Implementation and Evaluation of VPR Correction Methods Based on Multiple Volume Scans

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1. Introduction

The use of radar measurements to monitor and quantify rainfall is limited by errors and uncertainties in the estimation of surface precipitation. Weather radars use different elevation angles to measure the reflectivity of hydrometeors and from these measurements, the precipitation at surface level can be estimated. Due to the earth's curvature the height of the volume sampled by the radar increases with the distance, and the measurements get less and less representative of surface conditions. Another important error is due to the vertical variation of the radar reflectivity. This non-uniformity of the vertical profile of reflectivity is caused by the growth, melting and evaporation of precipitation (Joss and Waldvogel, 1990). In particular, the melting produces an enhancement of reflectivity in the melting layer known as the bright band. This effect is much more present in vertical reflectivity profiles (VPR) of stratiform precipitation than in the convective ones.

Various methods have been proposed in literature to correct radar measurements from those errors. These methods consist in estimating the shape of the representative vertical profile of reflectivity and to use it for extrapolating reflectivity measurements aloft towards ground level. This representative profile can be determined by using climatological profiles, local profiles at short distances from the radar (Kitchen et al., 1994; Germann and Joss, 2002) or by means of an inverse theory (Andrieu and Creutin, 1995; Vignal et al., 1999). In the present work a simple VPR method, aimed for operational use, has been implemented. It is based on the identification of an average VPR by using volume reflectivity data at short range. The method is only applied to the stratiform areas. A version of the Steiner algorithm adapted to the Belgian climate is used for separating stratiform zones from convective zones. A criterion for the applicability of the average VPR is imposed to filter out unrealistic profiles. When the average VPR is discarded, a climatological profile is used.

The radar observations are available from a C-band Doppler radar located in the south of Belgium (Wideumont) and operated by the Royal Meteorological Institute of Belgium (RMI). The radar performs a 5-elevation scan every 5 minutes and a 10-elevation scan every 15 minutes. Both scans are used to obtain the best precipitation estimates and accumulation maps.

The evaluation is based on daily accumulations. These accumulations are first adjusted with gauge measurements from the automatic network operated by the hydrological service of the Walloon region. The verification is then performed by comparing with measurements from the RMI climatological network. The final goal is to develop the optimal VPR correction method for operational use.

2. Radar and gauge observations

As mentioned before, the radar observations are obtained from the Wideumont radar. It is a single-polarization C-band radar, situated in the south of Belgium. The radar performs different scans of the atmosphere, getting measurements of reflectivity up to a distance of 240Km. The beam width is 1 degree. The volume data used for this study come from two different volume scans: a 5-elevations scan (0.3º, 0.9º, 1.8º, 3.3º and 6.0º) with a polar resolution of 250m in range and 1º in azimuth produced every 5 minutes, and a 10-elevations scan (0.5º, 1.2º, 1.9º, 2.6º, 3.3º, 4.0º, 4.9º, 6.5º, 9.4º and 17.5º) every 15 minutes with a polar resolution of 500m in range and 1º in azimuth. A time-domain Doppler filtering is applied to the 5-elevation scan to eliminate the ground echoes. To both scans an additional ground clutter filter based on the vertical gradient of reflectivity between the lowest elevations is applied.

For the evaluation of the methodology developed, two different networks of rain gauges are used. The first one is operated by the hydrological service of the Walloon region (SPW) and is used to adjust the 24h accumulations derived from radar observations. It consists of a dense and integrated network of 90 telemetric rain gauges, most of them are tipping bucket system providing hourly rainfall accumulation. The rain gauges are controlled on site every three months and in a specialized workshop every year. Each day a quality control of the data is performed by the RMI using a comparison with neighboring stations. For validation purpose, the RMI climatological network is employed. It includes 270 stations with daily measurements of precipitation accumulation between 8 and 8 local time (LT). These stations are manual and the quality of the data is strictly controlled.

3. VPR Correction

The bright band is a layer of enhanced reflectivity caused by the scattering characteristics of the melting drops and their different velocities. This overestimation of the reflectivity can be observed in the Pseudo CAPPI product when the height of the bright band is close to the altitude of the PCAPPI. It appears as rings of enhanced reflectivity centered on the radar. Each ring occurs when one of the radar beams crosses the bright band layer. The different VPR correction methods aim not only to correct for this overestimation, but also to reduce the underestimation that occurs at long ranges, where the radar beams are quite high and so the measurements are not representative of the precipitation at ground level.

The importance of the errors caused by the non uniformity of the reflectivity varies according to the type of precipitation.

3.1 Steiner algorithm adapted to Belgian climate

The aim of the VPR correction scheme is to extrapolate the measurements of reflectivity, taken at a certain height, towards the ground. This is done by using the shape of a representative VPR, that has been estimated from volume data close to the radar. The shape of the VPR depends on the type of precipitation. VPRs corresponding to convective precipitation show more uniform values of reflectivity, having a significant vertical extension (up to 12 km). On the other hand, stratiform VPRs generally present an enhancement of reflectivity (bright band) close to the height of the melting layer.

This difference in the shape of the VPRs for stratiform and convective precipitation makes the VPR correction much more important for the stratiform precipitation. Therefore it is necessary to develop an algorithm able to separate convective zones from stratiform zones. In the literature, two types of algorithms based on reflectivity radar data, have been proposed. The first type of algorithms is based on the identification of the bright band, which occurs in stratiform precipitation (Collier et. al, 1980; Sanchez-Diezma et al., 2000). The main disadvantage of those methods is that they cannot be applied beyond the distance where the lowest PPI (Plan Position Indicator) is affected by the bright band. At that range, the observed VPRs will not have an elevation below the bright band (not affected by it), which is a necessary condition for the application of the algorithm. They are also very dependent on the scanning strategy (number of elevations used). The second group of algorithms looks for the identification of convective zones by detecting reflectivity peakedness on a horizontal reflectivity map (Steiner et al., 1995). For this project, the second approach has been chosen, so the first step is the separation of the stratiform zones from the convective ones by using the Steiner algorithm (Steiner et al., 1995). This method is easy to implement and it does not underestimate the stratiform zones (assuming a good calibration of the parameters). For the application of such an algorithm to Belgian climate, some changes have been performed. The original Steiner separation scheme works on Cartesian-gridded reflectivity data at an altitude of 3 km, with a mesh size of 2 km. For the application to the Wideumont radar, the data used is distributed into a polar grid and is coming from a 5 and/or 10 elevations scan that is produced every 5 and 15 minutes respectively.

The original algorithm was developed for the tropics where the freezing level (0ºC isotherm) is usually around 5 km above sea level, in such a way that, most of the time, the algorithm works below the bright band and is not affected by it. According to Belgian conditions, the altitude of the 0ºC isotherm can change between 0 km and 5 km, so the original algorithm will be affected by the bright band. Because of this and to avoid false detected convective zones when one of the PPIs intercepts the bright band, the Steiner algorithm will be applied to two different altitudes: 1.5 km and 4.0 km. One point will be labeled as convective, only if it has been labeled as convective in both altitudes. This condition ensures the vertical extension that characterizes convective precipitation. On the other hand, no-precipitation points are detected by the analysis of reflectivity values at 1.5 Km, independently of reflectivity values at higher altitudes.

The Steiner algorithm consists of three steps, which are described in Steiner et al. (1995).

- *Intensity step,* any grid point with a value of reflectivity higher or equal to 40 dBZ will be labeled as convective.
- *Peakedness step,* for any grid point that has not been labeled as convective in the first step, if the average reflectivity, taken over the surroundings, exceeds a certain reflectivity difference threshold, the point will be classified as convective. This reflectivity difference, ΔZ, is the difference between the reflectivity at a grid point and the background reflectivity, Z_{bg}. The background intensity is calculated as the linear average of the non-zero values of reflectivity within a radius of 11 Km around the grid point. The reflectivity difference threshold is:

$$Z_{bg} < 0\text{dBZ and } \Delta Z > 10\text{dBZ} \rightarrow \text{convective}$$
$$0\text{dBZ} \leq Z_{bg} < 42.43\text{dBZ and } \Delta Z > 10 - (Z_{bg})^2/180 \rightarrow \text{convective}$$
$$Z_{bg} \geq 42.43\text{dBZ and } \Delta Z > 0\text{dBZ} \rightarrow \text{convective}$$

- *Surrounding area step,* for each convective grid point, all surrounding grid points within an intensity-dependent radius, around that grid point, are also labeled as convective.

Once the points at both altitudes have been classified, a comparison between both results is performed to extract the final distribution of the stratiform and convective zones (*Table 1*). If a grid point has been labeled as convective in both altitudes, it will be classified as convective. If it has been labeled as convective only in the lower altitude, 1.5 km, it means that the precipitation does not have a large vertical extension (signature of convective precipitation), but a high value of reflectivity at the height of 1.5 km, implying the presence of a bright band around that altitude. On the other hand if it has been labeled as convective in the highest altitude and as stratiform in the lower, the point will be classified as stratiform, presenting a bright band around the height of 4 km. In the remaining cases, if the grid point is labeled as stratiform at 1.5km and as no precipitation or stratiform at 4 km, it will remain as stratiform. However, if it is labeled as no precipitation in the lowest level, it will be classified as no precipitation, even if it has been assigned as convective or stratiform at the upper level. Those are cases where the radar detects precipitation at the upper levels but not at the lower, due to evaporation between the measurement height and ground level (overhanging precipitation).

Table 1 Final label for each pixel after applying the Steiner algorithm to two different heights, 1.5 km and 4.0 km.

Level 1: 1.5 km	***Level 2: 4.0 km***	***Final Label***
Convective	*Convective*	*Convective*
Convective	*Stratiform/No precipitation*	*Stratiform*: bright band around 1.5 km
Stratiform	*Convective*	*Stratiform*: bright band around 4.0 km
No precipitation	*Convective/Stratiform*	*No precipitation*: evaporation

As can be noted, the principal modification that has been done to the original Steiner algorithm is the use of two heights. An example of the results of the modified Steiner algorithm is shown in *Fig.1*. The Pseudo CAPPI map at 1500m is also presented in order to give an idea of the quality of the results. Note that the validation of the separation algorithm is difficult, due to the fact that the position of the "real" stratiform and convective zones is unknown. However, taking in account that the principal goal of the algorithm is to separate the pure stratiform zones to the pure convective ones, the results obtained are quite realistic.

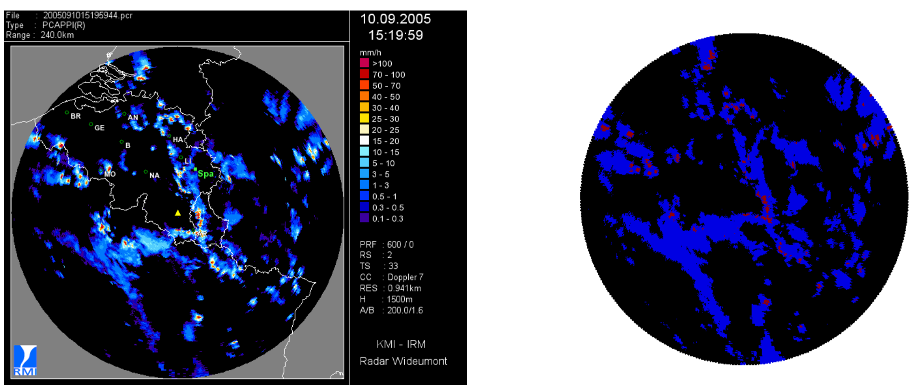

FIG.1. Pseudo CAPPI and output of the modified Steiner algorithm on 10/09/2005 at 15:19UT. Red points correspond to convective zones, blue points correspond to stratiform zones and black points to no precipitation zones.

3.2 Median Average VPR

Since only the stratiform zones are significantly affected by the bright band phenomena, it looks reasonable to extract the representative VPR only from stratifrom VPRs present in the volume data within a certain range. This range must be such that the variation of the reflectivity along the vertical is well caught, which implies that the highest elevation cannot be too low and the lowest elevation cannot be too high, so the cone of silence is avoided. According to this only data between 10 and 50 Km from the radar will be considered. The main objective of the calculation of the representative VPR is to determine its shape. Therefore, to compare and to average all the different shapes of the profiles present within the specified range, a normalization is first needed. This normalization will be done taking a reference altitude that is common to all the profiles. This reference height must be in a region where the vertical gradient of reflectivity is small, so the zone affected by the bright band must be avoided. In order to achieve this, an algorithm for the identification of the bright band has been developed; it is applied to the stratiform points within the specified range. The peak of the bright band is found by looking for the maximum of reflectivity by means of its vertical gradient, in particular by searching for a sign change. The vertical variation of the reflectivity above and below the peak must be high enough to ensure the existence of the bright band. Once the area where the bright band is located is known, the reference height for the normalization will be the minimum height that is common to all the points considered and that is out of the zone affected by the bright band. After this altitude is determined, the normalized values of reflectivity are computed by using the following expression:

$$Z_{norm}\left(r,\theta,h_i\right) = Z\left(r,\theta,h_i\right) - Z\left(r,\theta,h_{ref}\right) \tag{1}$$

Each reflectivity value, $Z\left(r,\theta,h_i\right)$, of every VPR is normalized by the reflectivity at the reference height, $Z\left(r,\theta,h_{ref}\right)$, both in dBZ units. Z_{norm} is the normalized reflectivity in dBZ, r and θ are the distance from the radar and azimuth, respectively.

To obtain the final median average VPR (MAVPR) from the normalized profiles, *Fig.2*, a moving average will be performed. According to it, the value of the final VPR at a certain height, h , will be the median value of all the points of the normalized profiles that are located within the vertical range. Where Δh_m is the size of the moving window, it is centered at the height at which the value of the final VPR is going to be computed. Several values for the moving window have been analyzed. Taking into account the resolution of the data and the computational cost, a window size of 100m has been chosen.

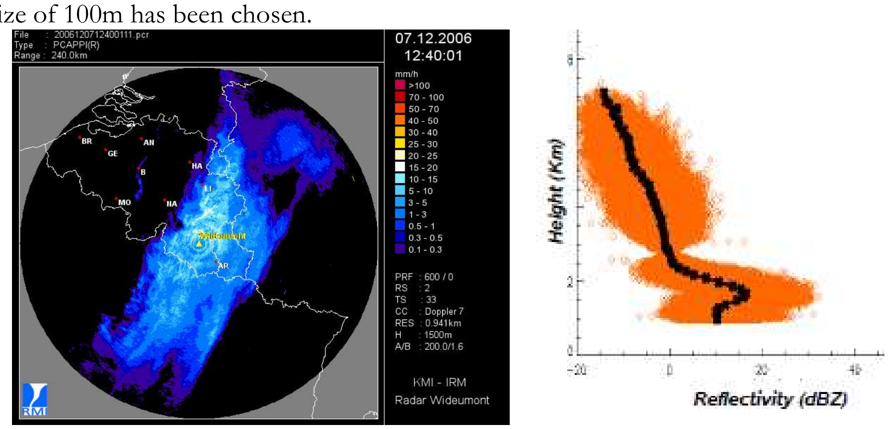

FIG. 2. Median Average VPR (right image, black) extracted from the normalized profiles (right image, orange) within a range of 10-50Km (black) for the stratiform case 07/12/2006 12:34UT, PCAPPI at 1500m (left).

3.3 Criteria of applicability

A criterion for the applicability of the MAVPR is imposed to filter out unrealistic profiles. The criteria are based on the amount of stratiform points within the range used to determine the MAVPR. To quantify this, the percentage of stratiform points with respect to the total amount of points between 10 Km and 50 Km from the radar is considered. The criteria also take into account the location of the bright band. So if the percentage of stratiform points within the specified range is above 70%, the MAVPR will be used to fit the observed values. If this percentage is between 40% and 70% and the bright band has been identified, the MAVPR will be employed as well. In the same case, but with no recognition of the bright band, the observations will be fitted by means of the climatological profile. It will be also applied in case the percentage of stratiform points is lower than 40%. When the MAVPR is discarded, a climatological profile with a slope of -4.0dBZ/Km above the freezing level and uniform reflectivity below is used. As a first approach a mean freezing level will be used. In Belgium, the height of the 0°C isotherm varies between 0 to 5 Km (Mohymont and Delobbe, 2008), therefore the mean freezing level will be placed at 3 Km height (data below 1 Km is not considered to avoid ground clutter contamination). In the future, the height of the freezing level will be provided by a Numerical Weather Prediction model. The value for the slope above the bright band was obtained from a yearly mean of the reflectivity profiles over Belgium (Mohymont and Delobbe, 2008).

3.4 **Estimation of rainfall at surface level**

The representative VPR (MAVPR or climatological profile) is employed to fit the observations, providing corrected VPRs from which the surface reflectivity is extracted. The fitting is performed by calculating the deviation of each observed VPR from the representative VPR. In order to have a smooth value of this deviation, a linear vertical interpolation between the measurements is done. Then, the difference between each interpolated value and the representative profile is calculated. The final value for the deviation is a weighted average of all those differences, being the weights inversely proportional to the height. The fitted VPRs are the result of applying the mean deviation, determined for each of them, to the representative VPR. This process must be applied to each pixel labeled as stratiform. Once it has been done, the reflectivity at surface level can be determined. For those points labeled as convective, the surface value will be the result of a linear interpolation around 1.0 Km height between the closest observed values. In case all the values are above or below that height, the closest one will be taken. For stratiform points the surface value will be the value of the corrected VPR at 1 Km height.

Finally, the reflectivity at ground level is converted into precipitation rate by using the Marshall-Palmer relation

$Z = aR^b$ with $a = 200$ and $b = 1.6$.

4. Results: validation with rain gauges

The evaluation of the performance of the VPR correction is based on 24h accumulations, from 8 to 8 in local time. The daily accumulations are first adjusted with gauge measurements from the automatic network operated by the hydrological service of the Walloon region (Goudenhoofdt and Delobbe, 2009). Then, the results are validated by being compared with the gauges from the RMI climatological network. Notice that at long distances from the radar, the accuracy of the precipitation estimates decreases, therefore the verification is done over a limited area of 100 Km around the radar.

A Mean Field Bias Correction assumes that radar data is affected by a uniform multiplicative error that can be caused by a bad electronic calibration or by an error in the multiplicative constant of the Z-R relationship. The adjustment factor is estimated as:

$$C_{MFB} = \frac{\sum_{i=1}^{N} G_i}{\sum_{i=1}^{N} R_i} \quad (2)$$

where N is the number of valid radar-gauge pairs, G_i and R_i are the gauge and radar values respectively. For this correction, only the pairs presenting radar and gauge values higher than 1mm were considered. The corrected accumulation is calculated only if there are at least 10 valid pairs.

As an example of the preliminary results, the accumulation over one particular day, 15/02/2006 8LT to 16/02/2006 8LT, is shown. For this case 5-elevation volume data has been used. It is a stratiform case with a clear bright band in the accumulation map. In *Fig.3* the adjusted accumulated precipitation is shown for both, raw radar data and radar data after applying the VPR correction.

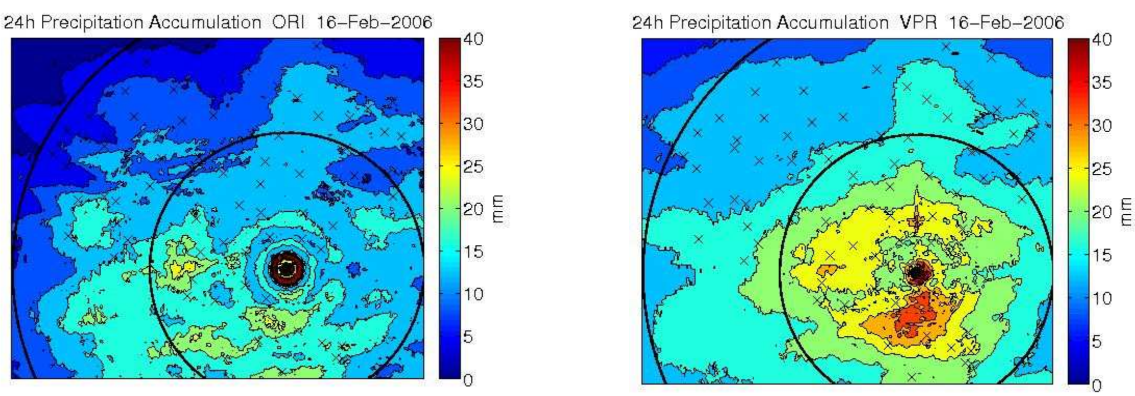

FIG. 3. Impact of the VPR correction for the accumulation over 15/02/2006 8LT to 16/02/2006 8LT. Daily accumulation based on PCAPPI data at 1500m is shown on the right image. On the left, the accumulated precipitation estimates over the same period.

As it can be observed, after the VPR correction the bright band almost disappears. More interesting results are obtained when looking to the accumulation maps after applying the Mean Field Bias correction (MFB). Keep in mind that due to the decrease of the quality of the radar data with the distance, the MFB correction has been performed only up to 100Km from the radar. A further investigation will be done to determine the impact of the variation of the range within the MFB correction. The corrected accumulation maps are observed in *Fig.4*. Notice how MFB correction tends to reduce the underestimation of the precipitation obtained after applying the VPR method. After performing a MFB correction to the original data the bright band signature is still visible, whereas it disappears by only using a VPR correction.

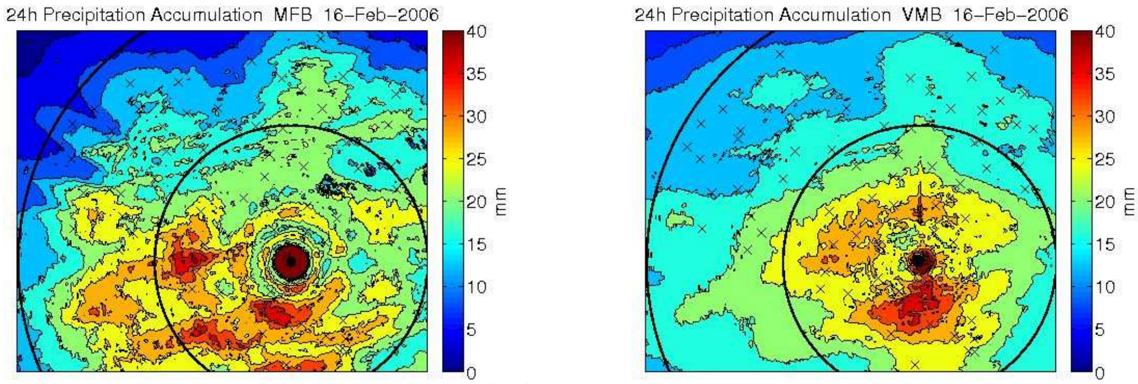

FIG. 4. Accumulated rainfall, 15/02/2006 8LT to 16/02/2006 8LT, after applying the MFB correction to the raw radar data (right) and to the VPR corrected data (left).

The performance of the MFB correction over the different accumulation maps, raw radar data and VPR corrected data, can be evaluated by comparing the adjusted data accumulations for both radar and VPR corrected data (R) to the measurements of the climatological network (G). Several quality parameters have been considered, between them the Mean Absolute Error (MAE), the scatter and the Root Mean Square Error (RMSE) have been choosing to illustrate the performance of the correction. The MAE is less sensitive to large errors and the RMSE is the most common parameter used in verification studies.

$$MAE = \frac{\sum_{i=1}^{N} \left| R_i - G_i \right|}{N} \qquad RMSE = \sqrt{\frac{\sum_{i=1}^{N} \left(R_i - G_i \right)^2}{N}} \qquad (3)$$

The error distribution is the cumulative contribution to total rainfall as a function of the R-G ratio expressed in dB. The scatter is half the distance between the 16% and the 84% percentiles of the error distribution, it provides a measure of the dispersion of the multiplicative error. In *Fig.4* the values obtained for the MAE, the RMSE and the scatter are shown. Notice how just by applying the VPR correction to the raw data the results are better, the values of the MAE, RMSE and scatter are lower. A further improvement is achieved when also the MFB correction is employed

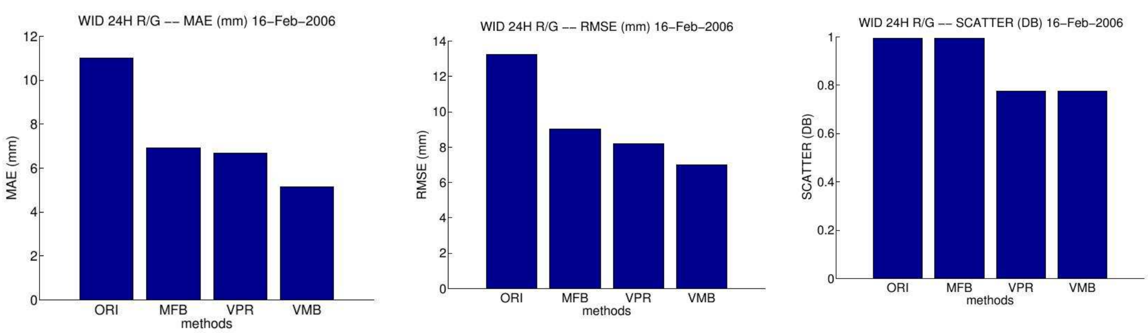

FIG. 4. Mean absolute error (left), the root mean square error (centre) and the scatter (right) for the 24h accumulated precipitation, 16/02/2006. Comparison between the original data (ORI), radar data after MFB correction (MFB), VPR corrected data (VPR) and VPR corrected data with MFB correction (MVB).

5. Conclusions and future perspectives

A simple VPR method aimed for operational use has been presented. It includes the adaptation of the Steiner algorithm for the separation of different types of precipitation to the Belgian climate, as well as the development of a bright band identification method based on the vertical gradient of reflectivity. The comparison of the VPR corrected data with gauge measurements shows promising results on the precipitation estimates. The bright band structure appearing in the daily accumulation maps gets quite smoother if not remove. It can be also observed how the mean absolute error is reduced just by applying the VPR correction to the raw data, without the Mean Field Bias correction.

Those are preliminary results. Further investigation must be carried out in order to evaluate the influence in the use of different volume scans, as well as the impact with the distance from the radar of such a VPR method. The performance of several radar-gauge merging techniques: from mean bias correction (already presented) to sophisticated geostatical merging methods (Goudenhoofdt and Delobbe, 2009), over raw data and VPR corrected data will be also investigated.

Acknowledgments

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