (c).

10.4.3 Comparison between radar and gauge accumulations: Upper Conwy

Figure 10.26 shows hourly gauge and radar rainfall accumulations measured across the Upper Conwy region between 0000 UTC 10 November 2005 and 1200 UTC on 13 November 2005. There is considerable variation between the rainfall measured and between radar quality at each gauge site and for each episode of rainfall shown.

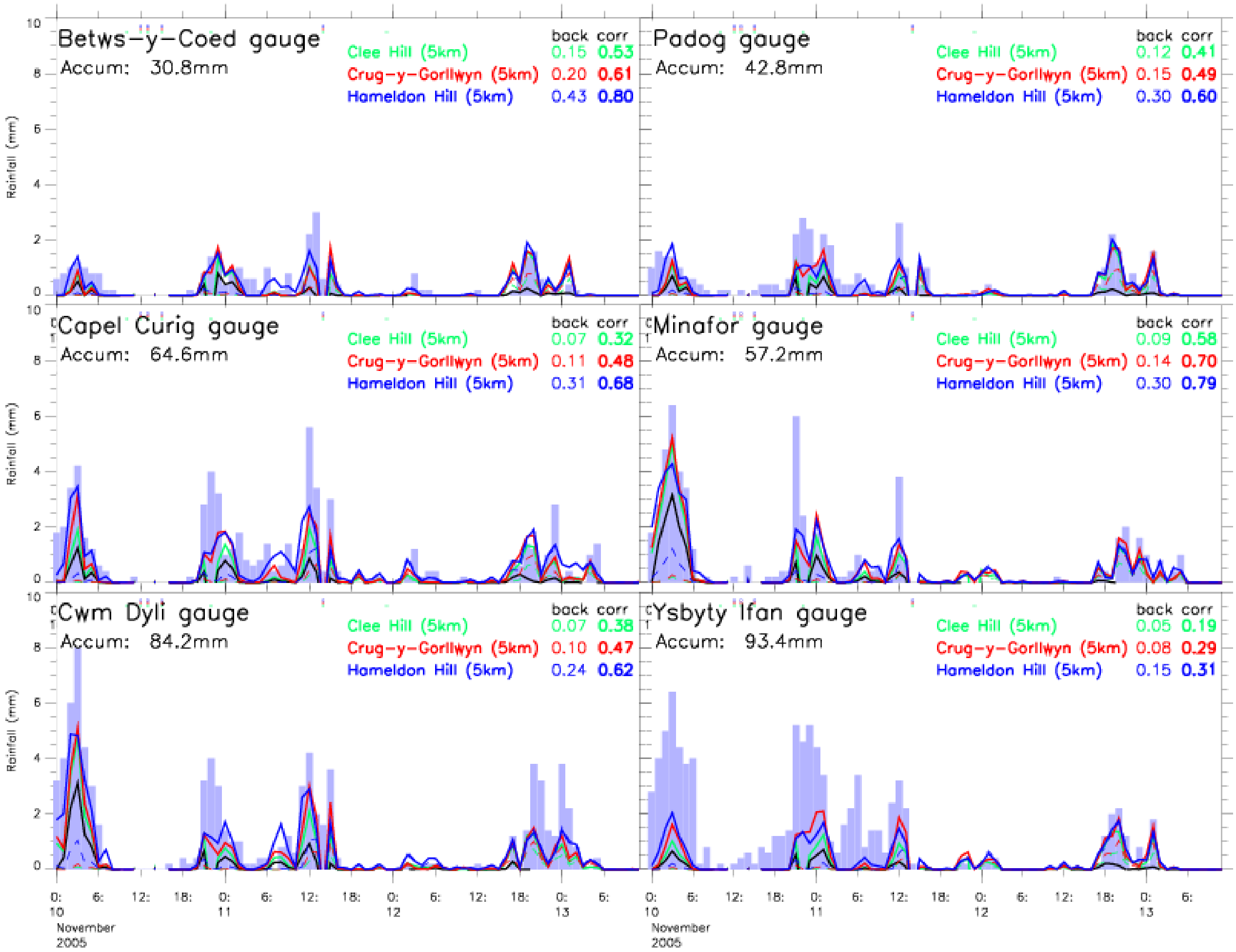


Figure 10.26: Time series of 5 minute rain gauge measurements (bars) and background (- - - -) and corrected (—) radar data for the closest pixel to each gauge site between 10 and 13 November 2005. The total rainfall measured by each gauge during the event is listed along with ratios of radar to gauge accumulations. The orographic correction applied to the radar data is plotted in black. Squares show missing periods of radar data.

The largest total rainfall measured during this period occurred at Ysbyty Ifan as a result of relatively heavy rain associated with each frontal passage and persistent light rain during the afternoon of 10 November 2005. While up to 6 mm was measured at Ysbyty Ifan during the morning of 10 November 2005, only 1.5 mm was measured by the nearby Padog gauge. This large spatial contrast was clearly not captured by the radar data, shown in Figure 10.26 to be very similar for both sites. While the radars gave reasonable agreement with the rainfall measured at Padog, the rain at Ysbyty Ifan was badly underestimated. Similar rainfall total at Minafor and Cwm Dyli were measured much more closely by the radars however. This period is shown in more detail in Figure 1.27. Best quantitative agreement between the radar and gauge measurements during this time occurred with Hameldon Hill radar data.

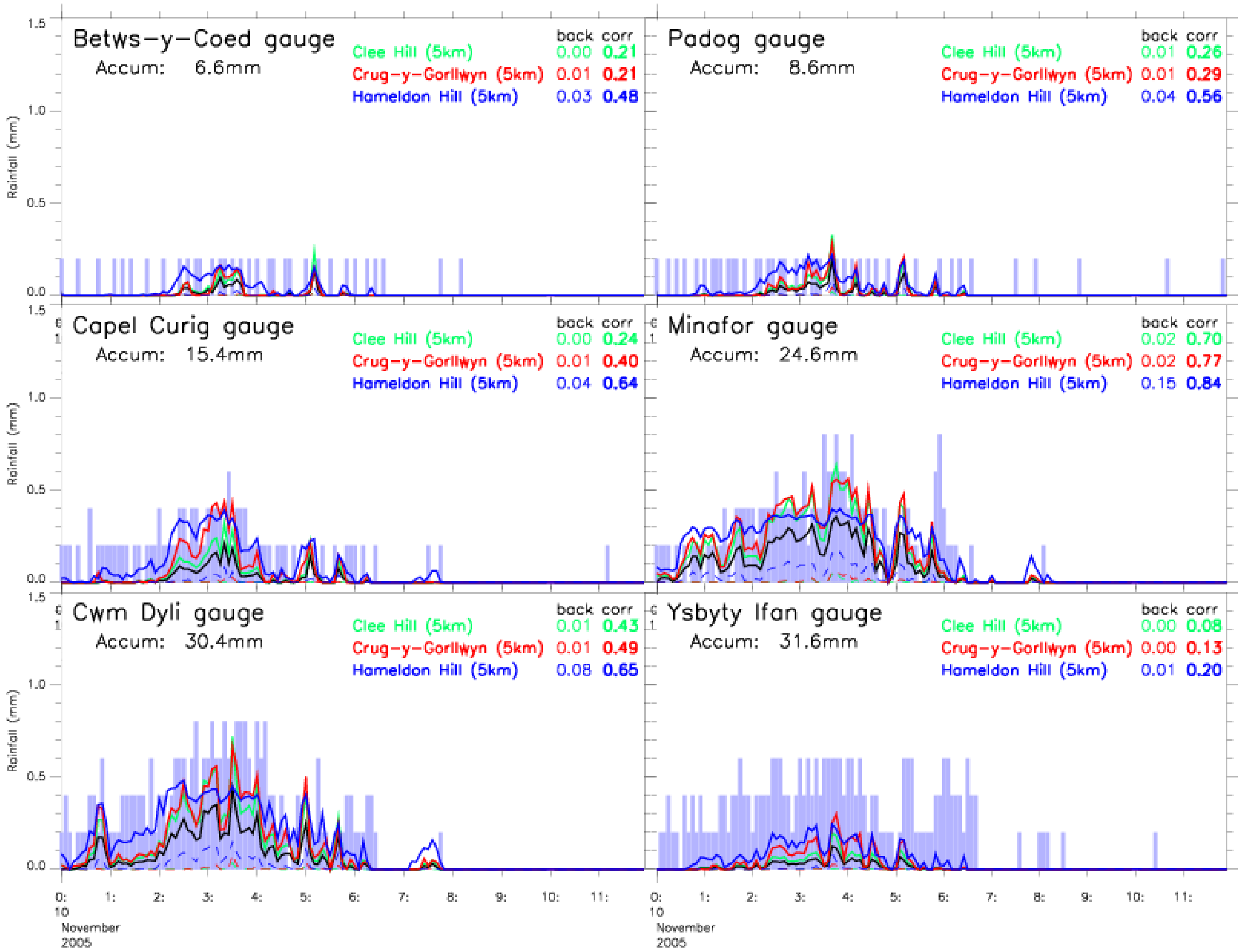


Figure 10.27: Time series of 5 minute rain gauge measurements (bars) and background (- - - -) and corrected (—) radar data for the closest pixel to each gauge site between 10 and 13 November 2005. Other details are as in Figure 10.26.

Figure 10.26 shows further significant rainfall underestimation by the radars as the warm front crossed the region on the night of 10 November 2005 at all but the Betws-y-Coed gauge. Sample radar images during this time are shown in Figure 10.28.

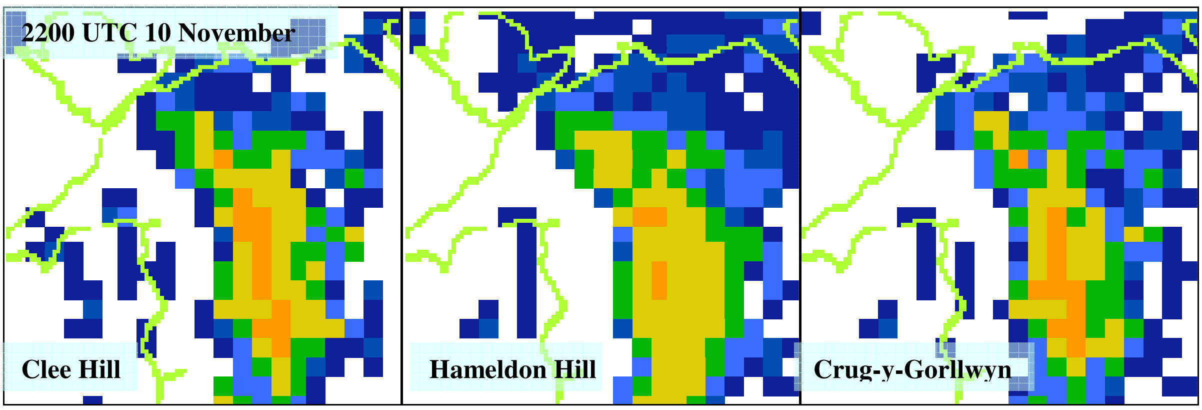
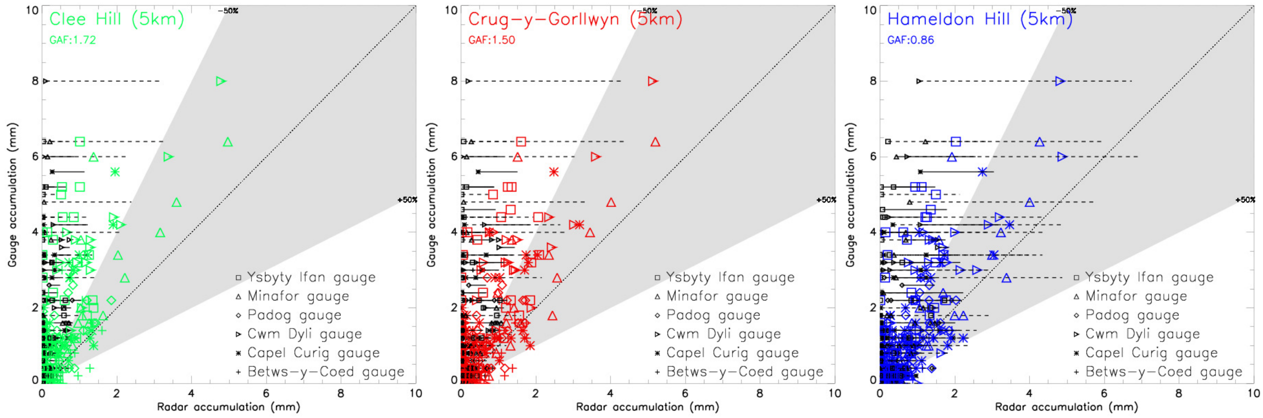


Figure 10.28: Comparison of 5 km resolution radar data at 2200 UTC on 10 November 2005.

The rain gauge measurements plotted in Figure 1.28 also show periods of light showery rain between the heavier rain bands at all sites. These were largely missed by the available radar measurements, perhaps because these were a low-level feature below the height of the lowest usable radar scan at the available range. It is anticipated that this might be improved with the provision of radar data across the region at closer range, although such rainfall was not particularly significant as a risk of potential flooding in the region.

The correlation between gauge and radar hourly accumulations measured during the entire period shown in Figure 10.26 is plotted in Figure 10.29. This indicates a systematic rainfall underestimation by each available radar for hourly gauge accumulations in excess of only 2 mm. The benefit of applying the orographic correction to the generally low background rainfall values is also clearly illustrated.



10.29: Correlation between hourly gauge measurements in the Upper Conwy area and background (small points) and corrected (large points) radar data between 0000 UTC 10 November 2005 and 1200 UTC on 13 November 2005. Horizontal lines show the orographic correction applied to background radar data.

10.4.4 Comparison between radar and gauge accumulations: Upper Exe

Figure 10.30 shows timeseries of rain gauge and radar data across the Upper Exe region between 0000 UTC 10 November 2005 and 1200 UTC 13 November 2005. The correlation between the gauge and radar hourly accumulations plotted in Figure 10.30 is shown in Figure 10.31.

Both Figures 10.30 and 10.31 highlight the considerable underestimation of surface rainfall by all available radars during this period, with corrected radar data as much as 60% smaller than gauge measurements. This is particularly clear during the morning of 10 November 2005 when the warm front crossed the region from the north-west. Figures 10.32 and 10.33 show sample radar images with coverage across the region at this time. Figure 10.30 shows large variation between rain gauge measurements across the region during this period, with considerable orographic enhancement at Kinsford Gate in the south-west of the region producing 31.6 mm rainfall within one day while almost no rain fell at Porlock in the north-east of the region. Data for all radars showed very low background rainfall values during this period and the orographic corrections of up to 1 mmh^{-1} applied to these data were clearly insufficient to account for the considerable enhancement observed at Kinsford Gate. Given that the rainfall distribution in this case varied so much on a local scale, it is possible that better quantitative agreement might have been achieved by computing orographic corrections at a smaller horizontal resolution where such radar data exist.

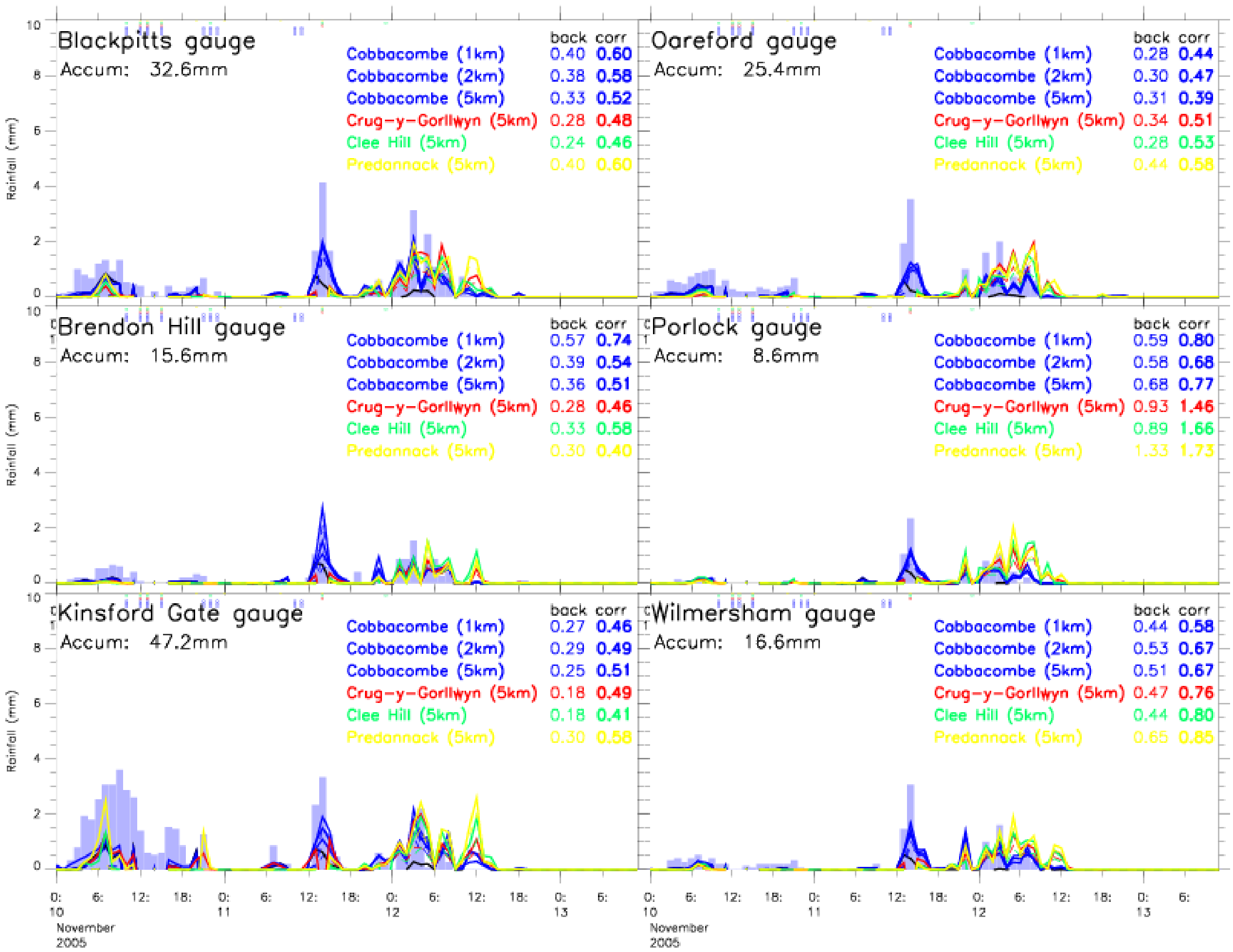


Figure 10.30: Time series of hourly rain gauge measurements (bars) and background (- - - -) and corrected (——) radar measurements for the closest pixel to each gauge site between 0000 UTC on 10 November and 1200 UTC on 13 November 2005. The total rainfall accumulation measured by each gauge during the event is listed along with the ratio of total radar to gauge accumulations for each radar (corrected values are shown in bold).

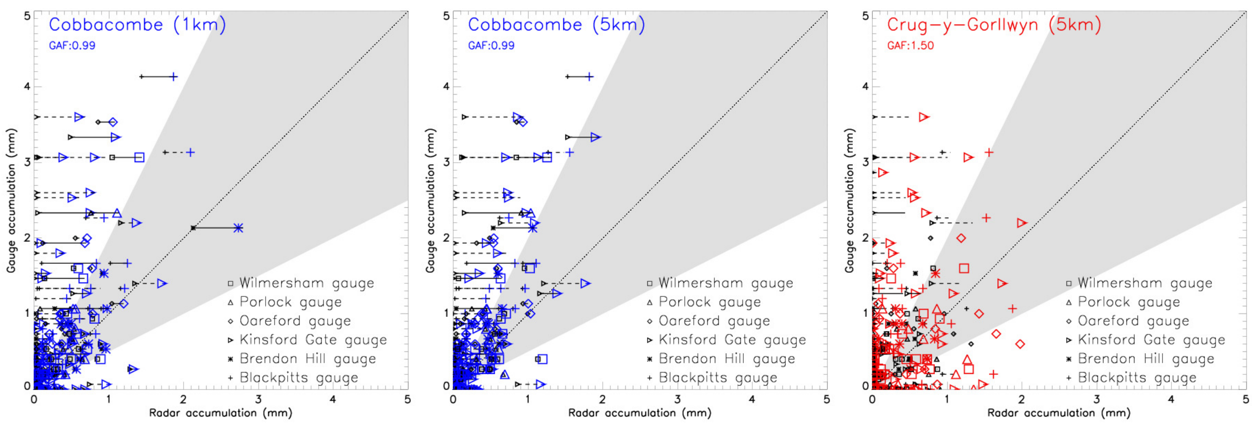


Figure 10.31: Correlation between hourly gauge measurements in the Upper Exe area and background (small points) and corrected (large points) radar data between 0000 UTC 10 November 2005 and 1200 UTC 13 November 2005. Horizontal lines show the orographic correction applied to background radar data.

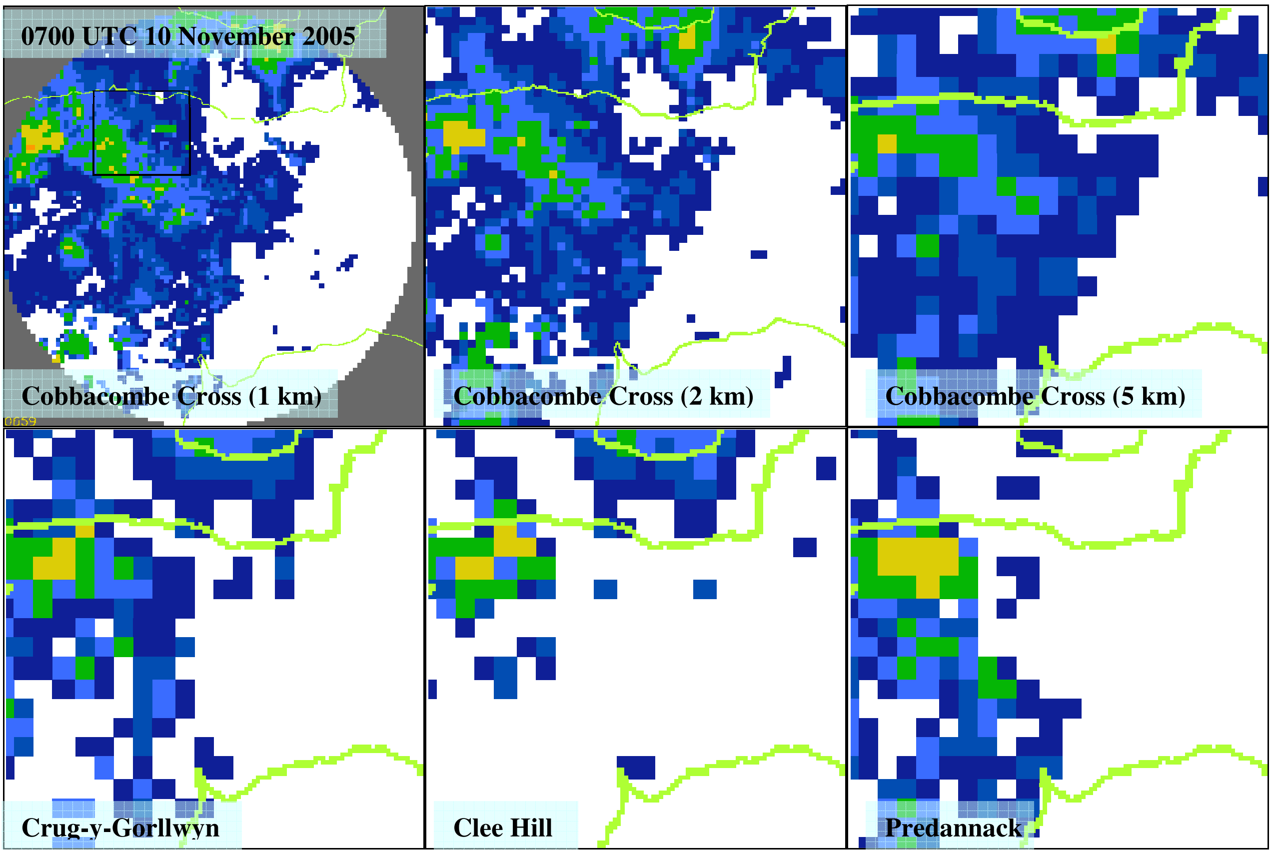


Figure 10.32: Comparison of available radar data across Upper Exe region at 0700 UTC on 10 November 2005.

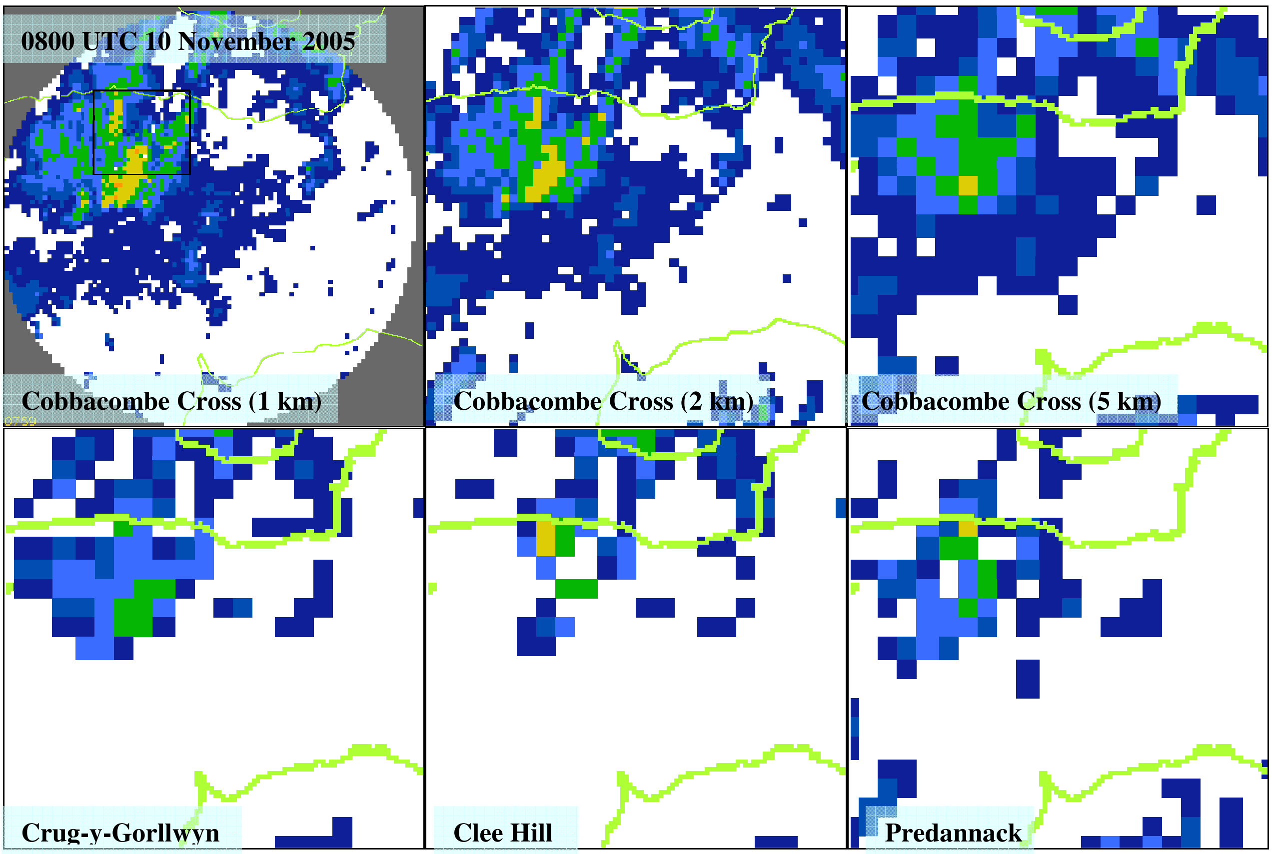


Figure 10.33: Comparison of available radar data across Upper Exe region at 0800 UTC on 10 November 2005.

PART III

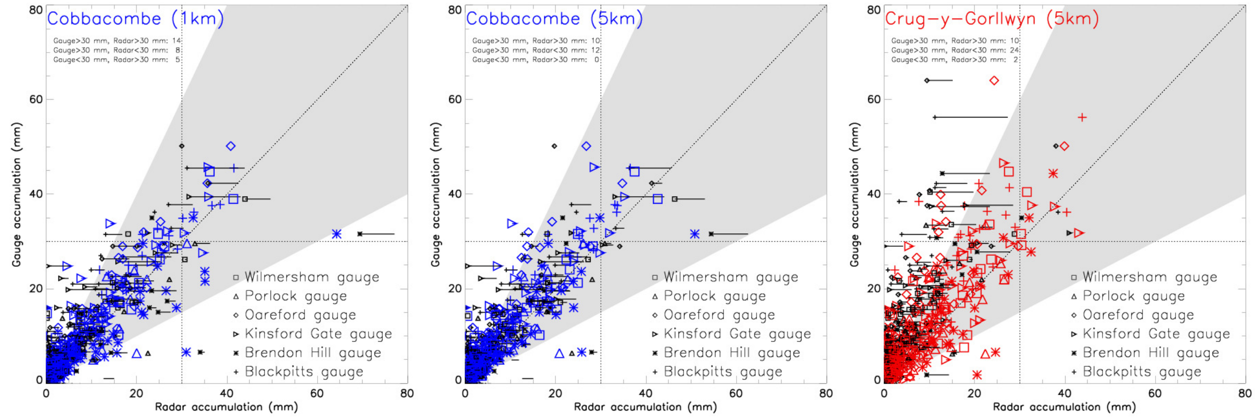
11 Implications for flood forecasting

The case study analyses presented highlight variable radar data quality across upland regions. In order to assess the likely implications of the radar data quality highlighted for flood forecasting applications, a comparison between total gauge and radar rainfall accumulations during each period of rainfall detected during the study period is conducted. This analysis enables inclusion of the potential case study periods not analysed in Sections 6-10 and consideration of radar data reliability over a longer timescale than provided by the comparison of hourly rainfall accumulations discussed in Section 5. The case accumulations are computed by assuming that each rainfall period was separated by at least 6 hours without rainfall. Note that only rainfall detected when both gauge and radar measurements were available is included in the accumulation.

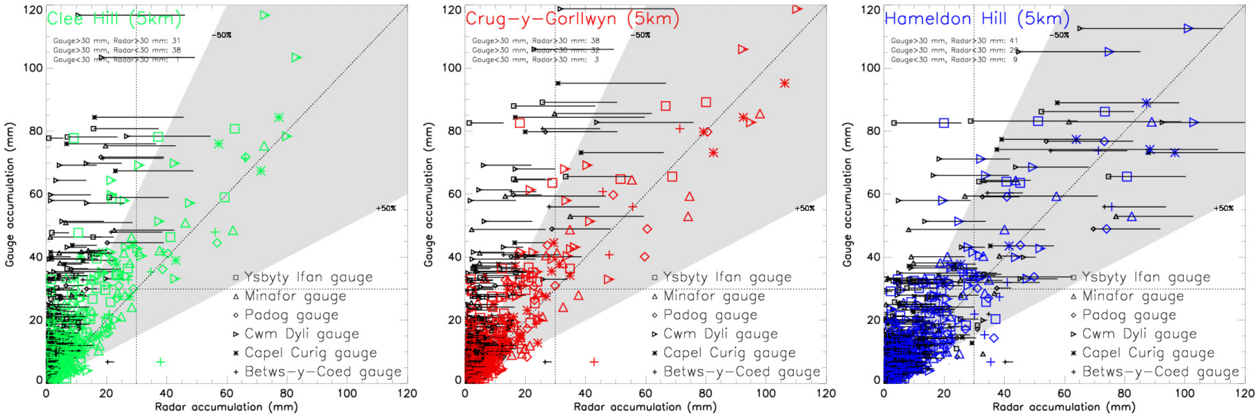
Figure 11.1 shows the correlation between gauge and radar rainfall accumulations during each period of rainfall detected in each of the upland regions of interest during the study period. As previously identified, best data quality is clearly observed for radar data across the Upper Exe study area from the closest radar at Cobbacombe Cross. The benefit of applying the orographic correction scheme in improving the agreement between gauge and radar data across the Upper Conwy and Upper Taff regions is also highlighted.

Assuming that case rainfall accumulations in excess of 30 mm pose greatest threat for flooding, an objective assessment of the reliability of radar data for flood forecasting and warnings in upland areas might be achieved by computing the proportion of cases when gauges measured more than 30 mm when the radar also measured in excess of 30 mm. This is termed the ‘hit rate’ and values are listed in Table 11.1 as a total measure for each radar compared with all gauges within a given region. The ‘false alarm rate’ values listed in Table 11.1 show the proportion of cases when the radar measured in excess of 30 mm when the corresponding gauge measurements recorded less than 30 mm. This quantifies the typical proportion of events when a case might be incorrectly highlighted as a potential flooding event if using the radar data alone.

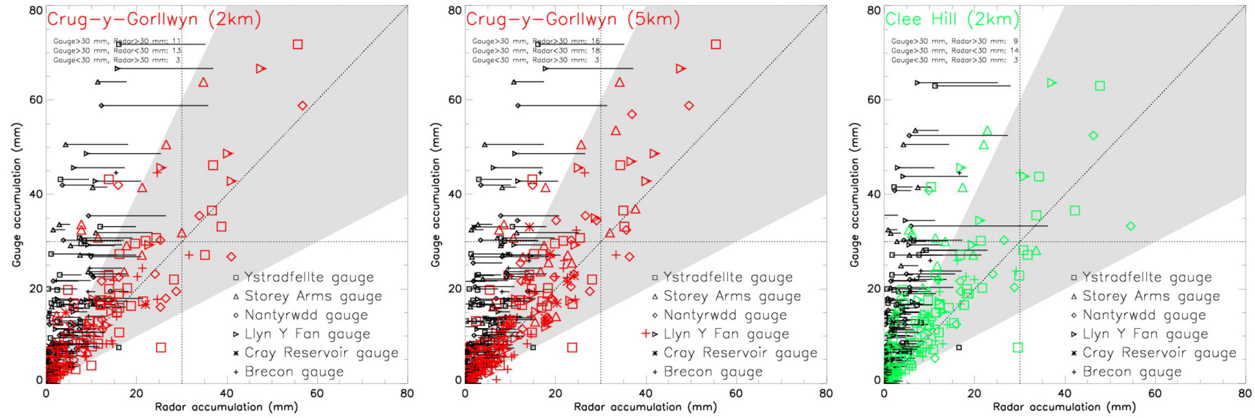
While Figure 11.1 shows that overall radar performance is best for Cobbacombe Cross data across the Upper Exe region, Table 11.1 highlights that performance for periods when in excess of 30 mm rainfall was recorded is generally similar for all three catchments. This is perhaps because heaviest rainfall events in the Upper Conwy region tend to be associated with prolonged frontal rainfall, which are best represented by the assumptions of the current orographic correction scheme. Hit rate values of 0.45 and 0.46 in the Upper Conwy and Upper Taff regions shown in Table 11.1 suggest that less than half of the rainfall events in excess of 30 mm recorded by rain gauges in those areas were also identified from the radar data as having a rainfall accumulation in excess of 30 mm. Results for the Upper Exe region show that 64% of rainfall events with accumulations in excess of 30 mm were also identified from the radar data. Similar statistics for each radar gauge pair within each study area show values in the range 0.5-1.0 across the Upper Exe region, 0.25-0.80 in the Upper Conwy region and 0.25-0.75 in the Upper Taff region for those radars typically used in the national composite in each case (Table 11.1). This clearly shows scope and a need for improving the quantitative accuracy of radar measurements across upland areas if it is to be used as a reliable flood warning tool. Were the radars used alone as a flood forecasting tool in upland areas, Table 11.1 also shows that typically between 10% and 30% of cases identified from the radar data as exceeding 30 mm were not diagnosed by the corresponding gauge measurements, suggesting that a false flood warning might be issued in these cases. The results for the Clee Hill radar across the Upper Conwy region show a false alarm rate of only 3%.



(a) Upper Exe



(b) Upper Conwy



(c) Upper Taff

Figure 11.1: Correlation between gauge and radar measurements of total rainfall event accumulations over the study period for selected radars with coverage across (a) Upper Exe, (b) Upper Conwy and (c) Upper Taff study areas. Accumulations derived from background radar data are shown as small black point and from corrected radar data are shown as large colour points. Horizontal lines show the magnitude of the orographic correction applied to the background radar data during each case.

Note that these statistics are likely to overestimate the true uncertainty of the radar data, since the analysis assumes that the rain gauge measurements represent a ground truth. In particular, it is likely that the false alarm ratio is overestimated since it is known that gauges underestimate rainfall in conditions of very heavy rainfall and strong wind speeds.

		No. cases G>30 mm R>30 mm	No. cases G>30 mm, R<30 mm	No. cases G<30 mm, R>30 mm	Hit rate	False alarm rate
Exe	**Cobbacombe (1km)**	**14**	**8**	**5**	**0.64**	**0.26**
	Cobbacombe (2km)	13	9	2	0.59	0.13
	Cobbacombe (5km)	10	12	0	0.45	0.00
	Crug-y-G (5 km)	10	24	2	0.29	0.17
	Clee Hill (5 km)	2	29	0	0.07	0.00
	Predannack (5 km)	6	28	4	0.18	0.40
Conwy	**Clee Hill (5 km)**	**31**	**38**	**1**	**0.45**	**0.03**
	Crug-y-G (5 km)	38	32	3	0.54	0.07
	Hameldon (5 km)	41	29	9	0.59	0.18
Taff	**Crug-y-G (2 km)**	**11**	**13**	**3**	**0.46**	**0.21**
	Crug-y-G (5 km)	16	18	3	0.47	0.16
	Clee Hill (2 km)	9	14	3	0.39	0.03
	Clee Hill (5 km)	10	23	4	0.30	0.29
	Chenies (5 km)	4	42	0	0.09	0.00

Table 11.1: Comparison of number of rainfall events during the study period when in excess of 30 mm were measured by the radar (R) or a gauge (G) in each of the study regions. The probability of detection (POD) shows the ratio of cases in excess of 30 mm correctly captured by the radar and the false alarm ratio (FAR) shows the ratio of cases measured by the radar to be in excess of 30 mm which were not verified by gauges. Data from radars listed in bold are typically included in the national composite product in each region.

Improved detection of potential flooding events can be achieved if events when gauges recorded accumulations in excess of 30 mm are diagnosed from radar accumulations in excess of 25 mm. This gives hit rate (false alarm rate) values of 0.73 (0.43), 0.59 (0.09) and 0.63 (0.35) for the closest available radar to the Upper Exe, Upper Conwy and Upper Taff regions respectively. Even by diagnosing heavy rainfall events from radar accumulations in excess of just 20 mm across the Upper Conwy region gives a hit rate of 0.77 and false alarm rate of 0.24. This might suggest some scope for considering modified rainfall thresholds to highlight potential cases of flooding for un-gauged upland regions where only radar data are available, although the potential for false warnings suggests that such an approach should be applied with caution with further investigation of a given storm event required before the data is used to issue a flood warning. Note that this study has shown that simply scaling the background radar data to surface gauge measurements in such a way is unlikely to give satisfactory results, since the orographic corrections applied provide some representation of the considerable spatial rainfall variations observed in upland areas.

In summary, these results show that the available radar data might be used to correctly diagnose about 50% of rainfall events in excess of 30 mm in upland areas. The similarity between results across each of the three regions suggests that a similar success rate might be anticipated in other upland regions across the UK. Reliable flood forecasting using radar data in upland regions would clearly benefit from developments to the radar system to improve the quantitative accuracy of surface rainfall estimates.

Figure 11.2 shows a comparison of rainfall event accumulations measured by each available gauge with that measured by the next nearest gauge. This illustrates the typical inter-gauge variability and the potential errors which may be incurred for flood warning applications by using point rainfall measurements from the available gauge network. Note that some adjustment for the altitude distribution of available rain gauges in a catchment is applied to the rain gauge data as part of the NFFS processing conducted by the Environment Agency to produce areal rainfall values in such regions.

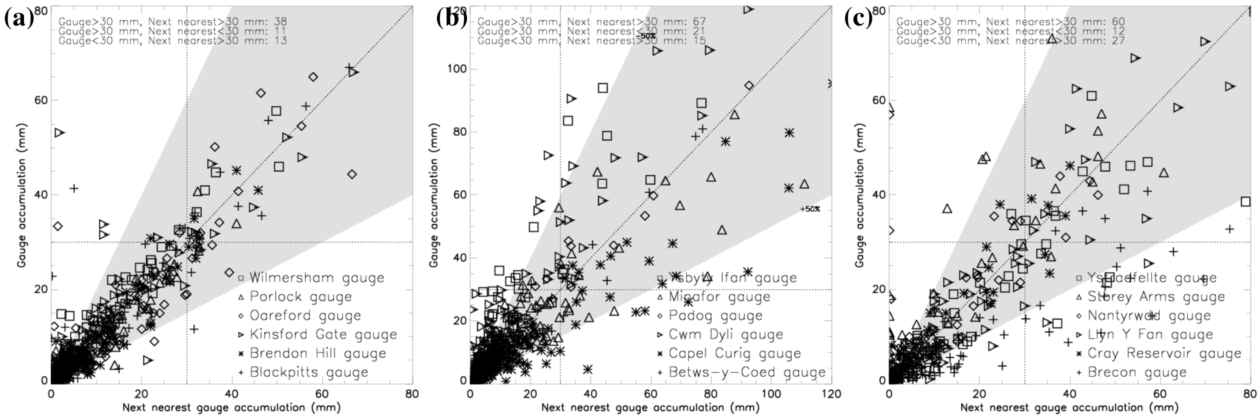


Figure 11.2: Correlation between gauge measurements of total rainfall event accumulations with that measured by the next nearest gauge across (a) Upper Exe, (b) Upper Conwy and (c) Upper Taff study areas.

The spread of data plotted in Figure 11.2 for the Upper Conwy and Upper Taff regions highlights the considerable spatial variation of rainfall observed in these areas. In contrast, the rainfall distribution across the Upper Exe region is more constant such that gauge measurements are generally typical of those at adjacent locations to within about 35%. Comparison of Figures 11.1 and 11.2 suggests that the current quantitative accuracy of the radar data is similar to the errors which might be incurred from relying on point rainfall measurements to represent rainfall at other locations within each of the upland areas of interest. In terms of its use for flood forecasting however, the results in Figure 11.2 actually indicate improved hit rate values for rainfall accumulations in excess of 30 mm of 0.78, 0.76 and 0.83 in the Upper Exe, Upper Conwy and Upper Taff regions respectively. The false alarm rate values of 0.25, 0.18 and 0.31 are generally similar to those in Table 11.1.

Despite the current limitations to radar data quality identified and the implications for its use as direct quantitative input to flood forecasting systems across upland areas, this study provides a measure of the typical accuracy of radar data and its variation between different rainfall periods. Given this information, there is clearly great scope for taking advantage of the spatial resolution of rainfall data provided by the radar network for flood forecasting, particularly across the many un-gauged upland catchments across the UK. The quantitative use of these data during any given rainfall event still requires careful comparison between the radar measurements with surface rainfall measurements from at least one gauge at an upland location within the rainfall region.

12 Summary and discussion of case study analyses

The analysis presented in Sections 6-11 highlights a range of case study periods when considerable rainfall accumulations were measured across the Upper Exe, Upper Conwy and Upper Taff study areas. All of the cases discussed illustrate strong regional rainfall variations over small spatial distances which can be directly linked to the surrounding terrain and the process of orographic rainfall enhancement over the hills and mountains of the UK. For example, on 11 October 2005 measurements across the Upper Exe study area showed rainfall accumulations over a 12 hour period at Oareford (343 m ASL) to be over 2.5 times larger than that recorded at Porlock (125 m ASL), located 8 km further east (Figure 8.7). On 24 October 2005 measurements across the Upper Taff region showed rainfall totals at the highest gauge site at Storey Arms (530 m ASL) to be over five times higher than that at the nearby Brecon site (168 m ASL), located only 10 km away (Figure 9.12). Similarly, on 10 November 2005, measurements across the Upper Conwy region showed rainfall totals at Cwm Dyli (180 m ASL) and Ysbyty Ifan gauges (392 m ASL) to be over 4.5 times higher than at Betws-y-Coed (22m ASL) (Figure 10.27). Although the gauge at Cwm Dyli itself is not located at high altitude, this analysis has shown that its position in a deep valley in the vicinity of steep terrain up to the summit of Snowdon at over 900 m leads to considerable rainfall being recorded at this site.

Comparison of the available radar data during these events with the corresponding surface gauge rainfall measurements has illustrated varying quality of radar performance, between different cases, between different regions, for different available radars with coverage across a region, and at different gauge locations within each study area. Evidence for periods when the available radars and operational processing performed extremely well when compared with the surface rainfall and when the radars performed very poorly have been identified.

12.1 The use of radar data to measure rainfall in upland areas

The rainfall associated with an occluded front across the Upper Conwy region during the morning of 24 October 2005 is one case when all available radars performed consistently well in capturing the temporal structure and magnitude of surface measured rainfall across the entire study area (Figure 9.4). In this case all but two of the twenty hourly rainfall accumulations measured across the region over a 24 hour period in excess of 4 mm were derived to within 20% from measurements by the Clee Hill and Crug-y-Gorllwyn radars (Figure 9.5). No systematic bias between radar and gauge measurements was evident, and all hourly accumulations were measured to within 35%. Consideration of the background and corrected radar data in this case demonstrates that the success of the radar system in achieving this level of accuracy can be largely attributed to the orographic correction scheme (Section 1.3) and subsequent scaling of the modified surface rainfall estimates by the gauge adjustment factor (Section 4.1). The background rainfall accumulations derived from the VPR calculation part of the operational processing chain applied to these radar data were consistently just 20% of the corresponding surface gauge value. The addition of constant orographic corrections on an hourly timescale led to surface rainfall estimates only 40% smaller than gauge values and final scaling by a gauge adjustment factor produced further improvement. Despite the complexity of the local terrain and relatively poor radar coverage provided by the current national radar network across this region, the spatial and temporal rainfall distribution observed by the surface gauges was reliably captured by the available radars in this case. This provides encouragement that radars can be a viable tool for rainfall measurement and used as a source of relatively high spatial and temporal resolution data for flood warning application in upland regions (Section 11).

12.2 The limits to radar measurements of rainfall in upland areas

The case of rainfall in the Upper Conwy study area on 24 October 2005 provides the best example of when good agreement between all available radars and gauges was observed. It is particularly surprising that such a case occurred in the Upper Conwy study area - the region where the poorest available radar coverage and most complex terrain were considered to be most detrimental to data quality. It appears that the nature of this event was consistent with the assumptions implied by the operational orographic correction scheme and that the precipitation layer was sufficiently deep to be detected by the radar beams at such long range.

While similarly good agreement between radar and gauge data is evident from some of the other cases discussed, the reliability of the radar measurements was more dependent on the location of the point of interest or on the particular radar making that measurement. Such uncertainty potentially places a limit on the use of radars for reliable quantitative measurements of rainfall in upland regions. At the very least, these uncertainties need to be understood for radars to be used in this way and to direct the required developments of the radar system, specifically of the radar hardware and methods of post-processing the radar data, to improve its reliability.

For example, comparison of radar and rain gauge measurements across the Upper Exe region on 28 September 2005 highlights considerable variation between radar data quality with both location and available radars (Figure 7.11). Rainfall estimates derived from measurements by the nearest radar at Cobbacombe Cross showed good agreement with the gauge measurements at Porlock, Oareford, Brendon Hill and Wilmersham Farm, particularly during the morning, but the radar consistently underestimated the larger rainfall accumulations recorded by the Blackpitts gauge (Figure 7.13) by 50%. In this case the applied orographic corrections were apparently insufficient to capture the rain enhancement observed at this site. In addition, most available rainfall measurements at longer range from the Crug-y-Gorllwyn, Clee Hill and Predannack radars consistently underestimated the observed rainfall by typically 50% but by as much as 90%. In this case the errors were attributed to attenuation of the radar beam power by surrounding rainfall and the radar beam overshooting the top of the precipitation layer. It is striking from the examples shown in Sections 6-11 how the performance of these radars across the Upper Exe was generally poor, systematically underestimating the observed surface rainfall (e.g. Figure 10.12). The data quality in these cases was often worse than that for the same radars at similar range across the more complex terrain of the Upper Conwy region. This was shown to be particularly significant on occasions when the radar at Cobbacombe was not operational, such as on 11 October 2005 (Figure 8.8) and 21 October 2005 (Figure 8.9). The dependence of data quality on which radar was available clearly has important consequences for the reliability of data included in the UK national radar composite product. On 11 October 2005 each of the available radars measured similar rainfall rates across the entire region and only small orographic corrections were applied to the background data. These factors led to underestimates of the surface gauge measured rain by up to 60% at upland sites such as Oareford, Blackpitts and Brendon Hill where considerable orographic enhancement was observed (Figure 8.7).

Notably inconsistent radar performance was found for all available radars at all locations during the cases identified in the Upper Taff study area. For example, on 7 and 8 November 2005 the available radars both over and underestimated the measured surface rainfall at most gauge sites in the region by over 50% (Figure 10.23). The background radar data from Crug-y-Gorllwyn and Clee Hill remained relatively small, with hourly accumulations of less than 2 mm, throughout and the poor radar performance was attributed to a failure of the orographic correction procedure. The applied corrections were apparently too high during 7 November 2005 when only moderate rainfall was observed at the surface while the orographic corrections were too small by a similar magnitude on 8 November 2005 when evidence for strong orographic enhancement was observed (Figure 10.22). These radars provided more reliable rainfall measurements at most sites in the Upper Taff region on 24 October 2005 when the observed orographic enhancement was captured reasonably well by the corrected radar data at Nantyrwdd and Llyn Y Fan (Figure 9.12). The radar measurements at these and more low-lying gauge sites were generally accurate to within 20% during this event. In contrast, the available radars failed to measure the high rainfall accumulations observed at Storey Arms where the radar rainfall values underestimated surface measurements by typically 70% (Figure 9.13). The difference in radar performance with location in this case was attributed to a failure of the orographic corrections to account for the stronger enhancement to the west of the region. This may be related back to errors with the model output used at this time. Given the availability of radar data at both 2 and 5 km resolution, it was proposed that calculation of orographic corrections might be performed at the highest available horizontal resolution to more accurately reflect the local terrain and rainfall distributions. On 3 November 2005, errors in the temporal rather than spatial variation of orographic corrections applied to the background radar data were thought to explain the relatively poor agreement between corrected radar and gauge data across the Upper Taff region (Figure 10.9). In this case the available radars accurately captured the magnitude of rainfall associated with a trough feature when it first arrived, but the radar-derived values subsequently underestimated the persistent rainfall which followed at all sites by up to 80% when decreasing orographic corrections were applied (Figure 10.8). A similar feature also occurred on 24 October 2005 (Figure 9.12). In all cases, the Upper Taff results also provided evidence of particularly poor radar performance at long range from the Chenies radar. It will be of interest to consider whether this is simply a feature of the radar measurements being made at long range, and by a radar beam at considerable height above the surface, or whether the data quality observed is even worse than might be anticipated over more low-lying regions of the UK. In this case, the influence of terrain elevation may need to be taken into account when considering suitable ranges for providing radar data at long range and for its inclusion in the national radar composite product.

12.3 Factors affecting radar measurements of rainfall in upland areas

The analysis of case study periods of rainfall measurements from several radars across each of the upland areas of interest has highlighted several factors which influence the corrected rainfall measurement derived from radar across upland areas and its value for applications such as flood forecasting in such regions.

- Radar range

  Results from the Upper Exe study area demonstrated a strong dependence of reliable radar data on the availability of measurements from the closest radar at Cobbacombe Cross (e.g. Figure 7.13). Despite being at considerably longer range, so that the height of the radar beam is a greater distance from the surface, measurements from the radars across the Upper Conwy region gave good agreement with surface rainfall values at times (e.g. Figure 9.5). Results from the Chenies radar across the Upper Taff region clearly demonstrated poor radar data quality at very long range in excess of 200 km.

- Radar data resolution

  While the available radars across the Upper Conwy study area were reasonably successful in detecting the occurrence of rainfall at the surface, the radar data often failed to capture the highly intensive, intermittent and localised rainfall peaks observed at upland gauge sites (e.g. Figure 6.3, Figure 8.5, Figure 10.20). This was particularly evident at Cwm Dyli for example. Similar behaviour was also observed at upland gauges in the Upper Taff region (e.g. Figure 10.22). Successful detection of such intensive rainfall is clearly of benefit in using radar data for flood warning applications in upland areas. The availability of radar data at improved spatial resolution, particularly across the Upper Conwy area where only 5 km data is available, was highlighted as one feature which might provide the required improvement. Availability of radar data at improved resolution would also allow scope for applying the orographic corrections at 1 and 2 km resolution to better represent the highly complex terrain found in regions such as the Upper Conwy. This suggestion might be considered to improve radar data quality across the Upper Exe area where 1 km resolution data is available, but the relatively smooth terrain in this region may not provide the best test for its use in other parts of the UK.

- Orographic correction

  Several of the cases discussed have shown radar rainfall estimates across upland areas to be highly dependent on the magnitude of the orographic correction applied to the background data (e.g. Figure 6.4). Cases when the radars successfully captured the spatial variability of rainfall often depended entirely on the spatial variability introduced by the correction scheme (e.g. Figure 9.5). Examples in each of the study areas considered when the applied corrections were too small to replicate the observed enhancement (Figure 8.7) and when corrections were unrealistically large (Figure 10.5) have been identified. Understanding the factors determining the magnitude of the correction deduced in all of these cases, such as the impact of errors in the model parameters used, will be important in making any future improvements to the current scheme. It is also of interest to consider whether the orographic correction scheme itself is still the most suitable to use. An assessment of the relative benefits and weaknesses which might be gained by applying the Alpert and Shafir (1989) corrections to radar data across England and Wales would be of use.

- Gauge adjustment factors

  This assessment is partly complicated by the cumulative impact of both orographic corrections and the gauge adjustment factors used to scale the corrected surface rainfall estimates on radar data quality in upland areas. Some evidence for the detrimental effect of applying gauge adjustments to Hameldon Hill radar data was found in the Upper Conwy region (Figure 6.5). It is of interest to consider the impact of applying gauge adjustment factors derived from comparisons of radar data and surface gauges across wide regions of varying terrain on measurements made across upland regions.

The analysis has therefore highlighted several deficiencies of radar rainfall measurements across upland areas and several factors which may contribute towards these deficiencies.

13 Improving radar data quality in upland areas

13.1 Options for an improved orographic correction scheme

The current radar data processing chain applies orographic corrections by applying enhancement fields to background rainfall estimates as described in Section 1.3. Fixed orographic enhancement fields are applied at 5 km horizontal resolution to background radar data. Corrections are only applied where model relative humidity values exceed 85% and the correction field applied is then selected dependent on model wind speed and direction. The magnitude and distribution of the orographic enhancements in each correction field is based on the rainfall climatology conducted by Hill (1983) across England and Wales and on the physical model developed by Alpert and Shafir (1989) across Scotland and continental Europe. This model equates the orographic enhancement to the moisture convergence induced by mechanical lifting by orography.

This study has shown that the current scheme is successful in improving the agreement between background radar and surface gauge rainfall measurements across upland regions of England and Wales. This has been demonstrated both in terms of improving long-term statistical measures of data quality and by analysing specific case study periods. The case studies have also highlighted periods when the corrections applied were insufficient to fully correct the measured radar data to match the observed surface rainfall and other periods when the applied corrections led to considerable overestimates of surface rainfall by the radar. In light of these results, there is clearly scope for improving the current orographic enhancement scheme. Further, the developments in the numerical models used as input to the correction scheme which have taken place since the orographic correction processing was first implemented provide opportunities to use additional information to derive the correction fields.

Several possibilities for improving the orographic corrections applied to radar data have been identified during this study. Given that the current corrections applied across England and Wales are based on climatology, there is little scope to modify the distribution or magnitude of these corrections or to take advantage of any developments to the available model output or of improved understanding of the characteristics of the enhancement process. Modifications to the correction fields applied across England and Wales therefore require a change to the approach used. The simplest option would be to replace the corrections based on Hill (1983) with the results of the Alpert and Shafir (1989) model, as currently applied across the rest of the radar network domain. This development offers several benefits over the current method.

- Consistency between the correction fields applied across the radar domain,
- Corrections can be defined at higher spatial resolution,
- Corrections can make use of additional model parameters,
- Corrections can be easily modified in light of future developments.

Cranston and Black (2006) conducted a study to assess radar data quality in an upland river catchment in central Scotland. This provided a useful measure of the likely performance of corrections based on the Alpert and Shafir (1989) method across similar terrain in other regions of the UK. Cranston and Black (2006) analysed radar and surface gauge rainfall measurements during 11 storm events (storm accumulations in the range 9.6-59.8 mm) and found no consistent bias and a mean absolute error in storm rainfall totals of 24%. The results were similar to those found in this study, suggesting that data quality using the Alpert and Shafir (1989) method across England

and Wales is likely to be at least similar to that presently observed. Weston and Roy (1994) suggested that the Alpert and Shafir (1989) model did not reproduce the observed rainfall distributions over high ground in the lee of the first range of hills encountered by an airstream. The effect of rain shadowing was included in the Hill (1983) climatology. The impact of this effect on radar-derived rainfall measurements across regions such as the Upper Taff will need to be investigated before applying the scheme on an operational basis.

Furthermore, the potential flexibility gained by using the Alpert and Shafir (1989) method across the whole radar domain introduces the possibility to implement additional improvements to the correction fields. The main opportunities for development are discussed below.

Application of corrections at higher resolution

The current operational scheme is applied at 5 km horizontal resolution, independent of the resolution of available radar data. Two factors contribute to the resolution at which corrections can be applied – the resolution of terrain considered (currently 5 km) and the resolution of model data used to derive the correction field (currently 12 km). The recent development of the mesoscale model to run at 4 km resolution across the UK provides a new opportunity to use considerably improved resolution model data. The availability of higher resolution model data makes consideration of higher (e.g. 1 km) resolution terrain data, which allows representation of more localised slopes, more appropriate.

Use of additional model parameters

The current implementation of the Alpert and Shafir (1989) model to derive constant correction fields for given wind direction and speed categories uses relatively few meteorological parameters to quantify the magnitude of orographic enhancement. In future, the use of additional model parameters could be used to describe the enhancement process with greater accuracy for a broader range of rain types. For example, consideration of the vertical wind speed may indicate whether the upper-level feeder cloud and rainfall is modified by the presence of orography as they pass over larger hills and mountains. The use of alternative models of the orographic enhancement process (e.g. Weston and Roy 1994) may provide improved results. Diagnosis of stratiform or convective cloud conditions from the model or using satellite-derived products might also provide a more robust description of when the enhancement process would be anticipated at low-levels, rather than simply replying on boundary-layer relative humidity estimates. Although the use of the Alpert and Shafir (1989) model across the whole radar domain facilitates these future changes, modifications to the operational scheme would only be possible following further research effort and development work.

Computation of corrections in real-time

In the immediate future, improvements to the way in which the Alpert and Shafir (1989) model itself is implemented in the radar processing chain could be implemented. Following the approach used by Hill (1983), the Alpert and Shafir (1989) corrections were derived for given wind speed and direction categories by using typical values for the low-level humidity. The humidity-dependence of the model was then replicated by applying a final scaling to the correction fields in real-time. This rather arbitrary restriction of corrections to wind speed categories could clearly be improved by deriving the orographic enhancement fields from the model equations in real-time. This has the additional benefit of using model relative humidity and temperature values to compute the corrections rather than applying a scaling factor as part of the radar data processing. The direct computation of orographic enhancement fields is a more robust approach which allows for a continuous range of correction factors rather than 36 constant fields. It is thought that implementation of the Alpert and Shafir (1989) model in real-time will provide more representative orographic correction fields. In addition, this approach enables the scheme to use improved model data and resolution as they become available in the future.

Computing the orographic corrections required in real-time as part of the radar data processing chain is likely to prove computationally expensive, particularly given increasing demands on the radar processing system from additional radars and other product developments. Fortunately, recent developments to the Met Office UK NWP post-processing methods used for nowcasting applications (STEPS) has involved adjusting the orographic correction fields used in this scheme to be derived in real-time using the Alpert and Shafir (1989) model as described above. As such, a readily available orographic correction product is already in existence and could be applied to the processing of the radar data itself. The benefits of the STEPS method over the current radar processing method have been outlined above. In addition, the use of STEPS data for correcting radar data would ensure consistency of approach to correcting both the initial rainfall observation by the radar and the subsequent production of short-term rainfall forecasts in the nowcasting processing chain. The principal features of using the STEPS orographic correction fields are:

- No additional computing power required
- Continuous correction fields, no need for fixed wind speed and direction categories
- No need to assume values for the relative humidity and temperature
- No additional humidity scaling required as part of the radar processing chain
- Uses 4 km resolution mesoscale model output
- Uses 2 km resolution terrain model
- Allows potential for future development

Figure 13.1 shows an example of the orographic correction field derived by STEPS for south-westerly winds typically between about 10 and 20 ms^{-1}. Regions where no corrections are shown correspond with regions where the model showed relative humidity of less than 80%. The equivalent correction field for similar wind conditions used in the current radar processing chain is also shown for comparison. The STEPS approach provides generally increased orographic corrections with considerably greater spatial variation than currently applied across England and Wales using the Hill (1983) method. The impact of the differences illustrated in Figure 13.1 on radar data quality will require investigation before using the modified corrections in the operational radar processing chain. Additional features of the STEPS scheme which would require consideration before committing to its use in the radar processing chain are,

- No corrections are applied in the STEPS scheme for relative humidity values less than 80%, rather than 85% as in current radar processing method.
- The STEPS scheme uses model data from model levels equivalent to about 802 and 925 m above the surface.
- The Alpert and Shafir (1989) formulation requires the use of tuning factors, applied to both precipitation rates and wind speed, to match surface observations.
- The apparent lack of sensitivity of the Alpert and Shafir (1989) method to the rain shadow effect.

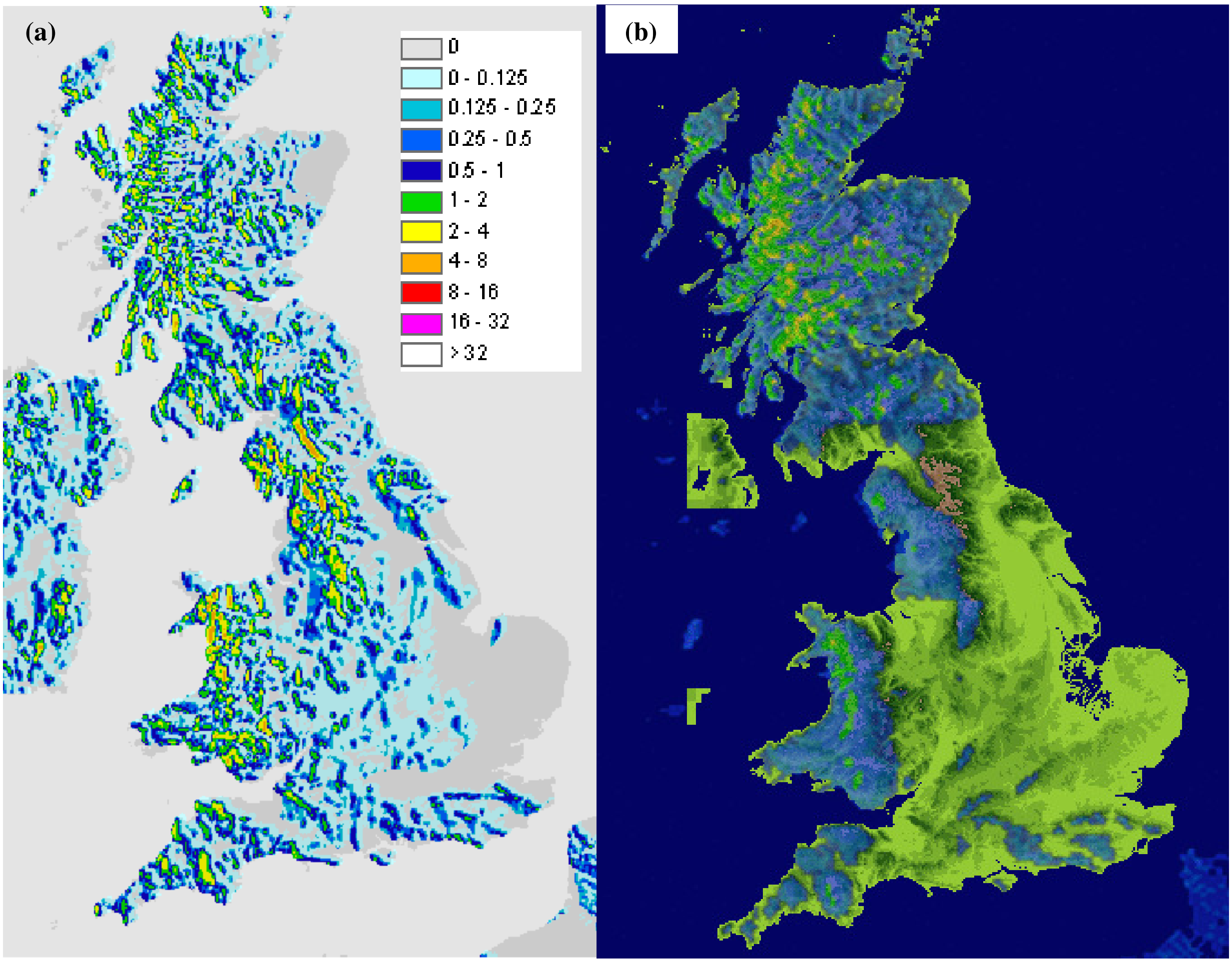


Figure 13.1: (a) Sample orographic correction field derived in real-time using 4 km mesoscale model wind speed, wind direction, relative humidity and temperature data as part of STEPS processing. (b) The corresponding static correction field for similar wind speed and directions applied in the current radar processing chain.

Proposal for future work

It is therefore strongly recommended that further study is conducted to assess the benefits for radar data quality of using the Alpert and Shafir (1989) orographic correction scheme in upland areas across England and Wales. The cases analysed in the current study provide an excellent reference against which any modifications can be assessed. Ideally, the revised scheme should be tested for at least two case study periods of contrasting data quality identified in each of the study periods considered in this study. The cases of 24 October 2005, 3 November 2005 and 10 November 2005 are suitable candidates for further study. If found to improve data quality, the modified correction scheme should be implemented in the operational processing chain. The main tasks required to complete this work are listed below.

- Recover hourly 4 km mesoscale model wind speed, wind direction, temperature and relative humidity data from the data archive during each case study period identified.
- Run existing routines to derive orographic corrections using the Alpert and Shafir (1989) model using 2 km resolution terrain.
- Apply corrections to the existing background radar data timeseries for each case, and scale corrected data by the gauge adjustment factors used at each timestep.
- Re-analyse case study periods, comparing original results with Alpert and Shafir (1989)

results in each region. The relative merits of both schemes should be assessed in terms of the total gauge and radar accumulations for each event and the correlation between hourly gauge and radar accumulations during each event.
- Produce brief summary report showing the impact of applying modified corrections on data quality across the Upper Exe, Upper Conwy and Upper Taff regions.

Should this short study provide evidence that the Alpert and Shafir (1989) model can deliver improved radar data quality, it is proposed that the operational radar processing system is modified to receive STEPS orographic enhancement fields in place of the current orographic corrections and that the current scaling of corrections by relative humidity is removed.

It is anticipated that this work can be achieved within a 5 week period:
- Derivation of correction fields for case study periods: 1 week
- Re-analysis of case study periods: 3 weeks
- (If suitable) Implementation of STEPS orographic corrections operationally: 1 week

Should resources permit, it would be beneficial to assess the relative quality of using the Alpert and Shafir (1989) model compared with more recent alternatives. Such a study would require a systematic review of the available model approaches and comparison of their performance during case study periods. The models developed by Alpert and Shafir (1989), Weston and Roy (1994), Sinclair (1994), Smith (2003) and Kunz and Kottmeier (2006) might be considered for example, with a subset selected for implementation to compare their relative performance during case study events. Further, a more robust assessment of the sensitivity of radar data to the tuning parameters currently employed in the Alpert and Shafir (1989) formulations used as part of the radar processing chain and in the STEPS schemes would be of use. The results of this work would directly impact on the orographic corrections derived for use in both the radar and nowcasting systems used in the Met Office.

13.2 Options for improved radar coverage

The current radar network provides relatively good coverage across the upland areas over the Upper Exe region, moderately good coverage across the Upper Taff region and relatively poor coverage across the Upper Conwy region. Whereas the closest radar to the Upper Exe study area at Cobbacombe Cross is located at a range of about 25 km, the closest radar to the Upper Conwy region at Clee Hill is located at a range of about 110 km. Under typical conditions, the radar beam attains a height of about 1600 m above the surface at this range.

This study has identified how the radars with coverage across the Upper Conwy region are currently successful in identifying the occurrence of rainfall, with average POD values of about 95%. The case study analyses suggest that the spatial variability and quantitative accuracy of the rainfall detected by each radar across the region is almost entirely a function of the magnitude of orographic corrections applied to the background data as part of the processing chain. In contrast, the background radar data across the Upper Exe region from Cobbacombe Cross were in generally good agreement with surface gauge measurements and displayed much of the spatial variability identified from the gauge network. This might suggest that improvements to radar data quality and its use for flood forecasting applications across the Upper Conwy region might be gained from improving the radar coverage and locating a new radar in north Wales.

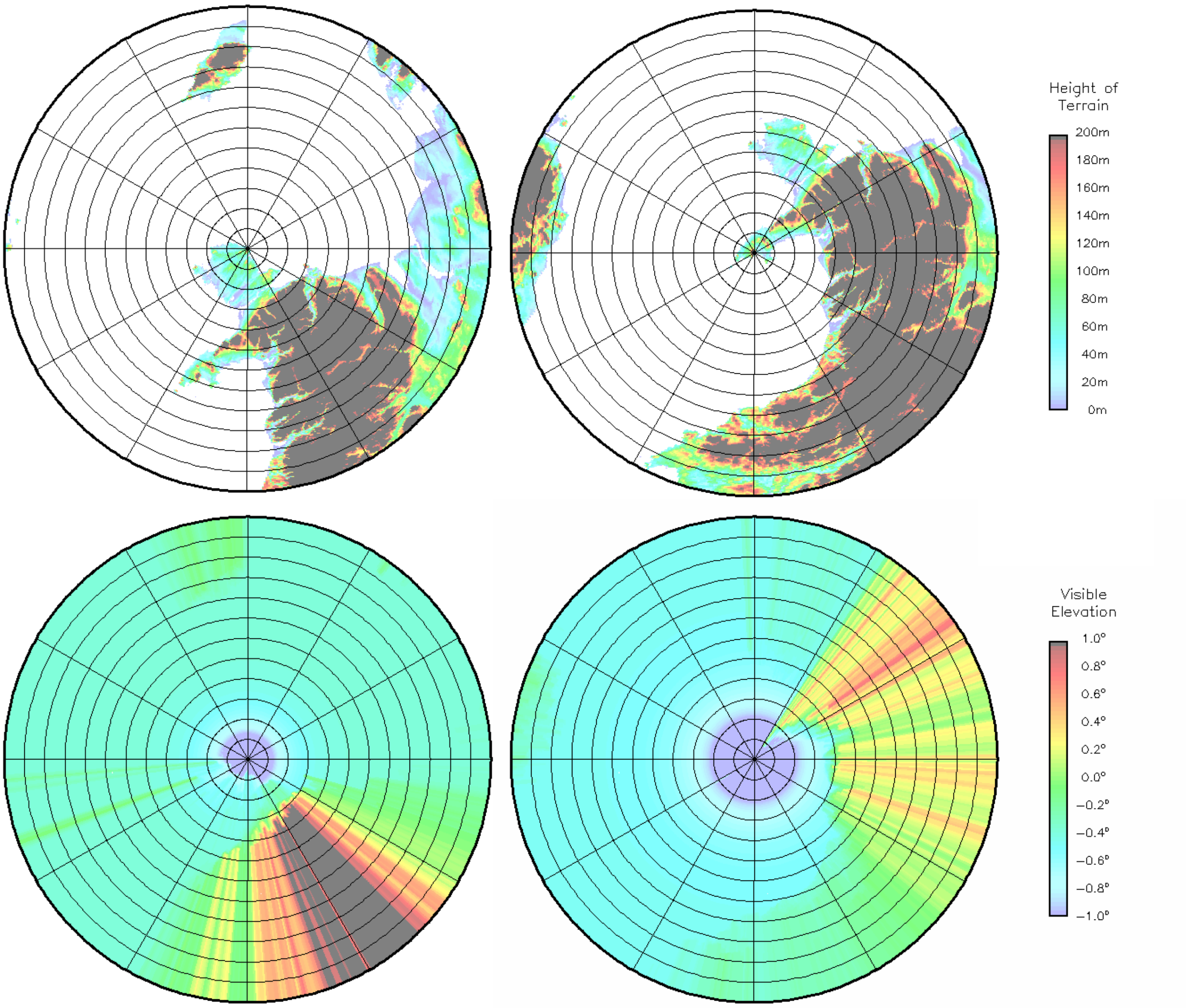
Potential benefits

The results of this study have highlighted the clear dependence of radar data quality on range from the radar. For example, the average RMS values for the closest radars to the Upper Exe, Taff and Conwy study areas calculated for occasions with an hourly accumulation in excess of 1 mm were 1.18, 1.54 and 1.59 respectively. Similarly, the average RMSF values of 2.89, 3.02 and 4.72 show a clear decrease of quantitative accuracy with range. This is because the height of the radar beam above the surface increases with range, increasing the dependence of surface rainfall estimates on the vertical corrections used and increasing the possibility of overshooting low-level precipitation completely. Further, the radar beam sampling volume increases with range, leading to decreasing spatial resolution. In principle, locating a radar within 30 km of the Upper Conwy region might be anticipated to provide similar quantitative accuracy to that observed across the Upper Exe. The most significant difference which would be achieved is that the radar beam might become low enough to be able to detect some of the low-level rainfall enhancement rather than relying on the orographic correction scheme to quantify that enhancement. In addition, the availability of radar data at closer range (lower elevation and higher spatial resolution) may capture some of the very localised, intense rainfall observed in the region, thought to originate from embedded convection within the larger-scale frontal system. Clearly, the addition of a new radar in north Wales would contribute to improved coverage and potentially improved data quality across the whole region, not just the Upper Conwy area itself.

Limitations to improved quality

In practice, it is not expected that a radar located within 30 km of the Upper Conwy region would provide the same level of accuracy as that observed across the Upper Exe. The case study analyses have demonstrated how the Upper Conwy study area is in a region of considerably more complex terrain with more complex rainfall distributions than across the Upper Exe region. As such, a radar located at close range in north Wales is more prone to errors due to beam blockage and ground clutter from the surrounding terrain than exist for Cobbacombe Cross. While some parts of the region may enjoy particularly good radar measurements of low-level rainfall features, it is inevitable that the radar will have restricted visibility of some other valleys where the reliance on radar data from higher elevation beams will requiring strong dependence on VPR corrections and the orographic correction scheme as at present.

The practical options for locating a radar in north Wales were investigated as part of the Weather Radar Network Review (Harrison and Gould 2001). It was acknowledged that identifying locations for a new radar was particularly challenging as a result of the complex topography. Two possible locations in north Wales were identified, although both of these would provide radar coverage at moderate distance rather than being located particularly close to the terrain features of interest across the Upper Conwy region. One possible location identified was at Mynydd Rhiw on the Lleyn Peninsula, located between 50 km and 65 km from the gauge sites considered in this study. The typical beam height at this range would be between 340 and 750 m above the ground surface across the region. This is similar to the coverage currently provided by the Crug-y-Gorllwyn radar across the Upper Taff region. A second possible site was identified at Mynydd Eilian on Anglesey, located between 43 km and 58 km from the Upper Conwy gauge sites. Figure 13.2 shows how a radar at this location would be liable to errors due to beam blockage for elevation angles less than 1°. As such, it is anticipated that typical radar beam heights of between 1240 m and 1575 m above the surface could be achieved. A radar located on north Anglesey is therefore not likely to provide any improvement to radar coverage and data quality than currently provided from the Clee Hill radar.



(a) Mynydd Eilian, Anglesey (177 m ASL) **(b) Mynydd Rhiw, Lleyn Peninsula (304 m ASL)**

Figure 13.2: Topographic map and modeled elevation angle of lowest usable beam within 120 km of potential radar sites in north Wales with coverage across the Upper Conwy region (Harrison and Gould, 2001).

The data across the Upper Taff region analysed in this study suggest that the availability of radar data across the Upper Conwy region at about 50 km range may bring variable data quality, with a more complicated dependence on both the orographic correction and measured data than currently observed across the region. The comparison of case accumulations in the Upper Conwy and Upper Taff study areas discussed in Section 11 also showed very similar performance in terms of radar data reliability for flood warnings between the two regions. Unless any developments of the current orographic correction scheme can provide clear improvements to radar data quality across the Upper Taff region, such that range remained the main limiting factor to data quality in upland areas, it is not thought that the location of an additional radar on the Lleyn Peninsula will bring a sufficient level of improvement required to justify the considerable expense incurred. Development of the radar network across North Wales should be reconsidered for viability once potential improvements to the orographic correction scheme are assessed.

14 Conclusions

This study has provided an assessment of radar data quality in upland areas. The uncertainties in radar measurements provided by the current operational radar processing chain have been quantified for three upland regions of contrasting terrain and radar coverage. Case study analyses have provided an indication of the variability of radar data quality between events characterised by the orographic enhancement process in upland regions and highlighted the main factors which affect this quality. The potential options for improving this quality by addressing these factors have been discussed.

Is radar data quality at long range over hills better or worse than over lowland areas?

It has been shown that radar data quality at long range over hills is currently worse than over lowland areas. Comparison of radar data with rainfall measurements from surface rain gauges over a year period show that typically 97% of hourly rainfall accumulations in excess of 1 mm are detected by the radar, similar to the average detection rate across all regions of the UK. The quantitative accuracy of those data, expressed as RMSF values, is as much as three times worse than observed in more lowland areas however.

What effect does quality of radar coverage over upland areas have on radar data quality?

Range from the radar is the most important factor affecting radar data quality across upland areas. Where a radar is located within 50 km range of an upland area, as observed for the Upper Exe study area, the ability to detect much of the low-level enhancement process at relatively high spatial resolution gives generally good radar data quality similar to that found across more lowland areas. Typically 97% of hourly rainfall accumulations in excess of 1 mm are successfully detected. An average RMS value of 1.18 and RMSF value of 2.89 has been computed for this case. Where the closest available radar is located at long range (in excess of 100 km), such as across the Upper Conwy region, radar data quality is relatively poor. Although typically 95% of hourly rainfall accumulations in excess of 1 mm are successfully detected, the average RMS value of 1.59 and RMSF value of 4.72 show generally poor quantitative agreement between radar rainfall estimates and the corresponding surface gauge measurement. Where radars are available at intermediate range, as across the Upper Taff region, an average RMS value of 1.54 and RMSF value of 3.04 reflect the generally variable radar performance observed.

What are the benefits gained from the current Met Office orographic correction scheme?

The impact of applying orographic corrections to the background radar data was found to be most beneficial for measurements across the Upper Conwy region, leading to improved agreement between radar and gauge data by typically 56%. The application of the current orographic correction scheme was found to improve radar data quality in each of the upland regions considered. For the highest gauges in the Upper Conwy and Upper Taff regions, the orographic corrections were still found to be insufficient to fully correct for a general underestimation of surface rainfall. In these cases, the corrected radar data typically underestimate the observed surface rainfall by 50%.

How variable is radar data quality between events characterised by orographic effects?

Radar data quality is highly variable between different events characterised by orographic effects and between different gauge locations within each region for a given event. Although overall radar data quality across the Upper Conwy region was shown to be poor, the level of agreement between gauges and the radar data during a given event was found to be particularly good. This was attributed to the orographic correction scheme, implying that the assumptions involved in the current scheme matched the observed rainfall characteristics during such events. It was found that almost all of the spatial variation of the radar data across the Upper Conwy region resulted from the addition of orographic corrections, with radar measurement typically detecting only whether any rainfall was present across the region. The radars were unable to capture small-scale features such as short-lived localised rainfall peaks associated with embedded convection in the Upper Conwy and Upper Taff regions. This was attributed to insufficient measurement resolution. Least consistent behaviour during case study events was observed for radar data across the Upper Taff region, where the impact of orographic corrections was found to be particularly variable. Developments to the correction scheme were identified as being necessary to improve data quality in this region. Cases when the radars underestimated surface rainfall by up to 50% at upland gauges in the Upper Exe region were also identified, despite the good radar coverage.

Is radar data over upland areas of sufficient quality for flood forecasting?
How representative are rain gauge measurements in upland areas?

Radar data quality over upland areas is currently of insufficient quality for quantitative use in flood forecasting. Analysis of total rainfall accumulations during rainfall events has shown that typically only 50% of rainfall events during the study period when in excess of 30 mm was recorded by surface gauges would have been detected as exceeding that threshold using the available radar data. The application of spatially and temporally varying orographic corrections was identified as having considerable benefit to these data. While gauge measurements are best suited to measuring surface rainfall at a given location, the inadequate spatial resolution provided by gauge data in upland areas has been highlighted. Used in conjunction with available gauge data and given the knowledge concerning radar data quality gained from this study it seems clear that radar data can be used as a key tool for flood forecasting in upland regions, particularly in those locations where gauge data is unavailable.

Would improvements to the UK weather radar network contribute significantly to improving flood forecasting in upland areas?

An assessment of the likely impact of improving the radar coverage across north Wales suggests that there is little to be gained for flood warning and forecasting in the Upper Conwy region from such a development, particularly given the practical limitations on suitable locations for additional radars in the region. The benefits of developing the radar coverage across the north Wales region should be reconsidered once the performance of the proposed improvements to the orographic correction scheme has been assessed.

Would improvements to the radar data processing contribute significantly to improving flood forecasting in upland areas?

Improvements to the radar data processing are likely to contribute most significantly to improving flood forecasting in upland areas. The quantitative accuracy of radar measurements in upland areas has been found to critically depend on the orographic corrections applied to the available background data, particularly in those upland regions where radar coverage is only available at ranges in excess of 50 km. The dependence of the orographic corrections applied across England and Wales on climatology has been identified as a potential source of error, and it is thought that adoption of a physical modelling approach across the entire radar domain may improve quantitative accuracy of the radar system. This development is likely to bring benefits to radar data quality across upland regions across the UK, other than those considered in this study.

15 Recommendations

1) Conduct an additional study to assess the relative benefits of applying orographic corrections derived using the Alpert and Shafir (1989) model during the case study events. If resources permit, it is recommended that alternative correction formulations are considered. The potential for locating a radar at closer range for coverage across north Wales might need to be reconsidered at this stage if the new formulation is found to improve data quality.

2) If found to produce the necessary improvements to data quality, implement the Alpert and Shafir (1989) as part of the operational radar data processing chain. It is suggested that this is conducted using the orographic enhancement fields currently produced as part of the STEPS post-processing system (Section 13). Should a comparison study of several alternative model approaches be conducted, the best performing correction algorithm should be implemented for use in both the radar and STEPS post-processing systems.

3) Monitor operational performance of radars across upland areas during future events characterised by orographic effects. In particular, it would be beneficial to analyse a strong rainfall event in the Upper Exe region involving northerly flow for which it is known that orographic enhancements in the region are largest. This would provide a very useful characterisation of radar performance at close range in conditions of orographic enhancement.

4) Develop radar data quality indicators, based on the magnitude of orographic corrections applied and complexity of the underlying terrain, to highlight regions and periods of increased uncertainty of the radar data. It is envisaged that these quality indicators should vary both spatially and temporally, defined for each radar pixel for every radar scan. Such information may be utilised in the selection of radar data to include in the composite product and is likely to be of use to highlight the level of uncertainty in rainfall measurements to flood forecasters.

5) Update the training material provided to Environment Agency flood forecasters to reflect the new understanding of radar data quality in upland areas and of its use for flood warning applications in these regions provided by this study.

6) Update the training material provided to Met Office forecasters to include guidance on radar data quality in upland areas.

Appendix I: Statistics

If

A = rain detected by gauge and rain detected by radar
B = rain detected by gauge but no rain detected by radar
C = no rain detected by gauge but rain detected by radar
D = no rain detected by gauge and no rain detected by radar

then define

Probability of detection (POD) = $\frac{A}{A+B}$ *perfect = 1*

False alarm ratio (FAR) = $\frac{C}{A+C}$ *perfect = 0*

Critical success index (CSI) = $\frac{A}{A+B+C}$ *perfect = 1*

These values are calculated for all instances where either the radar or gauge data is greater than or equal to a given rainfall accumulation threshold.

Given the gauge and radar data timeseries with elements $G = \{G_1 + G_2 + ... + G_N\}$ and $R = \{R_1 + R_2 + ... + R_N\}$ the following statistical measures of accuracy can be defined. These are defined for N events where both the gauge and radar values are in excess of a threshold rainfall accumulation.

Bias = $\frac{1}{N}\sum_{i=1}^{N}(R_i - G_i)$ *perfect =0*

Ratio of total accumulations = $\frac{\sum_{i=1}^{N} R_i}{\sum_{i=1}^{N} G_i}$ *perfect = 1*

Root mean square error (RMS) = $\left(\frac{1}{N}\sum_{i=1}^{N}(R_i - G_i)^2\right)^{\frac{1}{2}}$ *perfect = 0*

Root mean square factor (RMSF) = $\exp\left[\left(\frac{1}{N}\sum_{i=1}^{N}\left(\ln\frac{R_i}{G_i}\right)^2\right)^{\frac{1}{2}}\right]$ *perfect = 0*

These values are calculated for all instances when both the radar and gauge are greater than zero and either the radar or gauge measurement is greater than or equal to a given rainfall accumulation threshold.

References

Alpert, P. 1986: Mesoscale indexing of the distribution of orographic precipitation over high mountains. *J. Clim. and Appl. Meteorol.,* **25**, p 532-545

Alpert, P. and Shafir, H., 1989: Meso-γ distribution of orographic precipitation: numerical study and comparison with precipitation derived from radar measurements. *J. Appl. Meteorol*., **28**. 1105-1117

Alpert, P. and Shafir, H., 1989: A physical model to complement rainfall normals over complex terrain. *J. Hydrol.*, **110**, p 51-62

Alpert, P. and Shafir, H., 1991: Role of detailed wind-topography interaction in orographic rainfall. *Q. J. R. Meteorol. Soc.*, **117**, p 421-426

Bader, M.J. and Roach, W.T., 1977: Orographic rainfall in warm sectors of depressions. *Q. J. R. Meteorol. Soc.*, **103**, p 269-280

Bergeron, T., 1965: On the low-level redistribution of atmospheric water caused by orography. *Suppl. Proc. Int. Conf. on Cloud Physics,* Tokyo 1965, p 96-100

Bleasdale, A. and Douglas, C.K.M. 1952: Storm over Exmoor on August 15 1952. *Meteorol. Mag.*, **81**, p 353-367

Bradley, S.G., Gray, W.R., Pigott, L.D., Seed, A.W., Stow, C.D. and Austin, G.L. 1997: Rainfall redistribution over low hills due to flow perturbation. *J. Hydrology*, **202**, p 33-47

Browning, K.A., Hill, F.F. and Pardoe, C.W. 1974: Structure and mechanism of precipitation and the effect of orography in a wintertime warm sector. *Q. J. R. Meteorol. Soc.*, **100**, p 309-330

Burt, S. 2005: Cloudburst upon Hendraburnick Down: The Boscastle storm of 16 August 2004. *Weather*, **60**, p 219-227

Carruthers, D.J. and Choularton, T.W., 1983: A model of the feeder-seeder mechanism of orographic rain including stratification and wind drift effects. *Q. J. R. Meteorol. Soc.*, **109**, p 575-588

Collier, C.G., 1996: Applications of weather radar systems: a guide to uses of radar data in meteorology and hydrology. John Wiley and Sons Ltd

Dore, A.J. and Choularton, T.W., 1992: A three-dimensional model of airflow and orographic rainfall enhancement. *Q. J. R. Meteorol. Soc.*, **118**, p 1041-1056

Douglas, C.K.M., Glasspole, J. 1947: Meteorological conditions in heavy orographic rainfall in the British Isles. *Q. J. R. Meteorol. Soc.*, **73**, p 11-38

Driscoll, S.J., Harrison, D.L. and Kitchen, M. 1997: Heavy rainfall over Exmoor on 26/27th June 1997 – an assessment of radar data quality. *Observations Based Products Technical Report No. 5*, Meteorological Office, UK (unpublished)

Gray, W.R. and Seed, A.W. 2000: The characterisation of orographic rainfall. *Meteorol. Appl.*, **7**, 105-119

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

Harrison, D.L. and Gould, C. 2001: Weather radar network review. Met Office/Environment Agency Project Report (unpublished)

Hill, F.F., Browning, K.A. and Bader, M.J. 1981: Radar and raingauge observations of orographic rain over South Wales. *Q. J. R. Meteorol. Soc.*, **107**, p 643-670

Hill, F.F. 1983: The use of average annual rainfall to derive estimates of orographic enhancement of frontal rain over England and Wales for different wind directions. *J. Clim.*, **3**, p 113-129

Joss, J. and Lee, R. 1995: The application of radar-gauge comparisons to operational precipitation profile corrections. *J. Appl. Meteorol.,* **34**, 2612-2630

Joss, J. and Waldvogel, A. 1990: Precipitation measurements and hydrology. In *Radar in Meteorology. Batten Memorial and 40th Radar Meteorology Conference.* Ed. D. Atlas, American Meteorological Society, p 577-606

Kitchen, M. and Blackall, R.M. 1992: Orographic rainfall over low hills and associated corrections to radar measurements. *J. Hydrol.*, **139**, 115-134

Kunz, M. and Kottmeier, C. 2006: Orographic enhancement of precipitation over low mountain ranges. Part I: Model formulation and idealized simulations. *J. Appl. Meteorol.,* **45**, 1025-1040

Robichaud, A.J. and Austin, G.L. 1988: On the modelling of warm orographic rain by the seeder-feeder mechanism. *Q. J. R. Meteorol. Soc.,* **114**, 967-988

Roe, G.H. 2005: Orographic precipitation. *Ann. Rev. Earth Planet Sci.,* **33**, 645-671

Roe, G.H. and Baker, M.B. 2006: Microphysical and geometrical controls on the pattern of orographic precipitation. *J. Atmos. Sci.,* **63**, 861-880

Sibley, A. 1995: Analysis of heavy orographic rainfall over North Wales, 3 and 4 February 2004. *Weather*, **60**, p 31-36

Sinclair, M.R. 1994: A diagnostic model for estimating orographic precipitation. *J. Appl. Meteorol.*, **33**, 1163-1175

Smith, R. 1979: The influence of mountains on the atmosphere. *Adv. Geophys.*, **21**, p 87-230

Smith, R.B. 2003: A linear upslope-time-delay model for orographic precipitation, *J. Hydrology*, **282**, 2-9

Seo, D.-J., Breidenbach, J.P. and Johnson, E.R. 1999: Real-time estimation of mean field bias in radar rainfall data. *J. Hydrology*, **223**, p 131-147

Weston, K.J. and Roy, M.G. 1994: The directional-dependence of the enhancement of rainfall over complex orography. *Met. Apps.*, **1**, 267-275

Wood, S.J., Jones, D.A. and Moore, R.J. 2000: Accuracy of rainfall measurement for scales of hydrological interest. *Hydrology and Earth System Sciences*, **4**, 531-543