

Comparison of model-derived and radar-observed freezing level heights: Implications for vertical reflectivity profile correction schemes

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SUMMARY

In the current operational Met Office scheme for deriving rainfall rates from radar, the height of the enhanced radar return associated with melting snow, the bright band, is determined using the height of the 0°C isotherm obtained from the Met Office Unified mesoscale model (UM) forecast. In this paper the potential errors of using model forecast heights as input to the bright band correction scheme are investigated. UM and ECMWF model forecast wet-bulb 0°C isotherm heights (WBZ) are compared to the height of the “step” increase in reflectivity in the vertical profiles recorded by the vertically pointing 94 GHz *Galileo* cloud radar at Chilbolton. High frequency radars do not measure an enhanced “bright band” at the melting layer, rather a sudden increase of reflectivity as the ice particles become coated in water. This sudden step can be used to locate accurately the height of the WBZ.

Results show that the UM predicts the WBZ height with a r.m.s. error of 147 m and a bias of 15 m. This is within the worst case tolerance of 200 m of the operational bright band correction scheme. Factors that may influence the accuracy are the presence of deep isothermal layers and timing errors concerning the passage of fronts but are found not to be serious. An investigation into the deterioration of the UM 36-h forecast shows that half the error is introduced at the initialisation time, highlighting the fact that further improvements can be achieved through a better definition of the initial state of the atmosphere. The ECMWF forecast is for a longer lead time but comparison for the same lead time errors as the UM shows that the performance of the two models is comparable.

An alternate approach is to derive the bright band height from volumetric radar scans at different elevations. This study suggests that, at least in the UK, operational model predictions of the freezing level height are within the specified 200 m error, but that the use of volumetric scans, even under idealised conditions, cannot achieve this accuracy.

KEYWORDS: radar vertical reflectivity profile freezing level bright band

1. INTRODUCTION

One of the largest contributions to the errors in deriving rainfall rate (R) from observed radar reflectivity (Z) arises from the vertical profile of radar reflectivity (VPR) and in particular the layer of enhanced reflectivity associated with melting snow. The height of the radar beam above the ground increases with range so that if the bright band is, say, at 1 km, then at short ranges the beam should only sample raindrops, but at longer ranges the beam samples the melting layer and the enhanced values of the Z leads to a large overestimate of the rainfall. At even greater ranges the beam samples the ice above the bright band and the rainfall is underestimated.

If accurate surface rain rates are to be made with operational radar networks then a correction scheme for the VPR is essential. Two quite different approaches have been proposed:

1. A vertical profile is derived by analysing the three dimensional radar reflectivity and this profile is used to correct observed values of Z at a given height to yield a rainfall rate at the ground.
2. A standard high resolution vertical profile is used for correction with the height of the top of the bright band set by the height of the 0°C wet-bulb temperature T_w (WBZ) derived from an operational forecast model.

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One example of the first approach is summarised in Sánchez-Diezma *et al.* (2000); indeed Sánchez-Diezma *et al.* (1999) suggest that the height of the bright band derived from the radar data themselves could be used to improve the temperature structure of an operational model. The second approach using the temperature from the model to fix the height of the bright band has been adopted by the UK Met Office and is described in Kitchen *et al.* (1994) and Harrison *et al.* (2000).

In this paper we address the fundamental question as to whether current mesoscale models have the required 200 m accuracy in the representation of the vertical structure of temperature to be of use in radar bright band correction schemes, suggested by sensitivity tests done by Kitchen *et al.* This is achieved by comparing, over a one-year period, the height of the step in reflectivity observed with an accuracy of 60 m using a vertically pointing cloud radar, with the height of WBZ in the operational analyses and forecasts of the ECMWF (European Centre for Medium Range Forecasts) and Met Office Unified mesoscale model (UM). The aims are to establish:

- the error characteristics of the 0°C isotherm in the operational forecast models and
- whether it is better for VPR correction schemes to derive the height of the bright band from multiple-elevation radar scans or from an operational forecast model.

2. VERTICAL PROFILE CORRECTION TECHNIQUES

(a) *Use of profile derived from multiple elevation radar data*

Germann and Joss (2002) provide a comprehensive summary of the various methods for deriving an average vertical profile from radar observations taken at different elevation angles. One question that arises is the optimum scale in space and time for deriving an average profile. If the averaging over space and time is too great then there is little advantage over a climatological mean, but on the other hand if the averaging is too small then the derived profile is not representative enough. For example Vignal *et al.* (2000) derived a mean profile from an hourly average over a 70 km radius cylinder (area 15000 km²) using the 20 different elevation scans of the Swiss radar network. They found a mean fractional standard error for the six-hourly rain gauge totals of 25% compared to 44% without any profile correction. When they used a more “local” profile as suggested by Andrieu and Creutin (1995a,b) and averaged over an area of 400 km², this error was reduced to 23%, an improvement of only 2%. The system being implemented operationally in Switzerland, uses a profile averaged over 70 km weighted with an exponentially decaying function which has a time constant varying from 25 minutes when the volume is full of precipitation to more than 3 hours when 10% of the volume is filled with precipitation.

Sánchez-Diezma *et al.* (2000) considered the idealised situation when the true vertical profile of radar reflectivity was constant out to a range of 150 km, and computed the profiles which would be observed with an operational radar as a function of range, scanning at various elevations. In such an idealised situation they estimated that the bright band could be estimated to within an accuracy of 300–500 m out to a range of 70 km. In reality this performance will not be achieved because rainfall is never constant over such a large area.

Westrick *et al.* (1999) describe the limitations of the WSR-88D NEXRAD radar network in estimating precipitation over the coastal western USA. Vignal and Krajewski (2001) report that two different VPR correction schemes (a mean and a local VPR

derived from multi-elevation data). Both brought about significant improvements but had “serious shortcomings as far as being considered for operational real-time application”. Therefore currently no vertical profile correction scheme is applied to the NEXRAD data (J. Keeler, personal communication).

(b) *Use of standard vertical profile and mesoscale model temperatures*

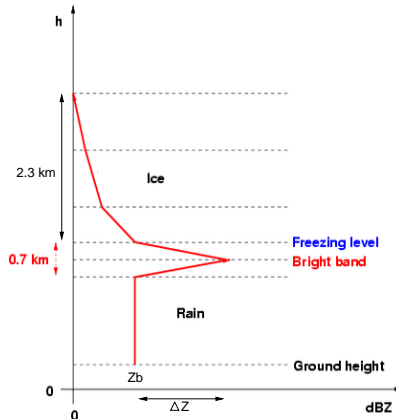


Figure 1. The standard profile template that is used for VPR correction (after Kitchen *et al.* (1994)). It is an average profile compiled from three years’ high resolution data collected with 3 GHz Chilbolton radar.

The second approach for vertical profile correction involves using a standard VPR together with a bright band height that is derived from the temperature structure predicted by an operational model. The method adopted by the Met Office as described by Kitchen *et al.* (1994) uses this technique and is based on the standard vertical profile in Fig. 1, which has been derived from 112 days of rainfall over three years of high resolution vertical scans taken with the 0.25° beamwidth radar at Chilbolton. In this profile the “background” reflectivity in the rain, Z_b , is constant, the bright band enhancement occurs over a depth of 700 m, and then Z decreases with height above the bright band. In the bright band Z rises linearly for 350 m by ΔZ and then falls linearly back to Z_b over the next 350 m, where ΔZ (in $\text{mm}^6 \text{m}^{-3}$) is given by:

$$\log \Delta Z = 1.42 \log Z_b - 0.44 \quad (1)$$

so that the enhancement for a Z_b of 20, 30 and 40 dBZ (equivalent to rainfall rates of 0.65, 2.7 and 11.5 mm h^{-1} using the Marshall-Palmer relationship) would be 5.4, 8.7 and 12 dBZ, respectively. Above the bright band the cloud top is inferred from the infrared satellite temperatures, to be a height of 1, 2, 3 or a maximum of 4 km above the bright band peak and the reflectivity in dBZ is linearly reduced to zero. The correction procedure is as follows:

1. The standard VPR in Fig. 1 is shifted in height so that the top of the bright band coincides with the height of the WBZ from the model.
2. The VPR is scaled in magnitude (with accompanying changes to the bright band enhancement), so that when the the profile is multiplied by the operational radar beam pattern at the appropriate height, the radar reflectivity matches the observed value.

3. The best estimate of the rainfall rate at the ground is given by the value of Z_b of the scaled profile.

TABLE 1. Peak errors at 50 and 100 km in inferred ground-based reflectivity for a bright band peak enhancement of 8.7 dB and the height range for the centre of the radar beam over which the reflectivity error exceeds 50%.

| | at 50 km | | at 100 km | |
|-----------------------------------|------------|------------|------------|------------|
| | Peak error | Range >50% | Peak error | Range >50% |
| (a) <i>No correction applied</i> | 320% | 900 m | 220% | 1200 m |
| (b) <i>Correction applied</i> | | | | |
| but with a 500 m WBZ height error | 310% | 1300 m | 190% | 1200 m |
| but with a 200 m WBZ height error | 60% | 300 m | <30% | – |

Table 1 assesses the impact of height errors on the VPR correction scheme’s ability to remove the effects of the bright band for the profile in Fig. 1 and a Gaussian beamwidth having a two-way half-power beamwidth of 0.65° appropriate for the Met Office radar network. The calculations were done for a bright band enhancement of 8.7 dB (a surface rain rate of 2.7 mm h^{-1}). If no correction is applied then at a range of 50 km the peak error in the inferred ground-based reflectivity is 320% and the errors exceed 50% for a 900 m range in beam heights. Applying the VPR correction algorithm, but with the bright band height wrong by 500 m leads to negligible improvement in rainfall estimates, whereas an inaccuracy of 200 m in the bright band height leads to a peak error in the inferred reflectivity in the rain of only 60%. This confirms Kitchen *et al.*’s statement that the algorithm requires the height of the bright band to be known to within 200 m.

Another advantage of this correction scheme is that it is applied over each 5 km x 5 km area of every low level radar scan, thus avoiding all the difficulties that arise for volumetric scans in choosing an appropriate scale in space and time over which the average profile is derived; these scales could also vary with precipitation type and geographic location. The algorithm is suppressed, however, when the value of Z exceeds 30 dBZ at a height of 1.5 km above the freezing level. An analysis by Smyth and Illingworth (1998) has shown this threshold to be a reliable indicator that no bright band is present, presumably associated with the high density graupel in convective cells. Harrison *et al.* (2000) found that over a twelve-month period the average reduction in the r.m.s. difference between the hourly gauge accumulations and the corresponding radar-estimated accumulations was approximately 30%. The r.m.s. differences were still a factor of two, as is expected for representativeness sampling errors if hourly totals are estimated with a 5 km resolution every 15 minutes (Kitchen and Blackall, 1992). According to Kitchen and Blackall these representativeness errors would be reduced to about 25% if 2 or 5 minute sampling with a spatial resolution of 2–3 km were used for the hourly totals; with this sampling the true impact of the VPR correction scheme could be quantified more accurately. An evaluation of the radar precipitation estimates by Kitchen and Harrison (2001) has shown that the “tractable” (i.e. non-sampling related) error in the ratio of the hourly gauge to radar rainfall ratio has been reduced by 50% through the introduction of their VPR correction methods.

A similar vertical profile correction scheme is used in France (Chèze *et al.* 1998). Rather surprisingly, Kitchen (1997) found no improvement in the bright band correction scheme when the higher elevation beams were included, presumably because of the vari-

ability in the profile in the ice above the bright band, thus supporting the assertion of Fabry *et al.* (1992) that beyond the range where the radar horizon intercepts the freezing level “any attempt to obtain quantitative rainfall estimates is futile”.

3. DERIVATION OF THE “STEP” HEIGHT FROM CLOUD RADAR DATA

From all available data collected by the vertically pointing 94 GHz *Galileo* cloud radar at Chilbolton in southern England (51.14° N and 1.44° W) between 1 May 1999 to 30 April 2000, 435 condensed hours were associated with rain rates exceeding 0.48 mm h⁻¹. Of this number 189 hours (43%) had VPRs with detectable melting level heights. Another 35% of the hours comprised very shallow rain or showery elements, leaving about 22% of the hours which were more convective and no bright band detected. Surface rain rates associated with individual bright band profiles were found up to 17.75 mm h⁻¹, although the majority are less than 5 mm h⁻¹. The radar provided time series of vertical reflectivity profiles at 60 m range resolution every 30 seconds with a minimum range of 250 m. Typical vertical profiles from the 3 GHz and 94 GHz Chilbolton radars are plotted in Fig. 2.

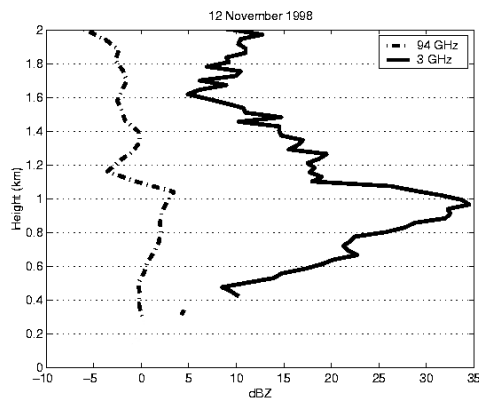


Figure 2. Typical vertical profiles sampling a stratiform rainfall area as seen at 3 and 94 GHz.

The 6-dB step in the 94 GHz vertical profile indicates the onset of melting. The more gradual rise in Z at 3 GHz (10 cm) is caused by the finite time it takes for the snow flakes to acquire a sufficient liquid water coating so that the dielectric factor, K , rises from the value of dry ice to that of liquid water. The fall in Z below the bright band is caused by the decreasing size and concentration of drops as they melt, the break up of large drops and increasing terminal velocities. The thickness of the liquid water shell required for a change in K is wavelength dependent and becomes very small at 94 GHz (Meneghini and Kozu, 1990). This accounts for the observed 6-dB step within one range gate. At these high frequencies Mie scattering and attenuation is responsible for much lower values of Z, and also explains why the 94 GHz VPR is less sensitive to changes in the size of melting particles when a spectrum of sizes is present. Accordingly we can identify the 6-dB jump occurring within one gate as the height at which melting starts and T_w reaches 0°C.

White *et al.* (2002) derive the height of the bright band by searching vertical profiles of Doppler velocity from a 915 MHz Doppler wind profiler from the bottom up for a change in velocity of 1.5 m s⁻¹ over a distance of 210 m. We have tested this technique

with the 94 GHz Doppler data, and find that the change in velocity is typically spread over 180–300 m and is offset by as much as 400 m below the step in reflectivity which occurs when the particles become wet. Presumably they need to fall this distance to melt sufficiently so that the terminal velocity increases. As discussed in the previous section a 400 m offset in determining the bright band height is not acceptable.

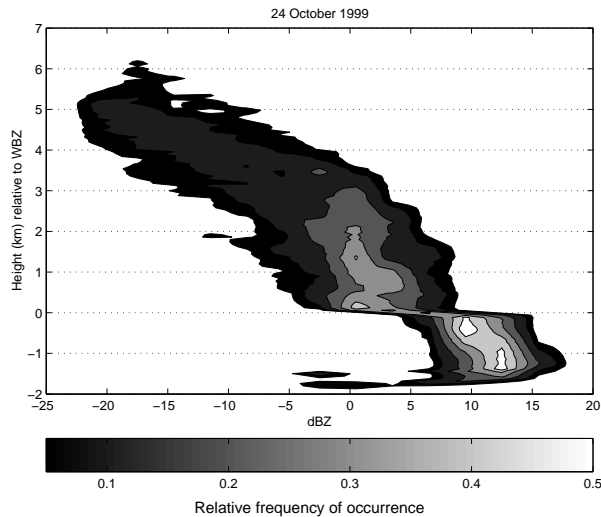


Figure 3. A contoured-frequency-by-altitude diagram (CFAD) of the vertical profile structure for 24 October 1999. Contours are at 0.1 intervals.

The vertical structure of reflectivity can also be summarised in the form of contoured-frequency-by-altitude diagrams or CFADs, as a function of height relative to the bright band height of each profile, as described by for example Yuter and Houze (1995). Figure 3 shows the CFAD for all the identified profiles on 24 October 1999. Again the step transition showing the onset of melting under stratiform conditions is clearly evident and very sharp, indicating that the WBZ can be determined to within 60 m or one range gate. The maximum rain rate did not exceed 5 mm h^{-1} .

A vertical profile was only included in the analysis if the near-ground reflectivity was greater than -10 dBZ , the corresponding 30-second rain rate from a drop-counting gauge exceeded the detection threshold of 0.48 mm h^{-1} and a step in the VPR in the vicinity of the WBZ height. The hourly heights were calculated as the mean of the 120 30-second profiles. A 5% data threshold was imposed, so that only hours with more than 6 30-second profiles were included for analysis. The technique is completely independent of radar calibration or attenuation by rain.

4. DERIVATION OF TEMPERATURE PROFILES FROM MODEL DATA

Wet-bulb temperature profiles were derived from the relative humidity fields for both the ECMWF and UM forecasts. During the period in question the ECMWF model had a horizontal grid resolution of 60 km with 50 vertical levels (after 13 October 1999 the horizontal resolution changed to 50 km and 60 vertical levels). There is one run each day at midday, with forecasts being produced hourly from $t+12\text{h}$ to $t+36\text{h}$ (midnight to midnight). The mesoscale version of the UM had a grid resolution of around 15 km with 35 vertical levels and was initialised every 6 hours. The $t+0\text{h}$ to $t+5\text{h}$ forecasts were used

for most of this analysis. Hourly forecasts are available out to $t+36\text{h}$. At heights between 0.5 and 3 km, model layer depths range between 170 to 500 m, but before 13 October 1999 ECMWF layer depths had less resolution below 2 km. Because temperature profiles are often quite complicated, linear interpolation was found most reliable. Experiments carried out with more complex fits did not yield significantly different heights for the interpolated values. The algorithm extracts the height at which T_w first rises to 0°C , when one searches downwards. Two parameters were derived from the interpolated model profiles to study the height and temperature errors: (i) WBZ and (ii) T_w at the observed step height of radar reflectivity.

5. RESULTS OF THE RADAR AND MODEL COMPARISON

This study investigated:

- The model errors of WBZ heights to establish whether using the model heights is the optimum approach.
- The performance of the model in predicting changes in WBZ heights, such as the mean error in the timing of frontal passages.
- The performance of the model in predicting isothermal layers at or near 0°C . The formation of deep or double bright bands could have an impact on the effectiveness of the VPR correction scheme.
- Degradation of the UM forecast over a 36-hour lead period.

(a) Overall performance evaluation

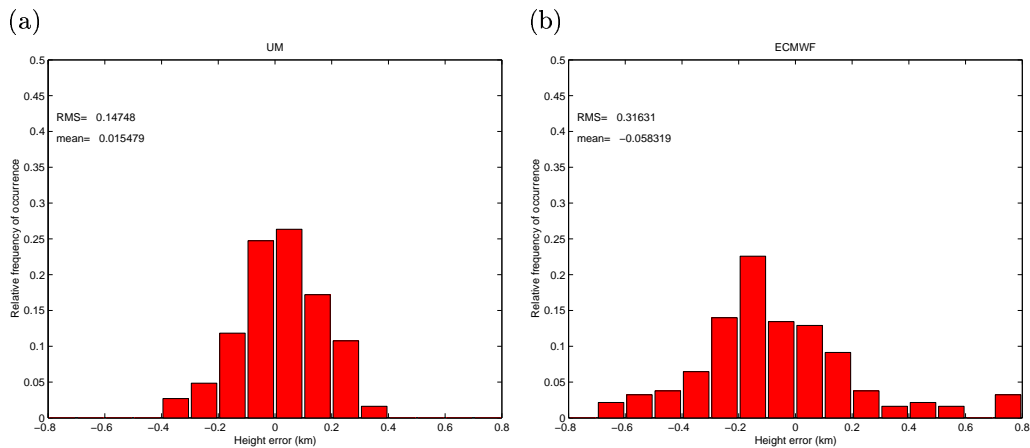


Figure 4. Histograms of the height differences between (a) the UM $t+0$ to $t+5$ h forecast, (b) the ECMWF WBZ heights and the observed radar heights.

Histograms of the relative frequency of occurrence of height differences (radar–model) with respect to the WBZ for a sample of 189 hours obtained during the 12-month period are given in Fig. 4(a) for the UM and Fig. 4(b) for ECMWF. The r.m.s. error for the UM for the $t+0\text{h}$ to $t+5\text{h}$ values is 147 m with a bias of only 15 m below the observed height. The ECMWF profiles have a r.m.s. error of 316 m with a bias of 58 m above the observed bright band height; but of course this increase may be because the ECMWF

time series is a $t+12\text{h}$ to $t+36\text{h}$ forecast. When the same period is considered for the UM forecast, the r.m.s. error is 250 m with a bias of 95 m above the observed height.

It is important to notice the encouraging lack of outliers in the error distribution for the UM, with no occasions of differences above 400 m. The hourly differences exceeding 800 m for the ECMWF error analysis are due to a single case where the model failed to predict the development of a deep isothermal layer.

(b) *Comparison with Met Office continuous radiosonde validation results*

The Met Office continually monitor the temperatures by comparisons with radiosonde data, over the whole model domain. The r.m.s. errors of 170 m (D. Forrester, personal communication) for the period April 2000 to June 2001 are very similar to those reported in Fig. 4(a). The radiosonde data are not truly independent however, they are themselves assimilated into the model. In addition the validation is performed over the whole domain every 12 hours whereas the radar comparisons reported here are confined to rainfall events which may be expected to be more error prone, often associated with fronts and changes in temperature.

(c) *Frontal events and associated timing errors*

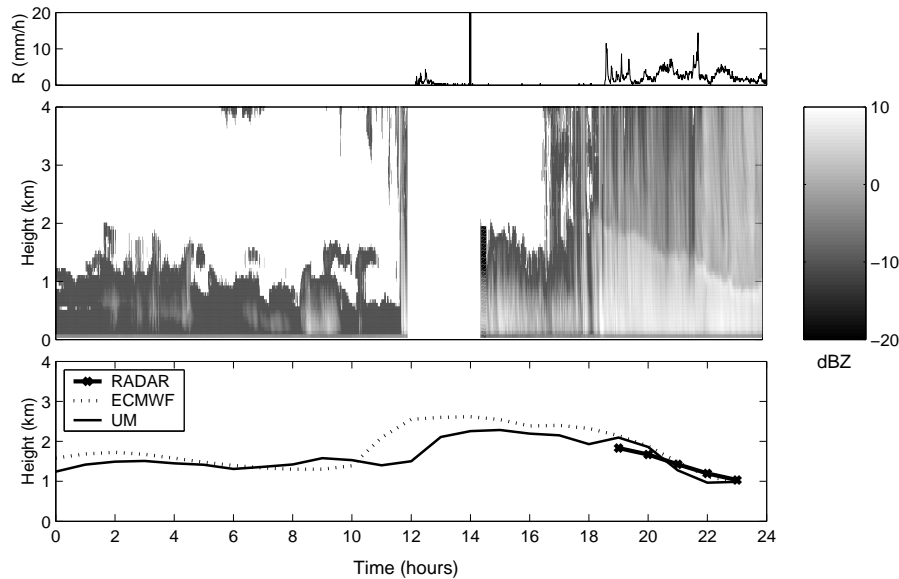


Figure 5. The daily 30-second time series of radar, rain-gauge rain rates, hourly radar freezing levels and model forecasts for 22 December 1999.

The passage of a front is typically associated with significant changes in the vertical temperature profile and also the freezing level height. It might well be thought that the occurrence of timing errors would cause frequent errors in the bright band correction scheme. An example of such a rapid change in the height of the freezing level is displayed

in Fig. 5. Note that gaps in the radar time series are when the radar is not vertically pointing but in scanning mode (at this time the radar was mounted on the side of the 3 GHz radar antenna dish at Chilbolton). The radar observations show that the freezing level dropped about 800 m in the space of 4 hours. The model WBZ heights tracked this change with considerable accuracy. For this particular front the model showed no significant timing errors.

To obtain a more “global” view, a simple analysis of the timing errors is presented here. Frontal events accompanied by temperature changes were isolated by searching the hourly time series for a change exceeding 250 m in 3 hours. In this way, 6 events were identified. The model timing was then assessed based on an analysis of trends, by matching the peaks and the periods of increase and decrease on an event-by-event basis. For 3 of the events no timing errors can be inferred. Two of the events however had substantial errors of between 3 and 8 hours, yet these errors were more associated with a difference in the rate of change in temperature rather than an outright model timing error. Only one event could be described to have a combination of model timing error and a difference in the rate of change in the height of the freezing level.

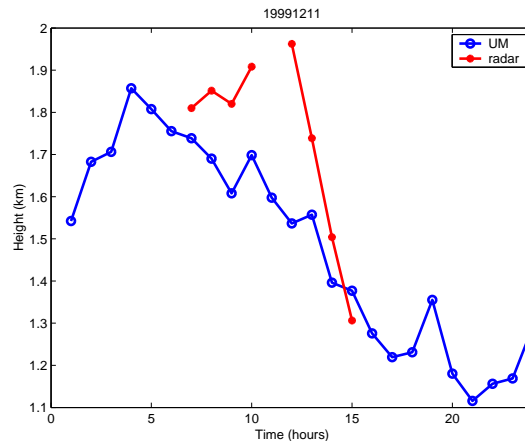


Figure 6. Hourly radar observed freezing level heights and model forecast WBZ heights for 11 December 1999.

The worst forecast was for the frontal passage on 11 December 1999 as shown in Fig. 6. The model predicted a steady fall in temperature starting at 0400Z, whereas the radar observations indicated a much greater rate of decrease starting at 1200Z. The model error at this time was more than 400 m, one of the worst performances in the data set considered. Fortunately it would appear that such events are rare and generally short-lived, affecting only 1 or 2% of rainfall cases and we conclude that errors due to poorly predicted frontal passages are not serious.

(d) *The presence of a deep isothermal layer at or near 0°C*

The performance of a model in predicting isothermal layers is very important. For several hours on 3 April 2000 the UM was accurately predicting the presence of a deep isothermal layer which cooled throughout the day until its temperature fluctuated about 0°C. The ECMWF WBZ was eventually 800 m lower than the UM WBZ height, and, more significantly the ECMWF forecast showed no sign of any isothermal layers through the day. An isothermal layer at or around the 0°C isotherm would imply that the bright band would be deeper than usual, as the melting in this layer is retarded.

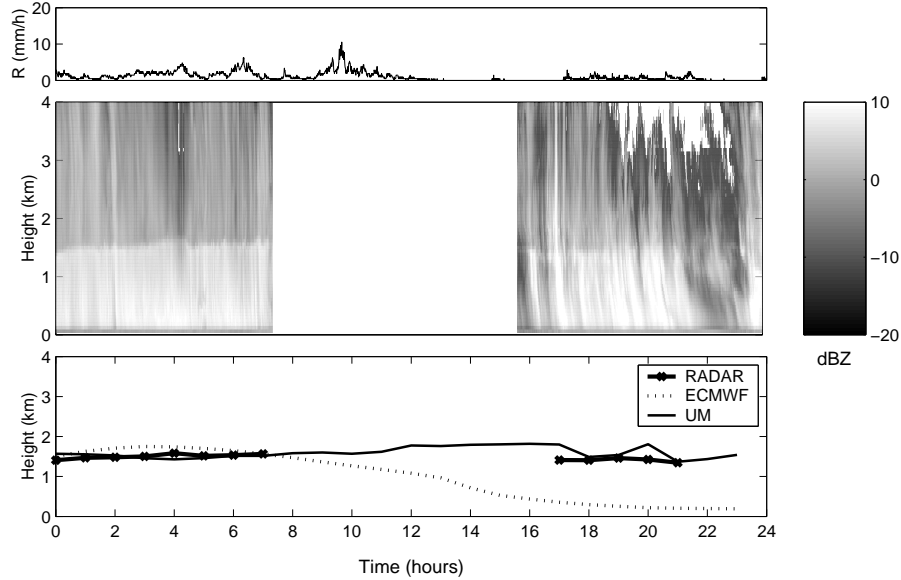


Figure 7. The daily 30-second time series of radar, rain-gauge rain rates, hourly radar freezing levels and model forecasts for 3 April 2000.

The 3-panel plot in Fig. 7 indicates the well defined melting level step. Note the more gradual decrease in the ECMWF WBZ height to near ground level as the day wore on. The large errors from this poor forecast would lead to a poor performance of the bright band correction scheme, and emphasise the importance of using the current analysis and 6h forecast scheme rather than the longer lead times of the daily ECMWF forecast.

(e) *Degradation of forecasts with increasing lead times*

The performance of the UM as a function of forecast lead time up to 36 hours is shown in Fig. 8. Whereas it is useful to evaluate the bright band correction scheme performance in terms of height errors, for the model's vertical temperature structure it is more convenient to express the errors in terms of temperature, so the value of T_w at the bright band height is plotted. It is encouraging to see that the bias stays fairly constant around 0.15°C but the r.m.s. error increases from 0.7°C to 1.4°C after $t+36\text{h}$, so half the error is introduced at initialisation time. For the ECMWF forecast lead times of $t+12\text{h}$ to $t+36\text{h}$, the UM forecast for the same lead time suggests an average error of 1.2°C 70% higher than $t+0\text{h}$ to $t+5\text{h}$. Accordingly we conclude that the larger r.m.s. errors of 316 m for the ECMWF scheme rather than 147 m for the UM arise because of the longer lead times and the lower horizontal resolution of the ECMWF forecast. This is confirmed by the comparison of ECMWF model temperatures with observations over Europe and the Northern Hemisphere for the last six months of 2001 (J.-F. Mahfouf, personal communication) which have an r.m.s. analysis error at 700 mb of $0.75\text{--}0.8^\circ\text{C}$ and $1\text{--}1.1^\circ\text{C}$ at $t+24\text{h}$ and are very similar to Fig. 8 for the UM. The Met Office continuous validation using sondes yield a worsening in the r.m.s. error from 170 m at $t+0\text{h}$ to 270 m

at $t+48\text{h}$ (D. Forrester, personal communication), which is consistent with the data in Fig. 8 and suggest that the temperature errors within precipitation are no worse than those for all conditions.

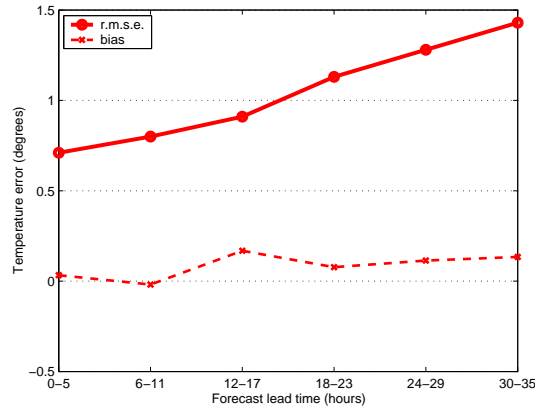


Figure 8. Summary of the temperature differences between the T_w at the observed bright band height and the T_w 0°C isotherm for the different forecast lead times of the UM.

These results demonstrate that if the initial analysis error could be further reduced, a significant improvement could be brought about for the entire forecast lead time.

6. DISCUSSION AND IMPLICATIONS

A one year analysis of 189 hours of rainfall over the UK has revealed that the r.m.s. error of the UM $t+0\text{h}$ to $t+5\text{h}$ forecasts of the WBZ during rainfall is 147 m with a bias of 15 m. The model was able to track changes in bright band heights which sometimes changed as much as 500–1000 m in 2–4 hours with good accuracy, although the 2% of occasions in which the errors reached their maximum value of 400 m were associated with frontal timing errors. For forecasts from $t+30\text{h}$ to $t+36\text{h}$ the r.m.s. error was doubled. These errors compare well with those obtained from the sonde comparisons for all weather conditions rather than the radar comparisons which were only during precipitation, even though sonde data is not independent as it is used in the model analysis. The performance of the ECMWF model over Europe and the Northern Hemisphere is similar when consideration is given to the longer forecast lead time and the degraded model resolution with an r.m.s. error of 316 m for $t+12\text{h}$ to $t+36\text{h}$ forecast. On one occasion during the 189 hours of comparisons an isothermal layer at least 800 m deep developed and persisted during 4 hours of rainfall. This layer and the height of the WBZ was accurately captured by the UM, but the ECMWF model, with its longer lead time, failed to predict it, and this event was responsible for the worst errors of 800 m for the ECMWF model comparison.

The results can be compared with the idealised accuracy of 300 to 500 m obtained from the simulation study of Sánchez-Diezma *et al.* (2000). This simulation assumed: (1) the bright band was at the same height and was the same shape at all distances out to 120 km; (2) a uniform rainfall rate and identical profiles regardless of range; and (3) that the profile was sampled by a 1° beamwidth radar at 24 elevations. These simulated accuracies appear to be rather worse than those of the operational forecast models. A comparison of one hour's data at 22 elevations of widespread stratiform rain with an independent estimate of the bright band height from a UHF vertically pointing

radar, found that the height of the bright band was relatively stable, but beyond 80 km it could not be detected. The advantage of using the model temperature field is that it always provides a bright band height and is not limited to rather unusual conditions when rainfall is continuous over a large distance.

Our analysis in the UK demonstrates that the mesoscale version of the UM with 12 km resolution run every 6 hours with hourly forecasts from t+0h to t+6h provides sufficiently accurate temperatures as does the ECMWF model over the Northern Hemisphere for similar lead times. Germann and Joss (2002) suggest that over the Alps the height of the melting layer varies both in space (air masses following the terrain) and time (temperature fronts) and that to use this temperature information in a correction scheme a model resolution of 30 minutes and 10 km would be required. It would be interesting to see results of radar comparisons with the ECMWF model temperature data in Switzerland and other parts of the world, but it appears that, in the UK at least, the errors in the operational forecast height of the WBZ from t+0h to t+6h are within the bounds of 200 m listed by Kitchen *et al.* (1994) and that the model-predicted height of the bright band height is more accurate than the height derived from the multiple elevation radar data itself.

We conclude that operational forecast models can provide the height of the bright band with an r.m.s. error of 150 m. If this model height is used in conjunction with an appropriately scaled and shifted standard VPR then it should lead to improved estimates of rainfall rates at the ground. If the error in the bright band height reaches 500 m then this technique will not lead to improved rainfall rates at the ground, but such large errors were not observed. An alternative method of deriving bright band heights has been proposed which involves the use of volumetric radar scans averaged over an area but at present it is not clear that such an approach can yield the required 200 m accuracy in the inferred bright band height.

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