THE DEVELOPMENT OF DIAGNOSTICS AND RADAR MONITORING CAPABILITY WITHIN A NEWLY IMPLEMENTED RADAR DATA QUALITY MANAGEMENT SYSTEM (RDQMS)

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1. INTRODUCTION

The use of radar based quantitative precipitation estimates (QPE) within hydrological applications, nowcasting and for assimilation into Numerical Weather Prediction (NWP) is currently limited by issues relating to radar data quality and reliability. Issues range from problems with the performance of radar hardware components to limitations associated with the post-processing algorithms.

A comprehensive radar data quality management system (RDQMS) is currently being developed within the Met Office. This will deliver a range of monitoring and verification information and tools, including: quality monitoring of the radar system performance, comparison of radar-based QPE with rain gauge measurements, and monitoring of Doppler wind and radar reflectivity data using NWP model fields. Long term statistical comparison between synthetic and real observations has the advantage of identifying individual radar calibration problems through relative comparisons with other radars. The effectiveness of the forward modelling of the reflectivity can also be evaluated through absolute statistical comparisons. Such an improved monitoring system and its associated diagnostic products are expected to result in earlier identification of any issues arising with the radars or radar data quality.

Presented here is an introduction to the main components of the RDQMS, including an analysis of the statistical information derived, and how this can be used to improve the quality of data from the UK radar network. Described in greater detail is the quality monitoring of UK network radars using synthesised observations from the Met Office Unified Model. This includes a description of the contribution made to the radar signal bias with range as a result of the combined effects of the bright band, attenuation and beam broadening.

2. QUALITY MONITORING OF THE RADAR SYSTEM PERFORMANCE

In the case of radar QPEs, quality is often quantified using comparisons with rain gauge measurements. Although this can be very useful, interpretation can be problematic due to the sampling differences.

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A comprehensive radar data quality management system (RDQMS) is being developed, which will deliver a range of monitoring and verification information and tools. These will incorporate a number of approaches including: (a) monitoring trends of selected parameters, flagging any significant deviations from expected trends (b) routine comparison with 'ground truth' observations (c) routine comparison with numerical weather prediction (NWP) model fields and (d) accumulating diagnostic products over time, analysing their self-consistency and identifying anomalies. It is envisaged that improved monitoring will ensure any problems are quickly identified, therefore facilitating faster resolution.

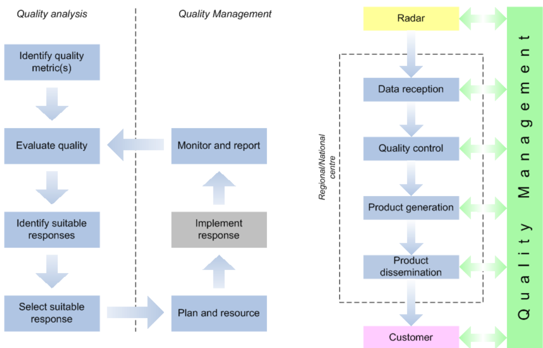


Fig 1: (a) The quality management cycle. (b) The quality management and radar data processing. Source – Harrison et al. (2011)

2.1 MONITORING HARDWARE PERFORMANCE

To achieve optimum quality from the radar products, it is important that the on site radar systems are functioning as best they can. The radar sites are unmanned, and it is therefore important that all of the required monitoring information is available centrally. Real time monitoring of meta data received with the reflectivity scan data is used on reception for this purpose. At first, the following diagnostics will be used to monitor site data quality:

a) Scan mean transmitter pulse power
b) Scan mean transmitter frequency (GHz)
c) Scan mean receiver noise (dBc)
d) Scan mean antenna rotation rate
e) Scan elevation

Significant deviation from the expected values for each of these parameters will lead to a more in depth investigation by engineers. A detailed description of these measures is provided in Harrison et al. (2011).

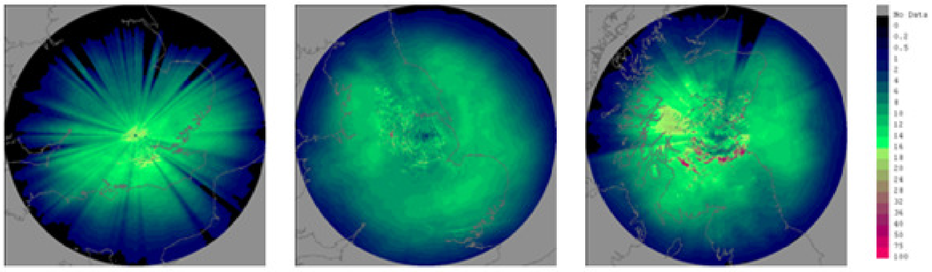
2.2. COMPARISON OF RADAR BASED QPE WITH RAIN GAUGE MEASUREMENTS

Long-term integrations of QPE products can help identify and quantify persistent anomalies, which may result from errors in the basic reflectivity measurement and/or limitations of any quality control (QC) and correction algorithms applied. When looking at accumulation periods greater than 1 month, the appearance of good quality products should correspond well with the climatological variance of precipitation, with variations due to the topography and aspect. Other anomalies may exist due to partial beam blockages or clutter breakthrough (Harrison et al., 2011).
Precipitation probability, accumulation and average rate (conditional on precipitation rate > 0.0 mm/h) have been produced from polar form radar products since October 2010. Figures 2-4 show examples for January 2011 for 3 UK radar sites, chosen to represent the range of quality seen: Chenies shows numerous sectors where poor correction for partial beam blockages is evident; Munduff Hill exhibits clutter breakthrough, whereas Ingham shows consistent performance over virtually its entire domain.

In addition to quality monitoring, the potential for using these diagnostic products in real-time QC is also being investigated. For example, clutter from wind turbines is an increasing problem and existing clutter detection techniques generally don't perform well as the target is often moving. Residual clutter can result in false flood or severe weather warnings where radar-based QPEs are used to drive meteorological and hydrological forecasting systems. Long-term frequency of detection and average reflectivity or average derived precipitation rate can be used to identify these small scale problematic features and exclude them from QPE products.

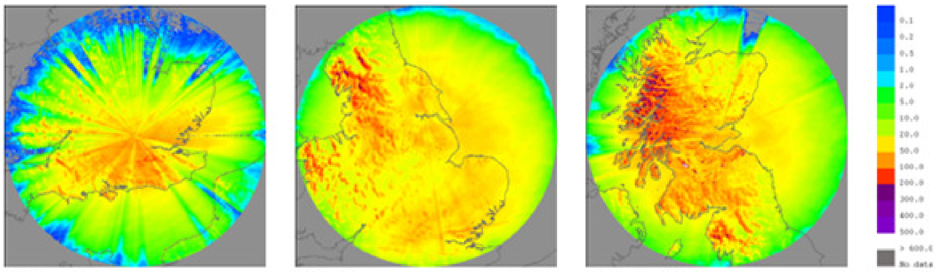
2.2.1 PROBABILITY OF PRECIPITATION (PoP)

As part of the Radarnet QC, spurious (non-precipitation) echoes are flagged using a method largely based on pulse-to-pulse signal variability (Sugier et al., 2002). The radar QPE uses reflectivity data from the lowest 'usable' (un-flagged) scan. Where there is no usable data in any scan the QPE is flagged as missing. Therefore, PoP (fig.2) across the radar domain should be relatively free from anomalies.



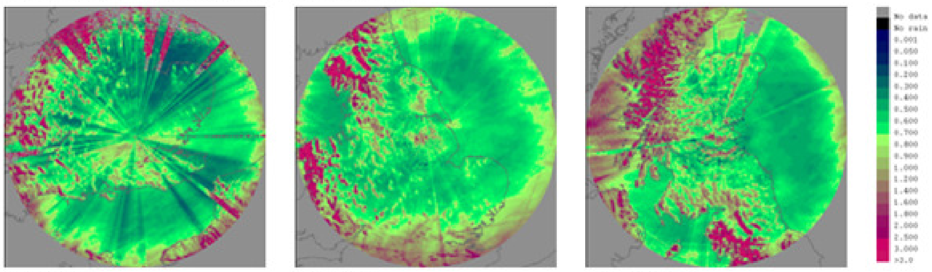
a) Chenies b) Ingham c)Munduff Hill

Fig. 2: Probability of precipitation (%), January 2011.



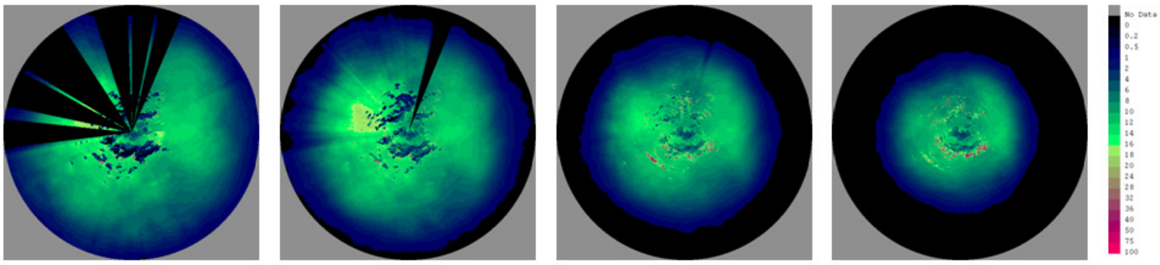
a) Chenies b) Ingham c)Munduff Hill

Fig. 3: Precipitation accumulation, January 2011.



a) Chenies b) Ingham c)Munduff Hill

Fig. 4: Average precipitation rate (conditional that precipitation rate > 0), January 2011.

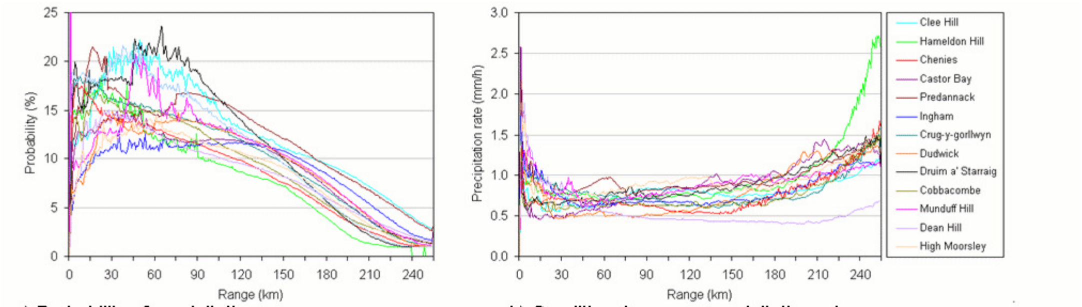


a) 0.5° elevation scan b) 1.5° elevation scan c) 2.5° elevation scan d) 4.0° elevation scan

Fig.5: Probability (%) of detection (reflectivity data flagged as usable), Munduff Hill, January 2011.

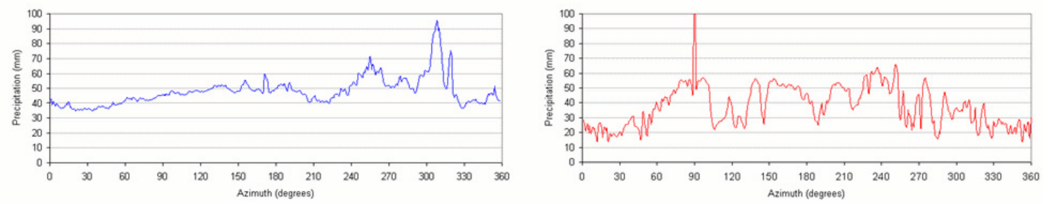
Anomalously high PoP is indicative of clutter breakthrough. It is evident that there is significant clutter breakthrough to the south of Edinburgh from the Munduff Hill radar (fig.2c), where there are areas with PoP > 40% rather than around 15%, as detected at similar range. This suggests that the existing clutter identification processes aren't effective at this site. By then examining probability of detection (PoD) based on quality controlled reflectivity scan data, it is possible to better understand the nature of the clutter breakthrough. Figure 5 shows the corresponding PoD based on each of the lowest four scan elevations for Munduff Hill, January 2011. It is evident that bins on the margins of clutter areas, particularly in the 2.5° and 4.0° elevation scans are being flagged as usable when almost certainly they contain clutter. Understanding the limitations of existing quality control techniques can help ensure that future research and developments focus on addressing these limitations. The other main feature of interest in the PoP products is variation with range from the radar site. PoP should decrease with increasing range, as the lowest usable scan begins to overshoot the top of shallow precipitation. In addition, the minimum detectable signal increases with range, so very light precipitation will not be detected. Figure 6 (a) shows average PoP versus range for January 2011. It is evident that some radar sites (e.g. Ingham) show relatively consistent PoP to beyond 120 km range whereas at others (e.g. Chenies) PoP declines steadily from 50 km range. It also illustrates at which sites problems with clutter breakthrough at short range exist.

The false alarm rate (FAR) in radar QPEs is often estimated using rain gauge data as ground truth. Results have indicated that an FAR of 3-4% is typical. This approach has limitations as it is limited to the gauge locations and relies on the gauge distribution to be representative. Monthly or seasonal PoP provides an alternative approach to estimate the FAR. The FAR can be estimated by analysing the frequency distribution of PoP, filtering out points with anomalously high PoP and calculating a spatially averaged PoP without these outliers.



a) Probability of precipitation b) Conditional average precipitation rate

Fig. 6: Variation in monthly diagnostics with range from the radar site, January 2011



a) Chenies b) Ingham

Fig. 7: Variation in average monthly precipitation with azimuth, January 2011

Deviation of PoP at a point from the spatially averaged PoP can provide an estimate of the FAR. This has the advantage of not requiring any other source of data as input and can therefore be used at all locations.

2.2.2 PRECIPITATION ACCUMULATION (AccP)

Monthly or seasonal AccP can be a useful product in its own right but is also useful in illustrating radar data quality. Figure 3 shows AccP for January 2011 for the same sites as figure 2. It is immediately apparent that Chenies' domain has numerous sectors where precipitation is significantly less than elsewhere. This is further illustrated in fig.7 (a) in contrast to 7 (b) which show the variation in precipitation (averaged over all ranges) with azimuth. It is evident that there are large sectors within Chenies domain where precipitation is less than 50% of that elsewhere. The precipitation estimation process on Radarnet includes identification of unusable rays/ sectors and a correction for partial beam blockage, but it is evident that this is not working effectively for Chenies. The reason is not entirely clear but it is possible that changes in the radar horizon have not been captured or that there are discrepancies between demand and actual antenna elevation angle.

2.2.3 AVERAGE PRECIPITATION RATE (CavP)

A further useful diagnostic is the conditional average precipitation rate (i.e. considering only instances where the QPE is > 0.0 mm/h). Although AccP will decrease with range, CavP is expected to increase, since the likelihood of overshooting shallow (and often light) precipitation and the minimum detectable signal will both increase. Figure 6(b) shows the variation CavP with range. There are a number of characteristics to examine. Residual bright-band effects (the Radarnet QPE process includes a bright-band correction) would manifest in an increased rain rate in a distinct range band. In January this would be within 75 km range from the radar site. Most of the sites show relatively consistent performance between 15 and 150 km range, with only Predannack showing any clear evidence of an increase in CavP between 50 and 70 km range. At far range it is useful to compare radar performance. There are two radars with markedly different trends. Dean Hill shows lower CavP beyond around 100 km range, which could point to some sort of calibration error. Conversely, Hameldon Hill shows a rapid increase in rates beyond 200 km. It also has the lowest detection rate at far range. This suggests a greater than expected loss in sensitivity.

3. MONITORING OF DOPPLER WIND DATA AND RADAR REFLECTIVITY USING NWP MODEL FIELDS

Within the Met Office, the numerical weather prediction (NWP) system uses the 1.5km unified model. This requires assimilation of observations high in spatial and temporal resolution. Since July 2011, Doppler radial winds have been assimilated using both the UK4 (4km) and the UKV (1.5km) unified model output. In the future it is expected that radar reflectivities will also be assimilated within NWP.

For the purpose of comparing radar and model data, it is necessary to average the rays and gates of the radar data to a similar resolution as that of the model. This is achieved by superobbing the observations, which involves spatially averaging the difference between the real observations and their synthetic equivalents produced using the model background fields.

Here we describe the statistical monitoring of the Doppler wind and radar reflectivity data against the model background and look at the improvement in accuracy achieved by applying a factor to account for gaseous attenuation, as suggested in a previous study (Harrison et al., 2011).

3.1 DOPPLER MONITORING

Monitoring of Doppler wind data has recently been implemented operationally as part of the RDQMS system, and involves monitoring of Doppler radial wind scans against the model background every three hours. Figure 8 shows an example of the observations and the difference between the modelled and observed values.

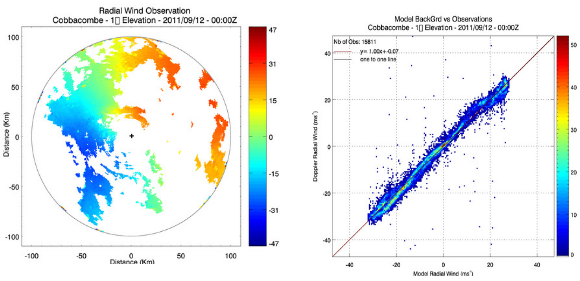


Fig 8: Cobbacombe Cross radar, SW England, 12 Sept 2011. (a)Radial wind observation (b) Model background vs. the observed radial winds.

The Doppler monitoring has proved useful in identifying issues within the Cyclops processing of radar data. An example is the identification of a location error, flagged by the observed – background (O-B) difference in the data. Once the criteria for testing the quality of the Doppler winds has been well defined, it is expected that this monitoring will form an integral part of the operational acceptance process for future testing of developments within Cyclops.

3.2 QUALITY MONITORING USING SYNTHESISED OBSERVATIONS FROM A HIGH RESOLUTION NWP MODEL

The Radarnet system delivers radar reflectivities and quality information to the Observation Processing System (OPS), which prepares meteorological observation data for input to the data assimilation component of the Met Office NWP model suite. Within the OPS, synthetic radar reflectivities are produced using high resolution (4km) NWP model fields, interpolated at the exact observation locations. Long term statistical comparison between synthetic and real observations has the advantage of identifying individual radar calibration problems through relative comparisons with other radars. The effectiveness of the forward modelling of the reflectivity can also be evaluated through absolute statistical comparisons. Described here is an analysis of statistical information derived from the quality monitoring system. Included is a description of the contribution made to the radar signal bias with range as a result of the combined effects of the bright band, attenuation by rain and clouds and beam broadening. In a previous study, these results have been used to demonstrate that the atmospheric gaseous attenuation makes a significant contribution to the overall range bias, and it is therefore beneficial to account for this within the radar site processing.

3.3 RADAR DATA PROCESSING IN THE OBSERVATION PROCESSING SYSTEM (OPS)

Within the current forward model, the attenuation due to atmospheric gases, rain and cloud is not accounted for. The bright band and beam broadening effects are also not currently simulated. At present only the mixing ratios for rain and ice are used, however, the forward model will be extended to incorporate graupel and snow mixing ratios.

Quality flags, produced by the radar pre-processing, are used in the superobbing process such that only observations that pass the minimum quality criteria are taken into account. Gaussiat (2008a) illustrates the benefits of using clutter flags and describes the importance of superobbing to reduce the amount of available data and minimise representative errors by best matching the sampling volume of the model and superobbed data. The key steps in producing the pre-processed radar reflectivities are detailed in Gaussiat (2008b). This involves flagging of radar bins affected by ground clutter, spikes and partial beam blockage. Figure 9 shows the observed and modelled observations, as well as the quality flags used and the superobbed reflectivities for a period of heavy rainfall and stormy conditions on 12 September 2011.

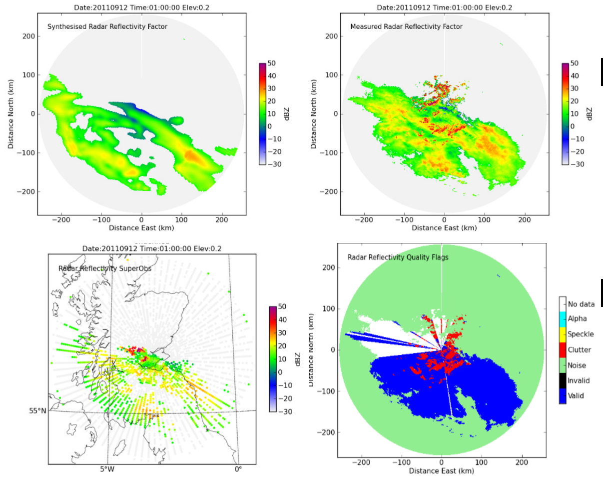


Fig. 9: Examples of the modelled & observed reflectivity values at the Crug-y-Gorllwyn radar on 12 Sept 2011.
(a) Modelled reflectivity factor.
(b) Measured radar reflectivity factor.
(c) Superobs of the measured radar reflectivity.
(d) Quality flags associated with the measured radar reflectivity.

3.4 STATISTICAL COMPARISON BETWEEN THE MODEL AND RADAR REFLECTIVITY DATA

The superobbed differences between real (radar) reflectivity measurements and the synthesised (model) reflectivity (the O-B value) are useful for three key areas of analysis: data assimilation (initialising the model with high resolution radar data), model verification and radar quality control (QC). Each area uses the same information over different time windows and observation domains. Currently, the O-B statistics (bias and standard deviation) are calculated for each superobbed cell, and netCDF files including this information are produced 8 times a day. For the purpose of data assimilation, the statistics are used to characterise observation representativeness errors. Therefore, short time windows are used to match the data assimilation window. Model verification is carried out by calculating the long term averaged O-B value over each model grid point.
For example, by looking at statistical differences it might be possible to quantify differences in the way the model acts over the sea compared with over land. With a sufficiently long archive of O-B values, mis-representation of the precipitation under different conditions could also be determined.
Recently the use of the OPS monitoring system has been extended to radar QC, and is being developed as part of the RDQMS. The OPS reflectivity monitoring system is still under development and forms part of this project. Currently, problems that may exist with individual weather radars are inferred by looking at their relative calibration to other radars in the UK network. This is achieved by averaging the O-B values over each range gate to determine how the bias varies with range.

3.5 DETERMINING THE OPTIMUM TIME PERIOD FOR AVERAGING OBSERVATIONS OVER

Finding the O-B value for one data time step alone is not useful as there are too few observations, and large bias variations between the data used at different times.
As a result, any relative comparisons between radars would be messy and unrepresentative of anomalies. It is therefore important for the bias and other statistics such as the root mean square error (RMSE) to be calculated using longer periods (fig.10).

Long term averaged results identify underlying issues regarding radar functionality, such as calibration problems. Biases arising from the bright band effect, beam broadening and attenuation can also be observed using long term averaged data. Calculation of the optimal averaging periods was carried out within a previous study (Georgiou et al., 2011). It was found that the variance between the radars is <1dB when time periods greater than 80 days are used. The variance is ~3dB when T = 5 to 10 days. When the variance is minimised by using a sufficiently long time period, the relative variance between the radars is largely representative of their differences in calibration.
It was also calculated that the variance becomes constant at around 0.5dB (T ~200 days), which shall be taken as the optimal average variance.
Over such a long period, the relative calibration between the radars is less useful as any radar calibration issues may already have been identified using statistics calculated over a shorter time period. Instead these statistics could be used as a long term average measure of the relative difference between radar and model reflectivity profiles. The shorter term averaged results for each radar could be assessed against this benchmark. If there are any significant anomalies, then it may be evident of a recent calibration error arising at that particular radar. It is therefore important that various time periods are used to calculate the statistics on a daily rolling basis. The shortest sensible time period has been determined as ~30 days, where the average variance is around 1.5dB.

In order to further reduce the response time, the use of shorter time periods, e.g. 5 days, could be useful for identifying large changes in relative calibration that result from radar hardware changes.

3.6 ATMOSPHERIC GASEOUS ATTENUATION

The radar signal is affected by varying attenuation due to clouds and hydrometeors and also by constant attenuation due to gases present in the atmosphere. Gaseous attenuation is an absorption process and results in the radar signal amplitude being reduced by the gases present in its transmission path. This attenuation varies directly with frequency. It is also temperature, pressure and humidity dependent (Liebe, 1985; Bean and Dutton, 1968).
The Met Office C band weather radars typically operate at a frequency of 5.625GHz (~5.3cm wavelength), at which the gaseous attenuation is mainly due to oxygen. Battan (1973) derived a one way gaseous attenuation value of approximately 0.008 dB km^{-1} due to oxygen and 0.0007 dB km^{-1} due to water vapour at 5.3cm wavelength (20^0C temperature and a pressure of one atmosphere).
This amounts to a two way gaseous attenuation of approximately 0.0174 dB km^{-1}. At 100km range from the radar, this will result in 1.74dB attenuation, increasing to 4.35dB at 250km. This value is significant and demonstrates that consideration should be given to adding a factor within the radar site processing to account for radar attenuation due to atmospheric gases.
The range biases that affect the signal received by UK radars, but which are not currently accounted for within the OPS reflectivity processing are due to the combined effect of the forward modelling being too simplistic (the two-way attenuation from atmospheric gases, clouds and precipitation, beam broadening and the bright-band effect are not simulated) and the precipitation vertical profile being mis-represented in the model.

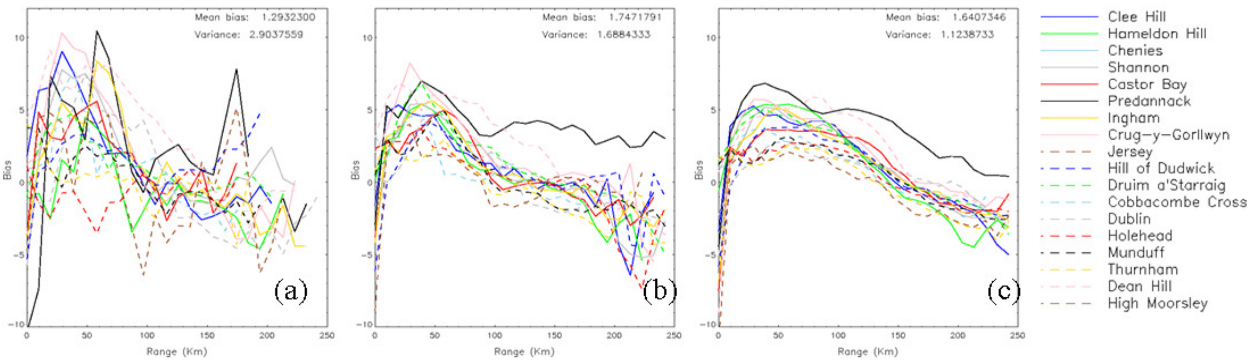


Fig. 10: Corrected bias between model and radar observations at 0.5 degree scan elevation calculated for a single window starting in May 2010 over time periods: (a) 5 days (b) 30 days (c) 90 days

The effect of the attenuation, in particular, is very noticeable when the difference between modelled and observed reflectivity values are averaged over a relatively long time period of 90 days or longer. A range bias value of 0.028 dB km^{-1} was calculated (Harrison et al., 2011). The gaseous attenuation value presented by Battan (1973) of 0.0174 dB km^{-1} is approximately two thirds the value we calculated.
The bias due to gaseous attenuation is linear, and can therefore be subtracted from the value calculated in table 1, resulting in an average range bias value of 0.0106 dB km^{-1}. This is due to the combined effect of beam broadening, the bright band effect and precipitation attenuation. Figure 11 shows the accumulation plotted as a function of range from the radar, before and after the gaseous attenuation factor has been applied.
The accumulations have been averaged over all the gauges present at each range. In this case, the vertical profile of reflectivity (VPR) processing (Kitchen, 1994) has been applied to the data, within which the effects of beam broadening and the bright band have already been accounted for.
These graphs demonstrate the benefits of applying a factor to account for the gaseous attenuation. As a first approximation, the attenuation due to atmospheric gases is often calculated as the product of a hardware specific constant and the range from the radar, and is commonly corrected for within the signal processor (Hannesen, 2001). However for the purpose of monitoring radar reflectivity against model fields, the attenuation due to the atmospheric gases would be more accurately accounted for by incorporating it within the forward modelling. By eliminating this bias source, the bias due to the bright band effect, beam broadening and attenuation by cloud/rain could be quantified in the same way with greater precision, making the bias due to other anomalies easier to distinguish.

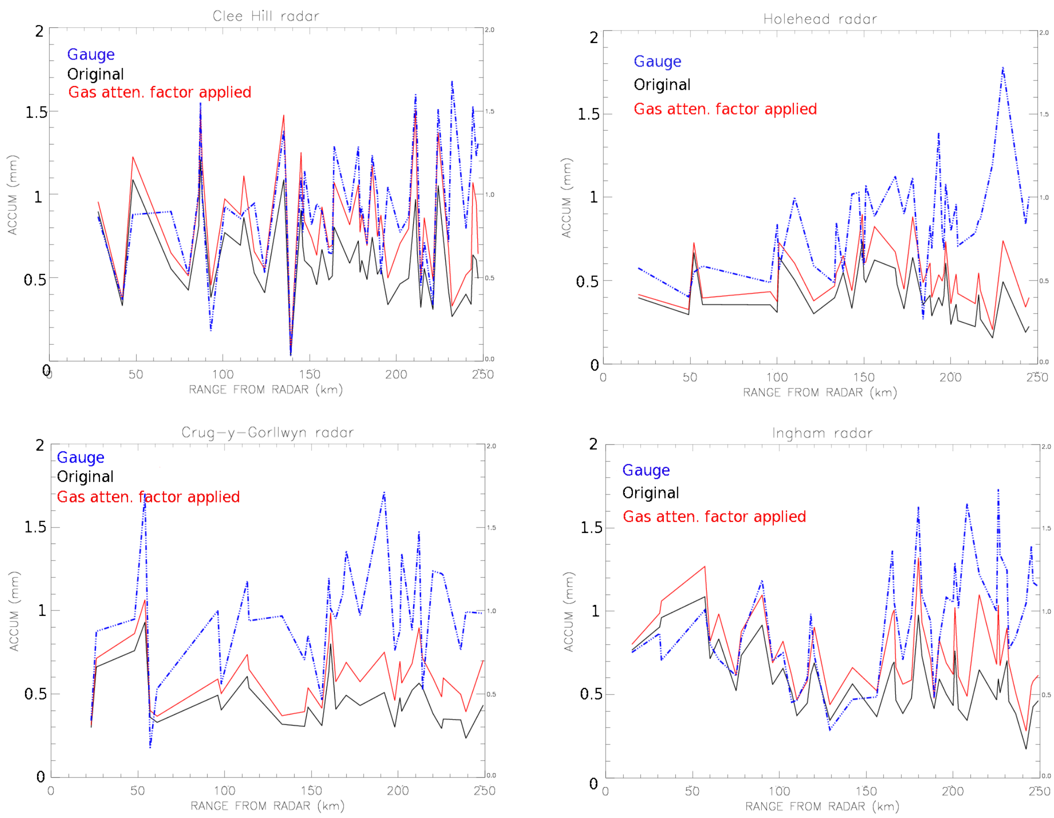


Fig. 11: Gauge and radar accumulations, with and without the gaseous attenuation factor applied as a function of range for the radars: (a) Clee Hill, (b) Ingham, (c) Crug-y-Gorllwyn and (d) Holehead

4. SUMMARY AND CONCLUSIONS

Optimum quality, and therefore usability, of radar data and products is dependent on effective end-to-end quality management. The development of an RDQMS at the Met Office represents a pro-active approach to ensuring radar product quality. Contrasting types of monitoring, from either end of the processing chain, have been presented. Already these have been effective in identifying several faults with radar system components and post processing algorithms, which have, in turn, been resolved. The diagnostic products are also proving useful in their own right within the QC processes. Over the coming year work will focus on putting in place the elements of the RDQMS. These will include long-term diagnostics based on reflectivity volume data, comparison of Doppler and NWP model radial winds and additional quality metrics from radar and rain gauge comparisons. It is anticipated that a complete RDQMS will lead to significant improvements in the quality and reliability of radar data and products, by quickly identifying any problems thus enabling either short term solutions and/or long-term improvement strategies to be devised. It is also envisaged that the QM information will serve to inform customers about radar product quality issues thus increasing confidence in the use of the products or promoting realistic expectations.

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