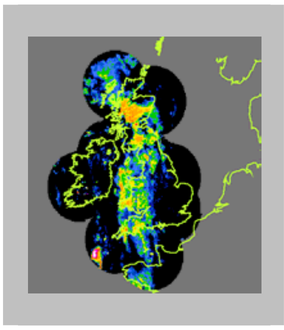

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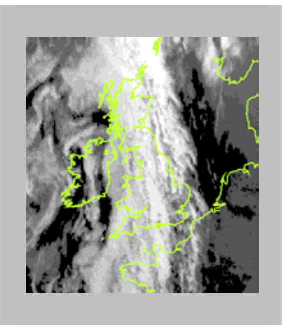

Improving precipitation estimates from weather radar using quality control and correction techniques

by

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Errors and uncertainty in radar estimates of precipitation result from both errors in the basic measurement of reflectivity and from attempts to relate this to the precipitation falling at the ground. If radar data are to be used to their full potential it is essential that effective measures are taken to mitigate these problems. The automatic processing of radar data which forms part of the UK Met. Office's Nimrod system addresses a number of specific sources of error. These include the identification and removal of spurious echoes resulting from anomalous propagation of the radar beam, errors resulting from variations in the vertical profile of reflectivity and radar sensitivity errors. Routine verification of the surface precipitation estimates has been undertaken, largely through comparison with rain gauge observations, over a range of timescales, which has allowed the benefits of the quality control and correction processes to be quantified. Although the improvement derived various according to the dominant synoptic situation an average reduction in the root-mean- square difference of 30% can be achieved..

1. Introduction

The quantitative use of radar data in both meteorological and hydrological applications has been limited by errors and uncertainty in the derived surface precipitation estimates. These arise in both the basic measurement of reflectivity and from attempts to relate this to the precipitation falling at the ground. If radar data are to be used to their full potential it is important that effective quality control and correction procedures are adopted to address these problems.

The automatic processing of radar data from a network of 15 C-Band radars forms part of the UK Meteorological Office's Nimrod system (see Golding (1998) for a general description). The radar data processing within Nimrod aims to address a number of types of error. The various techniques employed utilise a wide range of meteorological information, including numerical weather prediction (NWP) model output, satellite imagery and rain gauge data, as well as information relating to radar characteristics.

To assess the impact of the radar data quality control and correction procedures used, routine verification of the radar data is performed, mainly by comparison with rain gauges. The aims of the verification include:

- to help identify systematic errors in the basic radar measurements and to assist technicians to diagnose the underlying radar faults.
- to inform users as to the quality of the surface precipitation estimates produced.
- to highlight strengths and weaknesses in correction and quality control procedures.
- to help set priorities for further development.

Verification of the surface precipitation estimates is performed on a range of spatial and temporal scales. Verification based on long-term integrations of data have proved particularly valuable for highlighting residual systematic errors in the radar processing. In-depth investigations of specific heavy rainfall and flood events are also carried out, since it is the accuracy of the data on these occasions that is of greatest concern to hydrologists.

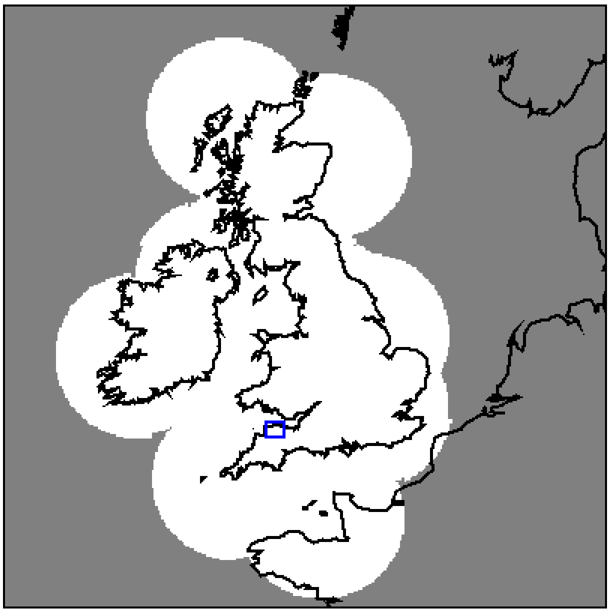


Figure 2.1. *Coverage of the British Isles provided by the current radar network (at 5km resolution).*

2. Radar data processing

Radar images from the 15 C-band (5.3 cm wavelength) radars around the British Isles (illustrated in fig. 2.1), at 5 km and 2 km resolution, are received by the Nimrod system at 15 minute and 5 minute intervals respectively. A significant amount of processing is performed at the radar sites including removal of permanent ground clutter by means of a fixed clutter map, conversion of measured reflectivity *(Z)* to precipitation rate *(R)* using a constant *Z-R* relationship $Z=200R^{1.6}$, spatial averaging and conversion from polar to cartesian co-ordinates (Archibald & Smith, 1997). Subsequent processing within the Nimrod system is described in sections 2.1-4.

2.1 Identification and removal of corrupt radar images

Complete images can be affected by either radar hardware or data transmission faults. For such cases complete images require discarding before any subsequent processing is attempted. The frequency distribution of echo intensities within an image is examined and the radar image rejected if the distribution falls outside the meteorological bounds suggested by Cheng & Brown (1993).

A method, described in Smith & Kitchen (1998), in which images from each radar are compared with those previously received from that radar and also with data from adjacent radars in the region of overlapping coverage (shown in Figure 2.1) is then used to help diagnose radar faults. Comparison statistics are generated which identify any sudden changes in the output level from a radar which could be indicative of, for example, a transmitter failure. If the change exceeds a specified threshold then the image can be excluded from further processing.

2.2 Identification and removal of anomolous propagation

The presence of spurious radar echoes, often resulting from anomalous propagation of the radar beam (anaprop), is a common source of radar error. Within Nimrod, infra-red and visible images from Meteosat are combined with elements of surface synoptic reports (present weather, cloud type and amount) to assess the probability of precipitation (PoP) using a method which is a development of that described by Pamment and Conway (1998). If the PoP is lower than a specified threshold then an echo is deleted from the radar image. The threshold PoP is set at a level such that the probability of removing real precipitation is extremely small. An example is shown in fig. 2.2.

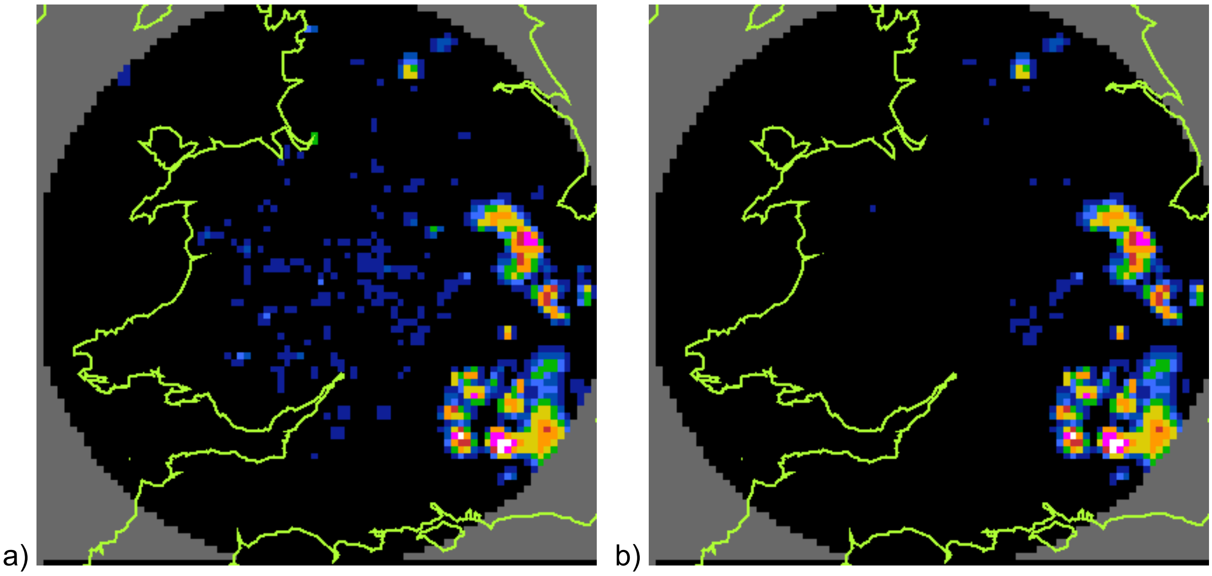


Figure 2.2. *An example showing the removal of spurious echoes for a Clee Hill radar image: a) shows the raw radar image and b) shows the image after deletion of spurious echoes.*

2.3 Accounting for variations in the vertical reflectivity profile

Several kinds of radar error (bright band, range, orographic growth) are all manifestations of variations in the vertical profile of reflectivity factor. The resulting errors can be very serious; typically up to a factor of five if left uncorrected (Joss & Waldwogel, 1990). Nimrod uses a physically-based correction scheme in which an idealised vertical profile of reflectivity is diagnosed

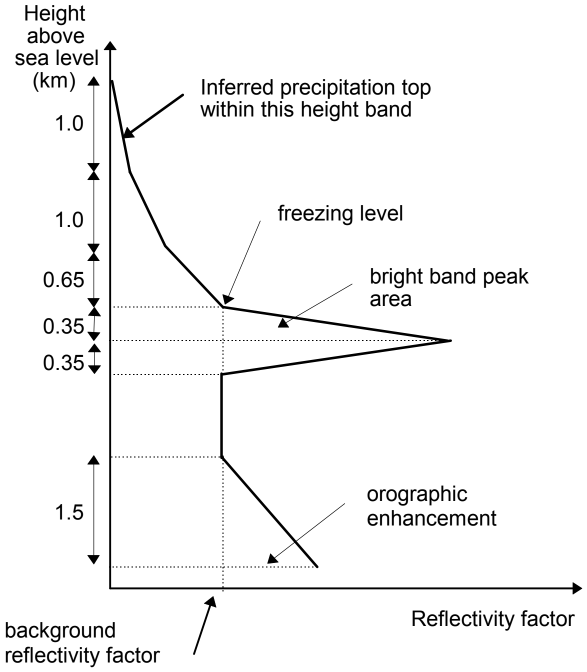


Figure 2.3. *Example of the construction of the isealized vertical reflectivity factor profile used in the correction method.*

at each radar pixel (Kitchen et al, 1994). The idealised profile, shown in Figure 2.3, incorporates simple parametrizations of the bright band and orographic growth of precipitation over hills. The method also uses a map of the radar horizon to make explicit corrections for occultation of the radar beam.

The correction scheme requires the following inputs:

- the background reflectivity factor
- freezing level height (from the UK Met. Office's mesoscale NWP model (UKMES))
- cloud top height (from Meteosat IR imagery and UKMES fields)
- the magnitude of anticipated orographic enhancement
- ground height above sea level
- radar parameters (beam elevation angle, beam occultation angle and radar range)

The parametrized vertical profile is then weighted by the radar-beam power profile and the surface precipitation rate found by an iterative method.

Fig 2.5 illustrates the sort of impact the correction scheme can have. A ring of enhanced rain rates is detectable in the raw image, indicating bright band contamination. After application of the vertical profile corrections this has been largely eliminated and rainfall rates over higher ground and at long range have been generally increased.

2.4 Gauge Adjustment

A crucial assumption of the vertical profile correction process that radar sensitivity is correct and stable. At any particular time, it is possible for a number of the network radars to have significant calibration errors. An adjustment factor, based upon

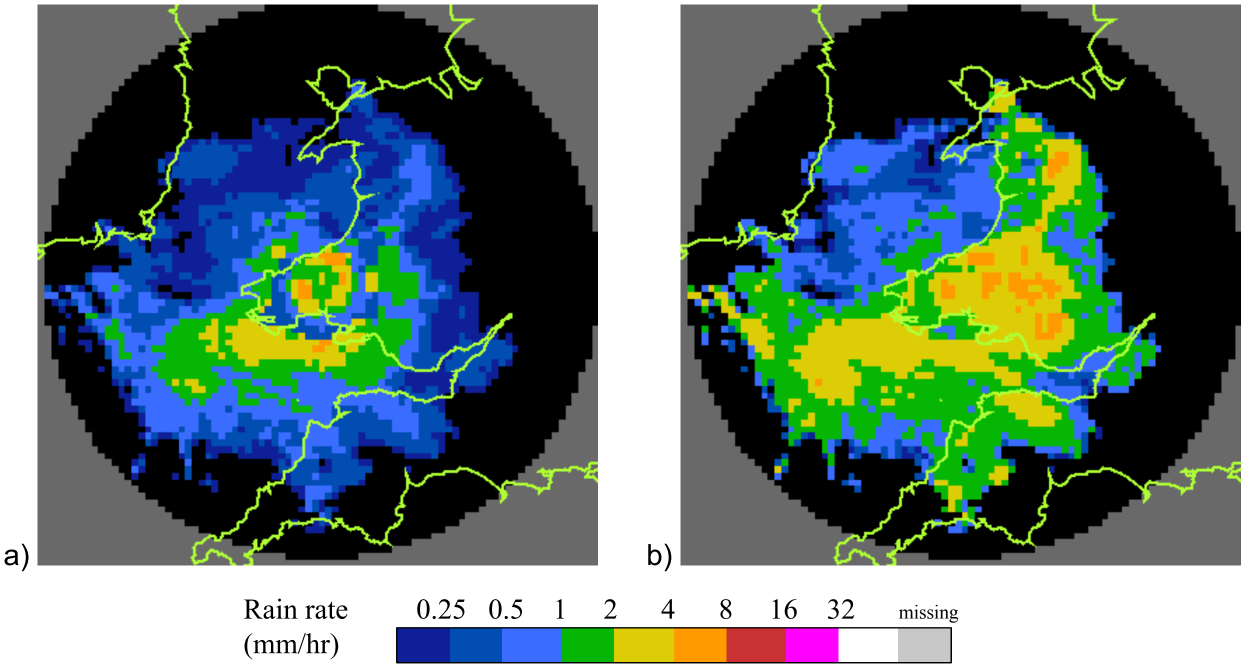


Figure 2.4. *An example illustrating the impact of the vertical profile correction scheme for a Crug-y-gorllwyn radar image: a) shows the image before and b) after the vertical profile corrections scheme has been applied.*

the results of comparing quality controlled and corrected radar data with hourly rain gauge reports (Hackett and Kitchen, 1995), is applied in an attempt to overcome this. Rain gauge data are not used to provide spatially varying corrections because the representativeness errors for individual gauges are often comparable to the required adjustment: the vertical profile correction procedure is designed to address the main sources of spatial variability. To try and avoid the imposition of detrimental adjustments, only comparisons meeting the following criteria are used in the adjustment process:

- the gauges must lie within 100 km of the radar.
- the radar must have detected precipitation in the gauge pixel during most of the hour.
- both radar and gauge must have recorded > 0.2 mm during the hour.
- the gauge must not be in an area subject to frequent clutter or anaprop.

Adjustment is only considered once per week and a factor is only applied if it deviates significantly from unity and has passed a significance test. The adjustment factor is calculated as the ratio of the gauge accumulation (integrated over all valid comparisons) to the integrated radar total.

3. Verification

In order to assess the impact of the radar data quality control and correction processes applied within Nimrod extensive verification has been undertaken, largely in the form of comparison with hourly rain gauge observations. Interpreting the results is in itself problematic, due to the different sampling volumes of the two instruments: rain gauges record precipitation accumulation at a point, whereas the radar measures some average instantaneous reflectivity in a sample volume, at intervals (typically 5 or 15 minutes). The impact of the different sampling strategies is greatest in convective situations, where spatial gradients are large and the life-time of individual storm cells may be similar to the radar scan cycle (Seed et al., 1996). In order to minimise the effect of these repesentativeness errors, verification over longer time periods has been introduced, and checks which examine the self-consistency of the radar data.

3.1 Gauge - radar comparisons

Hourly reporting rain gauges have been used to verify the quality controlled and corrected radar data. The Nimrod corrections can sometimes dramatically reduce the observed differences. The magnitude of this reduction varies greatly, depending on many factors including the dominant type of rainfall (frontal/convective), and the degree to which bright band and orographic effects impact on the raw data. Over a period of 12 months, the average reduction in the root-mean square difference was approximately 30%

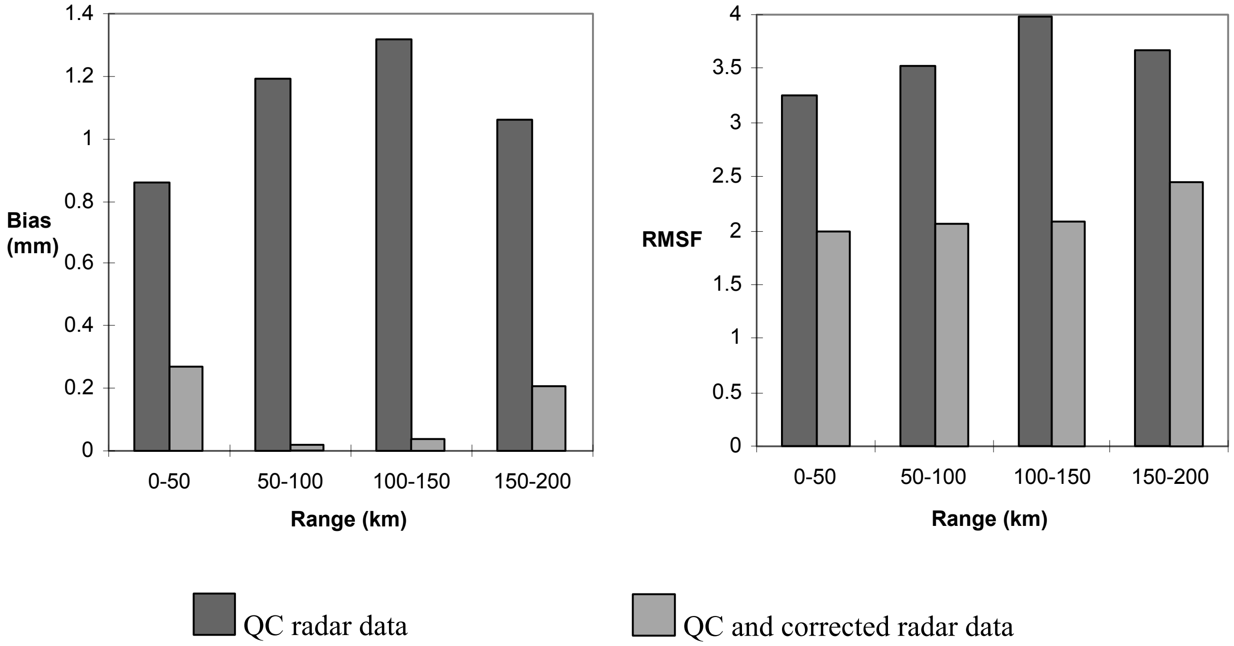
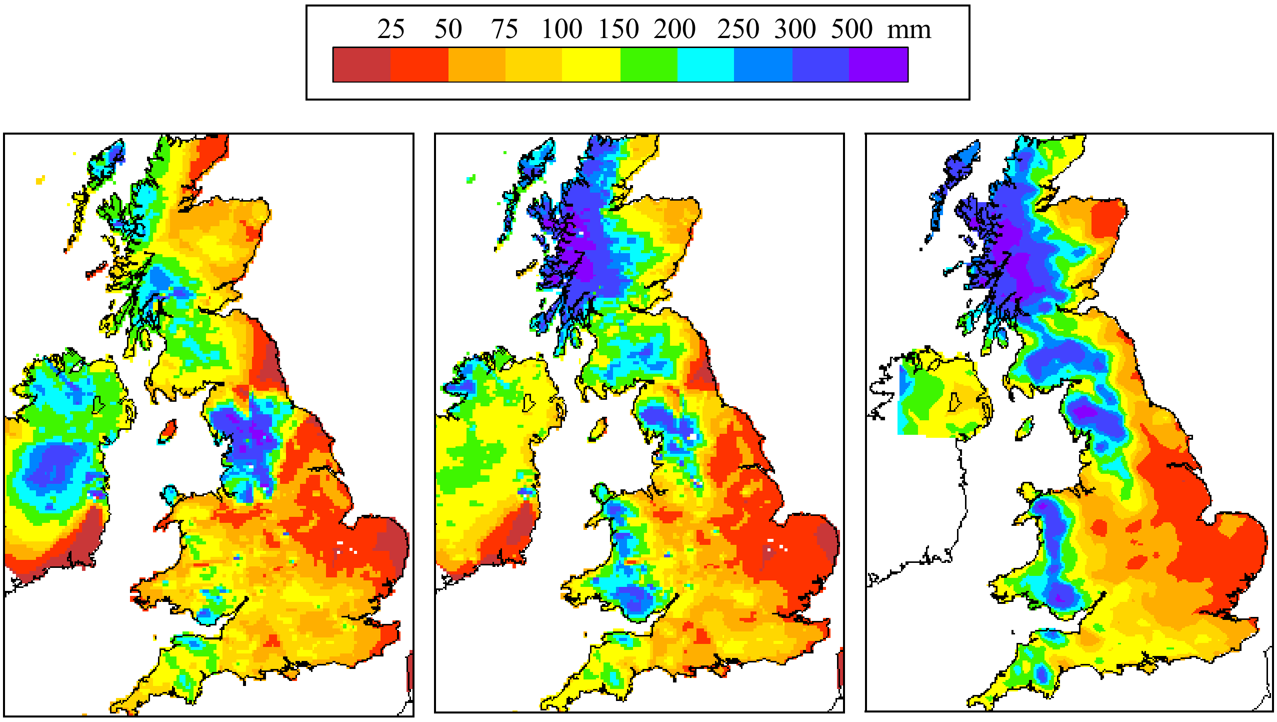


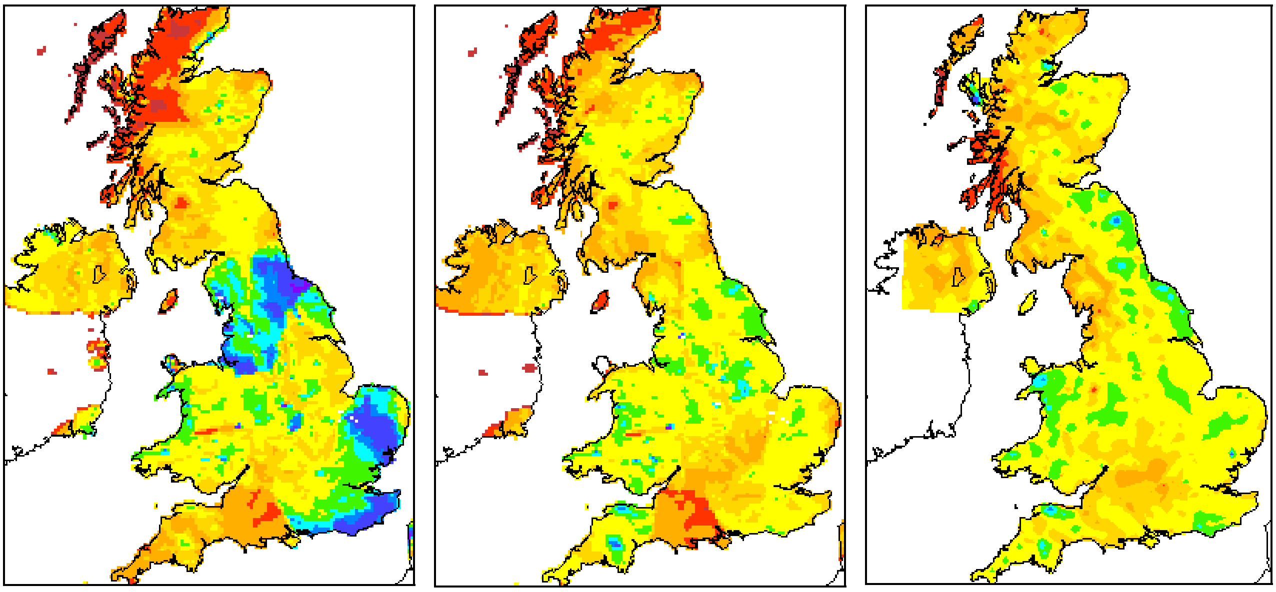
Figure 3.1. *Histograms showing the a) mean and b) rms factor difference between hourly gauge and radar rain accumulations over a period of one month: February 1997, using Crug-y-Gorllwyn radr data.*

Fig 3.1 shows the bias and random errors in hourly comparisons, averaged over a period of one month, for the Crug-y-Gorllwyn radar in south-west Wales. The comparisons are divided into different intervals of radar range to provide some assessment of the vertical reflectivity profile corrections. In this case the reduction in bias and scatter was achieved mainly by adjustment for radar insensitivity and the addition of orographic corrections (corrections of up to several mmh^{-1} can be applied over the South Wales hills in winter-time frontal rainfall). Representativeness errors place a lower limit on the RMS and RMSF values that can be achieved. RMSF values of around 2 are typical of corrected 5km radar data at all except the longest ranges.



Raw radar data *Quality controlled and corrected radar data* *Rain gauge data*

Figure 3.2*: Monthly rainfall accumulations for February 1997*



Raw radar data *Quality controlled and corrected radar data* *Rain gauge data*

Figure 3.3*: Monthly rainfall accumulations for June 1997*

Figs 3.2 and 3.3 show rainfall accumulations for two months during 1997, derived from the network of daily reporting rain gauges, Nimrod quality controlled and corrected radar data and data as received from the radar sites. The radar-derived monthly rainfall maps from Nimrod are in reasonable agreement with gauges, which is encouraging given the magnitude of the corrections which have been applied to the raw data. February 1997 was a month dominated by frontal rainfall, generally approaching from the South West. Under such conditions orographic effects have a significant impact on precipitation. It is difficult to examine the performance of the corrections for orographic growth using hourly gauge data because of their scarcity in upland regions. The network of 5000+ daily rain gauges in the UK is able to resolve the spatial detail in rainfall distribution caused by orographic enhancement, albeit over longer timescales than is ideal and not in real-time.

By contrast, in June 1997 it was bright band contamination which was the dominant source of error in the raw radar data. This is particularly noticeable in South East England where the monthly rain accumulations differ from the gauges by up to a factor of 5. During both months, calibration problems were experienced with the Hameldon Hill radar in North West England. The application of a gauge adjustment factor helped to reduce the impact of this problem. The remaining differences reflect residual systematic errors in the corrections and inherent problems in the radar measurement technique.

3.2 Long term integrations of radar data

Much information can be gained from looking at the self-consistency of radar data once small scale spatial and temporal variations in precipitation have been removed by time averaging. In particular, range dependent biases become apparent when quantities such as conditional average rainfall rate are plotted as a function of radar range (see Smith et al. for a similar study with NEXRAD precipitation estimates). Figure 3.4a exhibits evidence of the effect of the bright band in a winter month with enhanced rainfall rates out to approximately 70 km from the radar. This anomaly is largely removed by the vertical reflectivity profile corrections within Nimrod. At longer ranges, the Nimrod corrections have increased the rainfall rates over and above that prescribed by the range corrections applied at the radar site. It is reasonable to expect some increase in the conditional mean estimated surface rainfall rate at long range. This is because detection failures are significant at long range (Kitchen and Jackson, 1993) and therefore precipitation estimates will be biased towards those from deeper cloud, which are less likey to suffer from complete radar beam overshooting.

In the summer months the radar beam typically encounters the bright band at longer ranges, as shown in Figure 3.4b: its effect is clearly evident in the raw radar data around 100-150 km range. This shows that the bright band can be a serious problem, even in summer when rainfall is often convective. Again, the Nimrod corrections appears to have largely eliminated the spurious increase in the mean rainfall rates in this range band, although case studies have shown that overcorrection occurs in some situations (see section 3.3). This was confirmed by the results of hourly gauge comparisons which showed that at ranges 100 - 150 km, the mean gauge-radar difference was -1.1 mm compared to 0.4 mm for the corrected radar data.

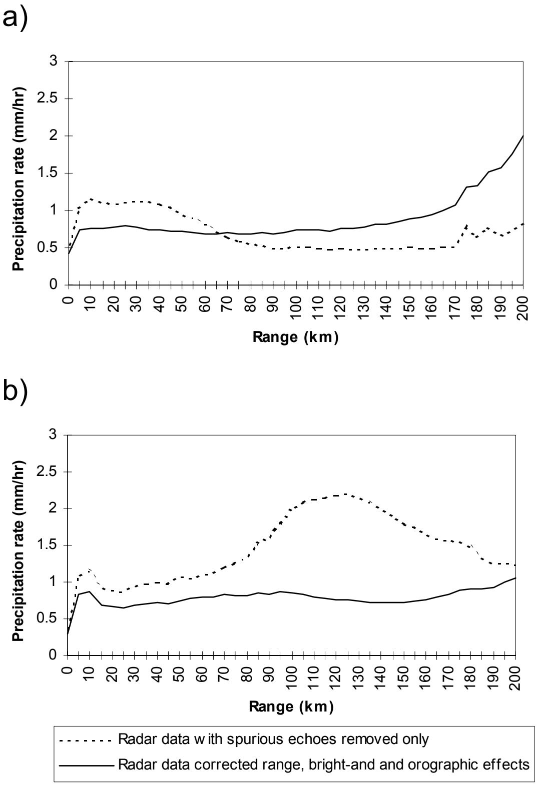


Figure 3.4. *Conditional average rain rate versus range for Chenies radar data, a) February 1996, b) August 1996.*

Whilst these results suggest good performance from the Nimrod vertical profile correction scheme overall, it is recognised that the accuracy of the surface precipitation estimates will vary considerably between individual cases.

Graphs such as Figure 3.4 can sometimes enable radar faults to be identified, for example range-dependent sensitivity. Monthly integrated data in image form (i.e. before averaging in azimuth) enables deficiencies in the occultation corrections and localised problems with persistent clutter to be identified (Lord et al, 1995).

3.3 Case Studies

Although routinely generated statistics are extremely useful in terms of assessing the general effectiveness of the quality control and correction processes, it is their performance during critical heavy rainfall events that is of most significance to operational hydrologists. Case study investigations are carried out on a number of such events. These have been useful for identifying strengths and weaknesses with the current radar data processing within Nimrod, which are not always apparent from

Table 3.1: *Summary of case study investigations*

Location/ Date	**Description**	**Overall impact of QC and corrections**	**Lessons learnt**
7th June 1996	Widespread severe thunderstorms and hail over Southern/Central England.	Positive. Raw radar data overestimated precipitation. Corrected data in better agreement.	Bright band corrections can have a positive impact even in convective situations. However, radar precipitiation rates, which are based on a single Z-R relationship will overestimate precipitation in hail. This may partially account for the improved agreement achieved.
12th August 1996	Convective storm causing flooding in Folkestone, Kent.	Negative. Raw radar data gave good agreement with gauge estimates. Corrected data underestimated rainfall by over a factor of 2.	Bright band corrections had a detrimental impact in this case. Highlighted need to seek an alternative correction method to be applied in strongly convective situations
8th July 1997	Thunderstorms over South West London, giving over 50 mm of rain in Leatherhead, Surrey in a single hour.	Slightly positive.	Storms occurred at a range where bright band corrections had little impact. Improvement mainly due to gauge adjustment factor applied.
26th June 1997	Convective storms causing minor flooding in Bognor Regis, West Sussex.	Negative. Raw radar data gave good agreement with gauge estimates. Corrected data significantly underestimated rainfall.	Confirmed lessons from Folkestone Storm
Exmoor, 26th -27th June 1997	Persistant, heavy rainfall over Exmoor, giving over 100mm in 24 hours.	Positive. A combination of gauge adjustment and orographic corrections resulted in improved agreement with observed rainfall.	Highlighted value of radar data in otherwise data sparse areas. This event was poorly observed by the gauge network. Radar data, gave good representation of the spatial variability of rainfall over a relatively small area.
8th - 10th April 1998	Continuous heavy rainfall resulting in widepread flooding across Central England.	Positive. Raw radar data significantly underestimted rain rates. Corrected data generally in good agreement with gauges.	Improvement largely due to effects of gauge adjustment.

the monthly quality evaluations. Table 3.1 gives a summary of cases that have been investigated, together with details of the effectiveness of the Nimrod quality control and correction processes.

Investigation of a number of cases of severe convective storms highlighted a specific problem with the vertical profile correction scheme. At present, a bright band correction is always applied where the radar beam intersects the melting layer. Although this is a reasonable assumption for frontal rainfall, for convective rainfall a recognisable bright band is sometimes absent (Smyth and Illingworth, 1998). This was particularly evident on the 12/08/96, when intense convective storms generated around 100mm of rain over the Folkestone area of South East England over a 4 hour period. In this case, the assumption of a bright band always present led to significant underestimation of the storm total. As a result, an amendment to the correction scheme, based on the proposal of Smyth and Illingworth (1998), was developed and tested (Kitchen and Driscoll, 1997). Smyth and Illingworth suggest that a 30dDz threshold reflectivity at ~1500m above the freezing level can be used to distinguish between snow and graupel aloft. Since graupel would not be expected to produce a significant bright band effect on melting this threshold can be used to identify occasions when a bright band correction should not be applied. This scheme will be introduced operationally as the necessary higher elevation scan data become available from the network radars in real time.

Another investigation was carried out following heavy and prolonged rainfall over Exmoor, in South West England, on 26-27th June 1997 (Driscoll et al., 1997). Due to the relatively small area affected (~1000 km^2), the event was poorly observed by the Met. Office synoptic observing network. For such cases, greater reliance has to be placed on radar data for issue of severe weather warnings. This, and other cases, has highlighted the need to improve the representation of small scale variations in rain rate by extending the real-time processing of higher resolution (2km/5minute) data within Nimrod to all the radars in the UK network.

4. Conclusions

The verification results outlined above demonstrate the benefit of quality control and correction of radar data. Comparison with hourly gauge accumulations suggests that the RMS fractional error in the radar estimates is within factor of two. Representativeness errors are likely to make up a significant part of this remaining difference. The results also indicate that the contribution of individual sources of error varies considerably in space and time. This highlights the importance of trying to address a whole range of error types. Both routine and event specific verification have pointed to areas of weakness in the current radar processing performed within Nimrod. This has helped determine priorities for future development work. Enhancements to the system in the near future will concentrate on increasing the use of radar data from higher elevation scan angles (to enable a method for avoiding detrimental bright band corrections in severe convection to be implemented) and at higher spatial resolution. The diagnosis of spurious radar echoes has also been identified as an area where significant improvement in performance is required.

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