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

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Errors and uncertainty in radar estimates of precipitation result both from 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 that 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 varies according to the dominant synoptic situation, an average reduction in the root-mean-square difference between gauge and radar data 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 (see section 2). 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 (5.3 cm wavelength) radars forms part of the UK Meteorological Office's Nimrod system (for a general description see Golding, 1998). The radar data processing within Nimrod aims to address a number of specific 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 the following:

- 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 has 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.

2. Problems with using radar to measure precipitation

There are many problems with using radar to estimate precipitation falling at the ground. Some of the main causes of significant errors are outlined in the following paragraphs (for a more comprehensive description of sources of radar error see Collier, 1996).

(a) Radar calibration and stability problems

Accurate precipitation estimates rely on stable radar hardware components (transmitter, receiver etc.) and an accurate sensitivity calibration. With up-to-date hardware such errors can be limited to within 2 dB or 36% error in precipitation rate (Joss & Waldvogel, 1990). Some of the radars in the UK network are now relatively old (up to 20 years) and maintaining stability of the hardware is more difficult. As a result, errors resulting from calibration and stability problems are likely to be significantly larger than quoted above.

(b) Contamination by clutter and anaprop

Ground clutter results where either the main radar beam or the side lobes encounter ground targets. Such echoes are often permanent and hence techniques which utilise a map of ground clutter locations to discard coincident radar echoes are often relatively successful. However, returns from ground targets which occur under conditions of anomalous radar beam propagation (anaprop) are more unpredictable in terms of location.

(c) Occultation

Occultation results where part of the radar beam is intercepted by the ground and causes a reduction in the radar beam power (and hence a reduction in the backscattered radiation from precipitation targets) at ranges beyond the obstacle.

(d) Attenuation

Attenuation of the radar signal by rain is a significant problem and one that becomes increasingly severe at wavelengths shorter than 10 cm (and one which is therefore a problem at C-band). The magnitude of attenuation at any point in range is approximately proportional to rain rate, but its effects are cumulative with range. In extreme conditions of heavy rain the entire radar signal may be lost. It is therefore important that steps are taken to mitigate its effects if reliable quantitative estimates of precipitation are to be obtained.

(e) Assumptions made about the drop size distribution

The relationship between measured reflectivity (Z) and precipitation rate (R) depends upon the nature of the drop size distribution (since Z is proportional to the sum of the sixth powers of the particle diameters). When employing empirical relationships of the form $Z = aR^b$ the most appropriate values for a and b depend on the type of precipitation being sampled and can differ greatly: Collier (1996) gives details of some of the typical relationships for particular rainfall types. It is recognised that use of a fixed Z–R relationship for all precipitation types will lead to uncertainty in the derived precipitation rate, which will be particularly significant in hail, for example.

(f) Variations in the vertical profile of reflectivity

Significant variability in the vertical profile of reflectivity occurs as a result of precipitation growth, evaporation, melting of ice particles and snow flakes and wind shear. Such variations mean that there can be large differences between the precipitation rate derived from the radar measurement and that occurring at the ground. Variations in the vertical profile of reflectivity are particularly pronounced where melting occurs. As melting begins, snow flakes acquire a shell of liquid water and the associated enhanced reflectivity which occurs is referred to as the bright band. Errors in precipitation intensity of up to a factor of five can result from the bright band alone, if left uncorrected (Joss & Waldwogel, 1990). Growth of precipitation at low levels over hills can also be a problem in some areas, particularly in situations where strong moist low-level winds occur. Rain falling through the lower-level cloud or fog sweeps out water drops, thereby dramatically increasing the rainfall at the surface. This process of orographic rainfall enhancement typically occurs in the lowest 1.5 km of the atmosphere (Hill *et al.*, 1981).

(g) Radar beam overshooting precipitation

For radars operating in PPI scanning mode, the height of the radar beam will increase with distance from the radar site as a result of both the scan elevation angle, which is normally greater than 0°, and the curvature of the earth's surface. The radar beam is likely to either partially or completely overshoot shallow precipitation at long range, resulting in either underestimation of the precipitation rate or complete failure to detect precipitation respectively.

3. Radar data processing within the Nimrod system

Radar images from the 15 C-band radars around the British Isles (illustrated in Figure 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 preliminary processing is performed at the radar site (see Archibald & Smith, 1997). Permanent ground clutter at each site is removed by means of a fixed clutter map as described by Edwards & Williams (1994). Measured reflectivity (Z) is converted to precipitation rate (R) using a constant Z–R relationship:

$$Z = 200R^{1.6}$$

which is applicable to stratiform rain (Marshall & Palmer, 1948). Corrections for attenuation are also applied using a cumulative gate-by-gate algorithm of the form:

$$A = 0.0044R^{1.17}$$

Figure 1. *Coverage of the British Isles provided by the current radar network (at 5 km resolution).*

based on the work of Gunn & East (1954). This procedure is prone to instability in conditions of severe attenuation, particularly if the radar sensitivity calibration is in error, so the corrections are capped at a factor of two increase in rain rate. Spatial averaging and conversion from polar to Cartesian co-ordinates is also carried out as part of the on-site processing. Subsequent processing within the Nimrod system is described in sections 3.1–3.4.

3.1. 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 need to be discarded 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 by 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 is then used to help diagnose radar faults such as transmitter failures. 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.

3.2. Identification and removal of anomalous 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 & 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 less than the average climatological PoP for the UK. Setting the threshold at such a low level means that the probability of removing real precipitation is very small. An example of the impact of the clutter/anaprop removal scheme is shown in Figure 2.

3.3. 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 at each radar pixel (Kitchen *et al.*, 1994). The idealised profile, shown in Figure 3, is defined by a single variable, the background reflectivity factor (i.e. the reflectivity in the rain just beneath the bright band), and incorporates simple parametrisations 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 operates with the following inputs.

- Freezing level height (from the UK Met. Office's mesoscale model).
- Cloud top height (derived from Meteosat IR imagery and UK Met. Office's mesoscale model fields).
- The magnitude of anticipated orographic enhance-

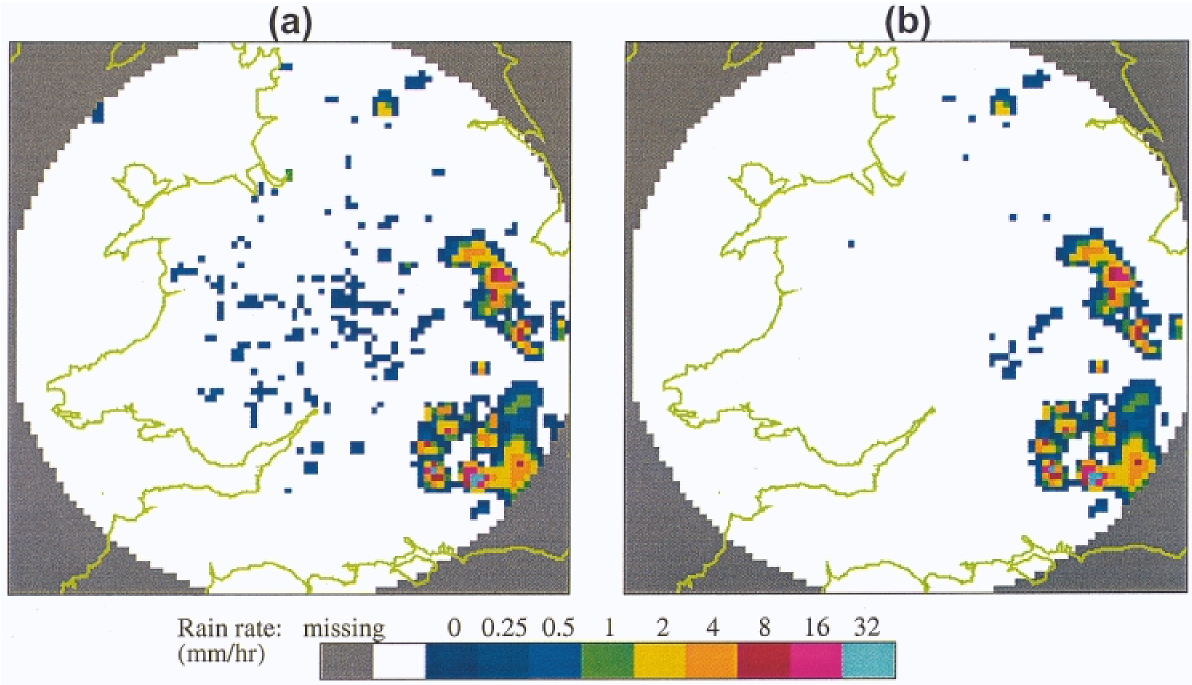

Figure 2. *An example showing the removal of spurious echoes for a Clee Hill radar image: (a) the raw radar image and (b) the image after deletion of spurious echoes.*

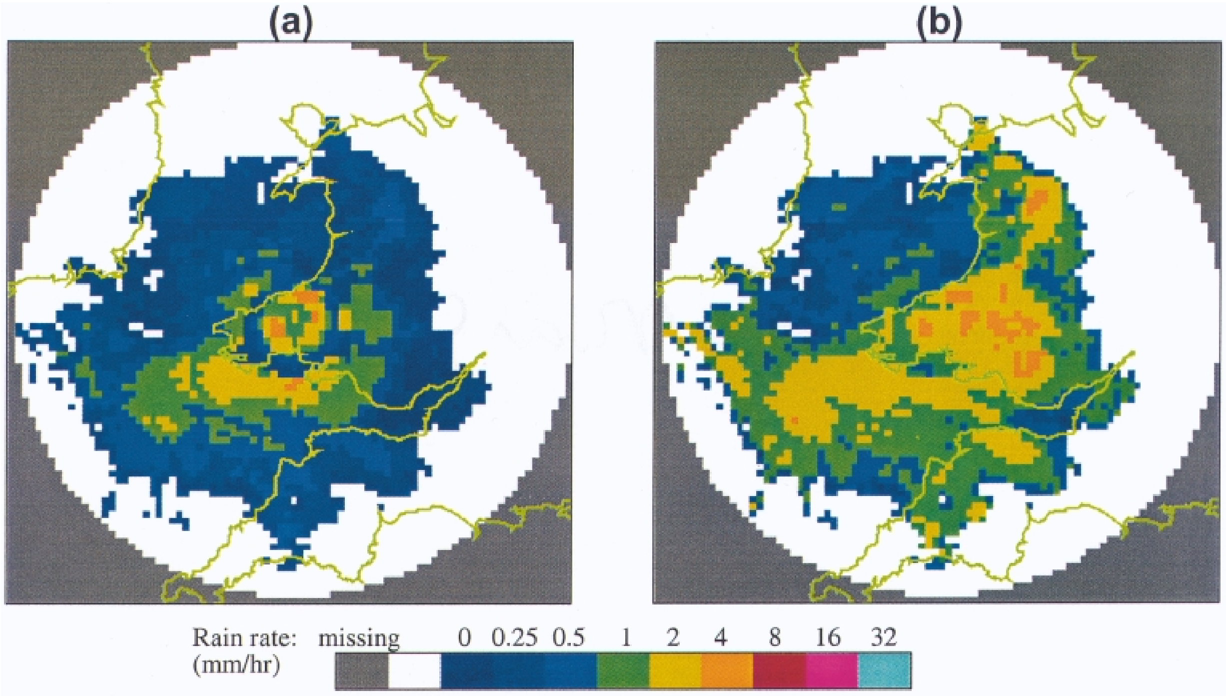

Figure 4. *An example illustrating the impact of the vertical profile correction scheme for a Crug-y-Gorllwyn radar image: the image (a) before and (b) after the vertical profile correction scheme has been applied.*

ment (using fields derived by Hill (1983), in which enhancements are specified as a function of humidity and wind speed and direction at the 800 m level).

- Ground height above mean sea level.
- Radar parameters (beam elevation angle, beam occultation angle and radar range).

The parametrised vertical profile is weighted by the radar-beam power profile and the background reflectivity factor, and hence the surface precipitation rate, found by an iterative method.

Figure 4 illustrates the impact that the correction scheme can have. A ring of enhanced rain rates close to

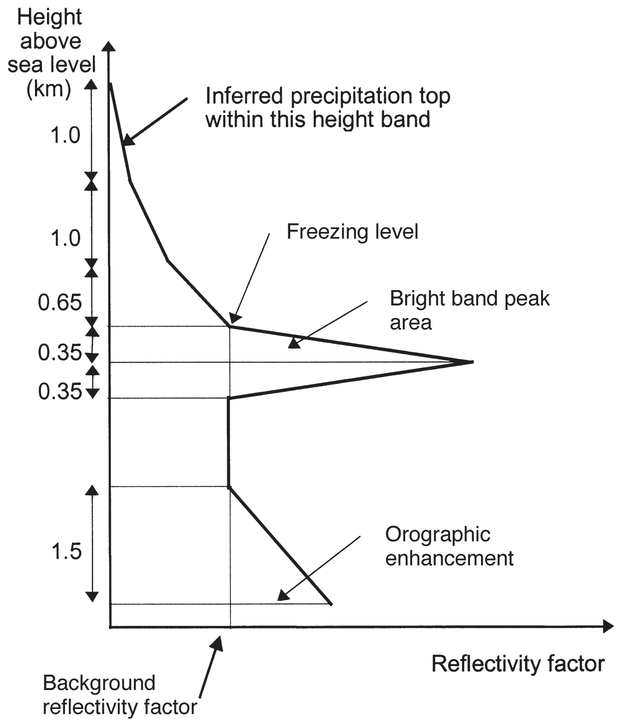

Figure 3. *Example of the construction of the idealised vertical reflectivity factor profile used in the Nimrod correction method, where the freezing level is within the precipitation layer and orographic growth is occurring at low levels (from Kitchen* et al.*, 1994).*

the radar site 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.

3.4. Gauge adjustment

A crucial assumption of the vertical profile correction process is that radar sensitivity calibration is accurate and stable. Unfortunately, at any particular time, it is possible for a number of the network radars to have significant calibration errors. An adjustment factor, based upon the results of comparing quality-controlled and corrected radar data with hourly rain gauge reports (Hackett & 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. At ranges beyond this, the radar beam partially overshooting precipitation is likely to be a significant problem.
- The radar must have detected precipitation in the collocated gauge pixel during most of the hour.
- Both radar and gauge must have recorded > 0.2 mm during the hour. Most of the Met. Office's hourly reporting rain gauges are of tipping bucket type and have a minimum tip of 0.2 mm. Comparisons for very low hourly rainfall accumulations are therefore unreliable.
- The gauge must not be in an area subject to frequent clutter or anaprop.

Adjustment is only considered once per week and a revised adjustment 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.

4. Verification

In order to assess the impact of the radar data quality control and correction processes applied within Nimrod extensive verification has been undertaken. This has largely taken the form of comparison with-hourly rain gauge observations, with the gauge reports taken as ground truth. Bias and random errors (root-mean-square (RMS) and RMS factor (RMSF) difference) have then been calculated over different spatial and temporal scales.

Interpreting the results of gauge–radar comparisons is in itself problematic, because of the different sampling characteristics of the two instruments. A rain gauge records precipitation at a point over a specific time interval, typically one hour. The radar-derived measurement represents average instantaneous rain rate over a pixel area, which for the results described in this paper is 5 × 5 km, sampled at intervals of 15 minutes. The magnitude of the resulting representativeness errors is difficult to quantify and varies significantly between rainfall events. 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, as well as checks which examine the self-consistency of the radar data.

4.1. 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 between hourly gauge rainfall and the radar-derived accumulation. 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 in 1997, the average reduction in the RMS difference between hourly gauge accumulations and corresponding rainfall accumulations based on integrations of 5 km resolution radar rain rate images was approximately 30%.

Figure 5 shows the bias and random errors in hourly gauge–radar 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 effectiveness 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 6 mm h^{-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 difference values that can be achieved. Kitchen & Blackall (1992) suggest that sampling differences alone can account for RMSF differences of between 1.26 and 2.51 in comparisons of hourly gauge observations with 5 km-resolution radar pixel values sampled at 15-minute intervals, with the higher end of this range being typical of highly convective conditions. Evaluation of the quality-controlled and corrected Nimrod data indicate that RMSF difference values of around 2 are typical of corrected 5 km radar data at all except the longest ranges.

Figures 6 and 7 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 more than 5 000 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 are 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.

4.2. Long-term integrations of radar data

Much information can be gained from looking at the self-consistency of radar data once small-scale spatial

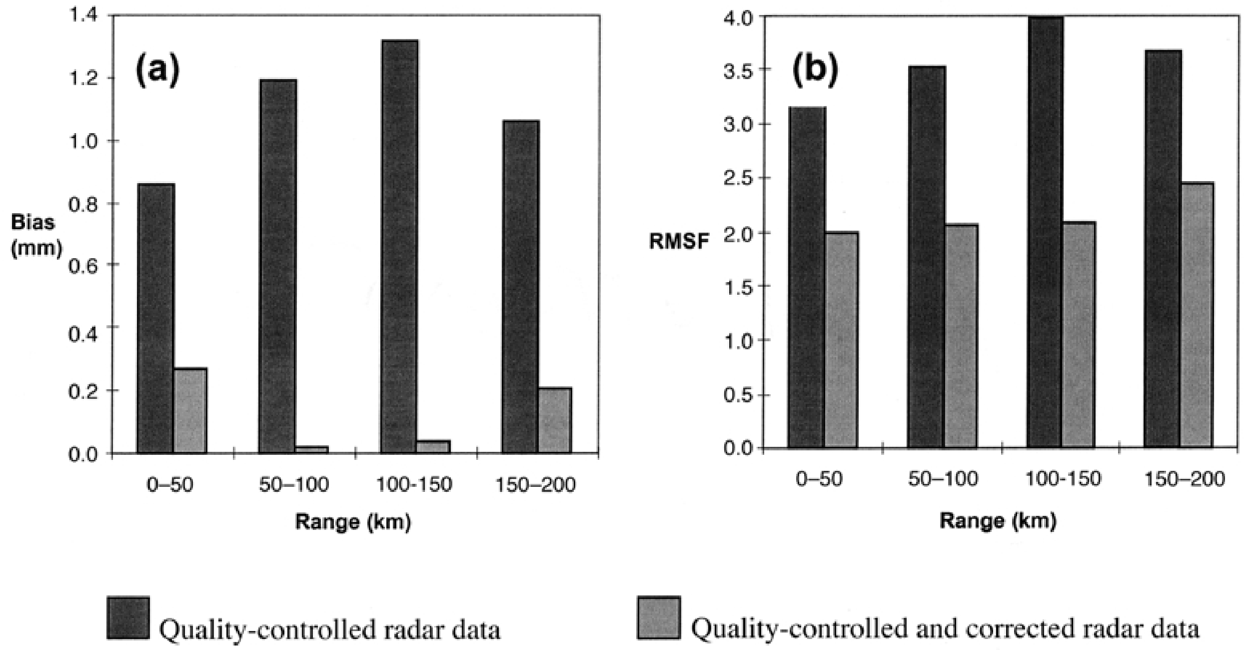

Figure 5. *Histograms showing (a) the mean and (b) the RMS factor difference between hourly gauge and radar rain accumulations for February 1997, using data from the Crug-y-Gorllwyn radar.*

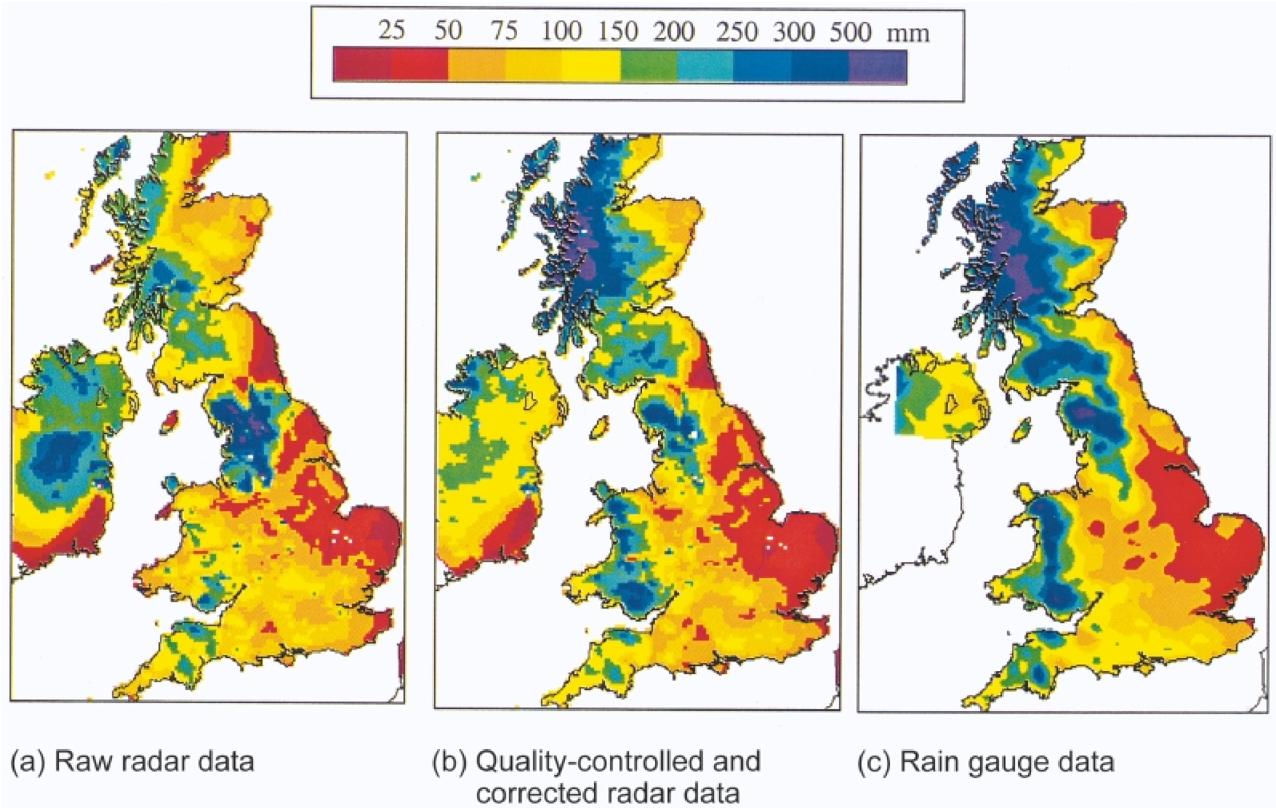

Figure 6. *Monthly rainfall accumulations for February 1997 for* (a) *raw radar data,* (b) *quality-controlled and corrected radar data and* (c) *rain gauge data.*

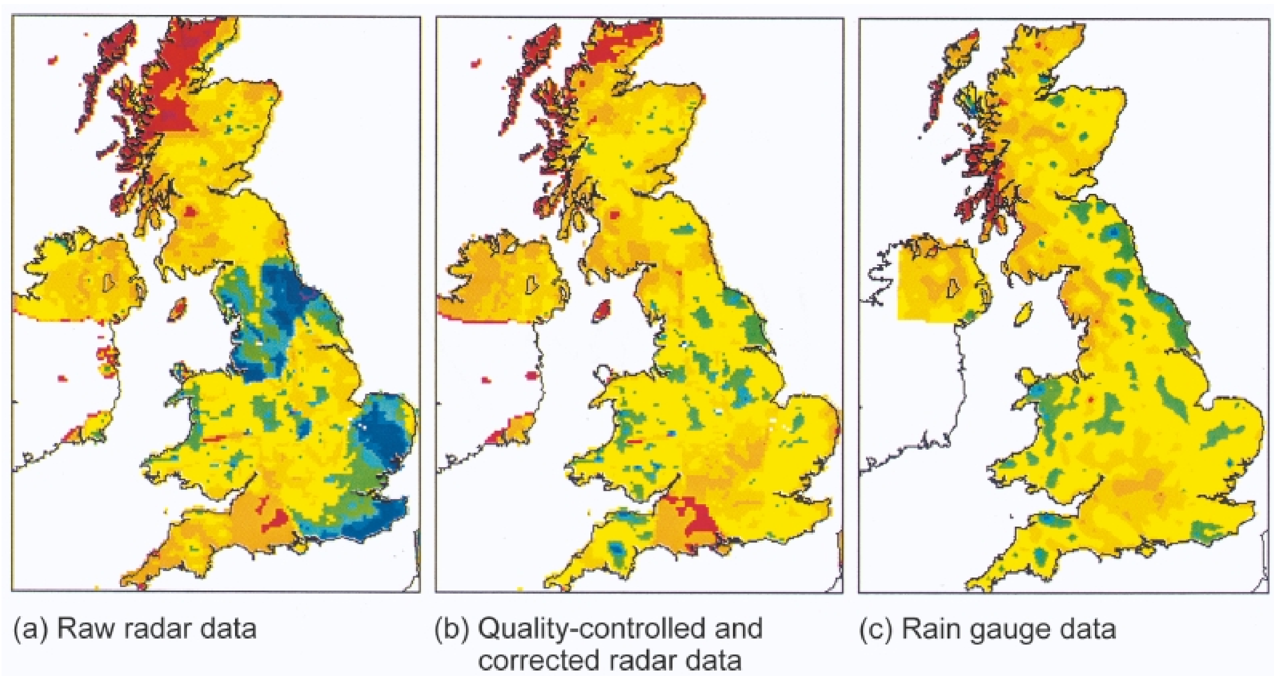

Figure 7. *Monthly rainfall accumulations for June 1997 for* (a) *raw radar data,* (b) *quality-controlled and corrected radar data and* (c) *rain gauge data.*

and temporal variations in precipitation have been removed by time averaging. In particular, range-dependent biases become apparent when quantities such as the average rainfall rate (excluding zeros) are plotted as a function of radar range (for a similar study with NEXRAD precipitation estimates see Smith *et al.*, 1996). Figure 8(*a*) 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 & Jackson, 1993), and therefore precipitation estimates will be biased towards those from deeper cloud, which are less likely 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 8(*b*): its effect is clearly evident in the raw radar data around the 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 appear 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 4.3). 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 with 0.4 mm for the corrected radar data.

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 those in Figure 8 can sometimes enable radar faults to be identified, for example range-dependent sensitivity variations. 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).

4.3. 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 heavy rainfall events (i.e. those which lead to serious flooding) that is of most significance to operational hydrologists. Case study investigations have been carried out on a number of such

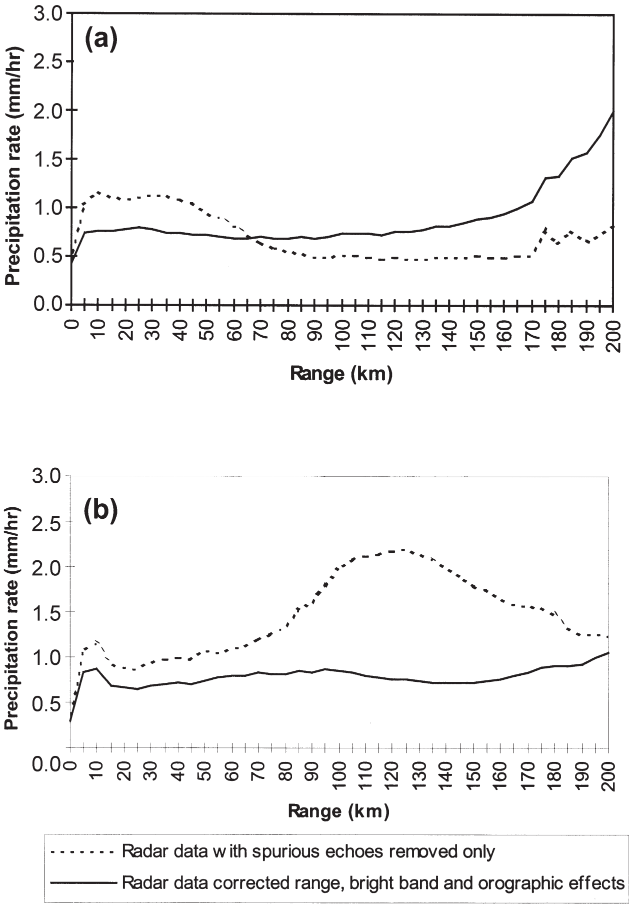

Figure 8. *Conditional average rain rate versus range for Chenies radar data for* (a) *February 1996 and* (b) *August 1996.*

events. These have been useful for identifying strengths and weaknesses with the current radar data processing within Nimrod, which are not always apparent from the monthly quality evaluations. Table 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 often absent (Smyth & Illingworth, 1998). This was particularly evident on 12 August 1996, when intense convective storms generated around 100 mm of rain over the Folkestone area of south-east England over a four-hour period. In this case, the assumption of a bright band always being present led to significant underestimation of the storm total. As a result, an amendment to the correction scheme, based on the proposal of Smyth & Illingworth (1998), was developed and tested (Kitchen & Driscoll, 1997). Smyth and Illingworth suggest that a 30 dBz threshold reflectivity at ~1500 m above the freezing

Table 1. *Summary of radar data quality for case study investigations*

Date	Description	Impact of quality control and corrections	Lessons learnt
7 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 precipitation rates, which are based on a single *Z–R* relationship, will overestimate precipitation in hail. This may partially account for the improved agreement achieved.
12 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.
8 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.
26 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.
26–27 June 1997	Persistent, heavy rainfall over Exmoor, giving over 100 mm 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.
8–10 April 1998	Continuous heavy rainfall resulting in widespread flooding across central England.	Positive. Raw radar data significantly underestimated rain rates. Corrected data generally in good agreement with gauges.	Improvement largely due to effects of gauge adjustment.

level can be used to distinguish between snow and graupel (soft hail) above the freezing level. 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). Owing 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 the 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 (2 km/5 minute) data within Nimrod to all the radars in the UK network.

5. Conclusions

Quality control and correction processes applied to radar rain rate estimates within the UK Met. Office's Nimrod system are designed to address a number of specific sources of error. These processes include the removal of spurious echoes (resulting from ground clutter and anaprop) and corrections to account for variations in the vertical profile of reflectivity and radar sensitivity errors. The results of extensive verification-results outlined above have demonstrated the benefit of these quality control and correction procedures.

Comparison of the radar-based precipitation estimates, both before and after correction, with hourly gauge accumulations suggests that the RMSF difference in the radar estimates be significantly reduced. Although the remaining RMSF difference is still approximately a factor of two, representativeness errors make up a significant part of this. The results also indicate that the contribution of the various 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 strength and 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 (primarily to enable a method of correction which distinguishes between bright band and non-bright band conditions 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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