Improvement of quantitative precipitation estimates in Belgium

L. Delobbe, E. Goudenhoofdt, and B. Mohymont
Royal Meteorological Institute of Belgium

1. Introduction

In this paper we describe the recent improvements of quantitative precipitation estimates (QPE) based on radar observations and rain gauge measurements and we present verification statistics. These improvements concern the implementation of an advection procedure aimed at correcting for the effect of the time sampling interval on accumulation maps and the implementation of several radar-gauge merging techniques. A first simplified correction based on a climatological Vertical Profile of Reflectivity (VPR) has been also implemented.

Radar observations are available from a C-band Doppler radar located in the south of the country (Wideumont) and operated by the Royal Meteorological Institute of Belgium (RMI). Gauge observations are available from the automatic network operated by the hydrological service of the Walloon region. Gauge observations from the RMI climatological network are used for verification purpose.

The radar-gauge merging techniques which have been implemented are of various degrees of complexity: from mean bias correction to sophisticated geostatistical radar-gauge merging techniques. The merging is performed using the gauge data from the automatic networks and applied to the 24h precipitation accumulation.

In this paper we first present the radar and gauge observations. The advection procedure, the VPR correction and the radar-gauge merging procedures are described in section 3, 4 and 5, respectively. Verification statistics using various quality parameters are presented in section 6 as well as a sensitivity analysis to the density of the gauge network used for the adjustment.

2. Radar and gauge observations

The Walloon region (MET/DGVH) operates a dense and integrated network of 90 telemetric rain gauges. Most of them are tipping bucket systems providing hourly rainfall accumulations. The collected data are used for hydrological modelling and directly sent to RMI. The rain gauges are controlled on site every three months and in a specialised workshop every year. Every day, a quality control of the data is performed by RMI using a comparison with neighbouring stations. Radar data are also used in this quality control for the elimination of outliers.

RMI maintains a climatological network including 270 stations with daily measurements of precipitation accumulation between 8 and 8 local time (LT). Most of these stations are manual and the data are generally available with a significant delay. The data undergo a drastic quality control. This network is used for the long-term verification of radar precipitation estimates.

The Wideumont radar is a single-polarization C-band weather radar. It performs a 5-elevation scan every 5 minutes with reflectivity measurements up to 240 km. A time-domain Doppler filtering is applied for ground clutter removal. An additional treatment is applied to the volume reflectivity file to eliminate residual permanent ground clutter caused by some surrounding hills. Reflectivity data contaminated by permanent ground clutter are replaced by data collected at a higher elevation. A Pseudo Cappi at 1500 m is extracted from the volume data and reflectivity factors are converted into precipitation rates using the Marshall-Palmer relation $Z=a R^b$ with $a=200$ and $b=1.6$. A monitoring of the electronic calibration is performed using the mean ground clutter reflectivity at short range and the reflectivity produced by three towers in the vicinity of the radar. These point targets also allow controlling range and azimuth assignments.

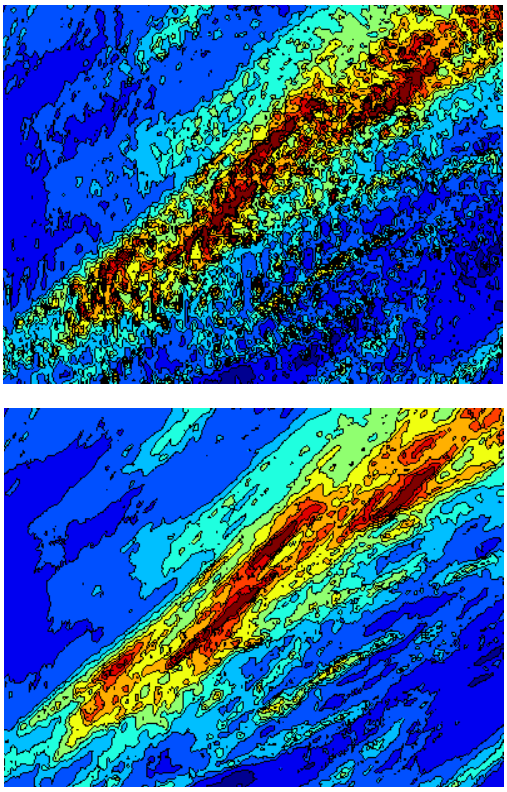

Fig. 1. Impact of the advection correction on the 24h precipitation accumulation starting at 18/05/2006 06 UTC.

3. Advection correction

An advection procedure has been implemented to correct for the effect of the time sampling interval on accumulation maps (Delobbe et al. 2006). It is assumed that the precipitation field moves at a constant velocity during the 5-min sampling interval and varies linearly in intensity.

The velocity vector between two successive images is determined using a cross-correlation algorithm. A single velocity vector is calculated for a 240 x 180 km^2 rectangular area including the region of interest. The advection correction allows a significant improvement of the visual aspect of accumulated maps in the case of rapidly moving small-scale precipitation structures.

An example of that correction can be found in Fig. 1. We can see that the correction removes the ripple structure from the original image. The effect on the verification score is however relatively limited. For this case, the Mean Absolute Error (MAE, see section 6) between radar and gauges values decreases from 2.4 to 2.3. A long-term evaluation of the advection correction is presented in section 6.

4. VPR correction

When the altitude of the bright band corresponds to the altitude of the PCAPPI one can observe on the PCAPPI rings of enhanced reflectivity centered on the radar. Each ring occurs when one of the radar beams crosses the bright band region. Radar-gauge merging methods do not allow to suppress this effect because usually the density of the gauge network is too low to correctly capture the structure of the rings. The bright band effect may not be visible on the PCAPPI when the altitude of the bright band is different from the altitude of the PCAPPI. However, even in this case, the estimated rainfall depths from the PCAPPI are generally affected by the bright band. This is explained by the fact that the reflectivity measured in the bright band region is larger than the reflectivity in the lowest part of the profile. VPR correction techniques attempt to correct for the bright band effect. The effect of underestimation at large distances from the radar can also be partially corrected. These techniques must be applied before radar-gauge merging methods.

We have implemented a first simple version of a VPR correction method. In this method the radar image is first separated into convective and stratiform zones by a modified version of the Steiner (1995) algorithm. More information on this algorithm can be found in Mohymont and Delobbe (2008). Only stratiform pixels are corrected. This is done by adjusting for each pixel an idealised chosen climatological VPR. This climatological VPR has a constant slope of –4.0 dBZ/km which is approximately the slope of the yearly mean stratiform VPR obtained for the Wideumont radar for the years 2005 and 2006. For a detailed description of the yearly mean VPRs obtained for the Wideumont radar, we refer again to Mohymont and Delobbe (2008). The adjustment of the climatological VPR at each pixel is obtained by mean of a weighted linear regression over the reflectivity values measured above that pixel. The weights decrease with the altitude reflecting the fact that lower measurements are more representative of ground level reflectivities. On the other hand weights for measurements situated at an altitude lower than 1 km are reduced because these measurements are often contaminated with ground clutter. The estimated value of the ground precipitation rate is finally obtained by converting the reflectivity of the adjusted climatological VPR at the height of 1 km by using the Marshall-Palmer relation $Z=a\,R^b$ with a=200 and b=1.6.

Fig. 2 (top) shows the accumulation over one particular day of the PCAPPIs at 1500 m obtained by the 5-elevation scan of the Wideumont radar. Rings of enhanced precipitation depths centered on the radar and due to the bright band phenomenon are clearly visible. Fig. 2 (bottom) shows the accumulated VPR-corrected image obtained by the 5-elevation scan for the same day. One can observe that most of the rings have disappeared and that precipitation depths at long distances are higher than for Fig. 2 (top) indicating that the underestimation at large distances is at least partially corrected. It is also apparent that the VPR correction is not applied at short range due to the presence of the cone-of-silence. For the example shown in Fig. 2., the VPR correction reduces by 9 % the Mean Absolute Error (MAE) between the radar estimated values and the gauge values of the climatological network. To estimate this reduction a mean field bias correction has been applied both on the original radar data and the VPR-corrected data. Seven other situations with a visible bright band phenomenon have been tested. For about half of the situations the MAE was reduced when using the VPR correction. Further investigation is needed to improve our VPR correction scheme in order to improve the verification statistics for most of the situations.

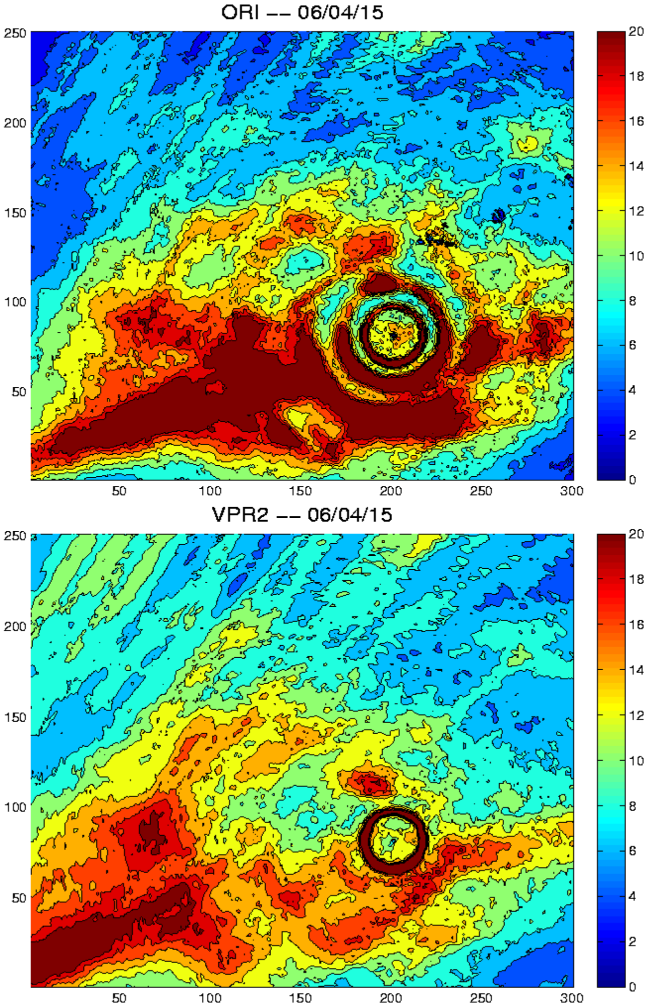

Fig. 2. PCAPPIs at 1500 m of the Wideumont radar accumulated over 24h from 08 LT on 15/04/2006 (top). VPR corrected radar images accumulated for the same period (bottom). The colored scale is in mm.

5. Radar-gauge merging methods

The merging of radar and gauge observations is applied to daily precipitation amounts between 8 and 8 in local time. Several techniques have been tested.

5.1 Mean field bias correction (MFB)

The adjustment factor is estimated as:

$$F_{MFB} = \frac{\sum_{i=1}^{N} G_i}{\sum_{i=1}^{N} R_i}$$

where G_i is the gauge measurement of the 24h rainfall amount, R_i the collocated radar estimate and N the number of valid radar-gauge pairs. Only the pairs where R and G exceed 1 mm are considered as valid.

5.2 Range-dependent adjustment (RDA)

A range dependent adjustment mainly based on the BALTEX adjustment method (Michelson et al. 2000) has been implemented. The relation between R/G expressed in dB and range is approximated by a second order polynomial whose coefficients are determined using a least squares fit. The range dependent multiplicative factor applied to the 24h accumulation factor is derived from the polynomial fit.

5.3 Static local bias correction (SRD)

The static local bias correction aims at correcting for visibility effects. The local bias correction is calculated from a one-year data set as follows. The 24h radar accumulations are first adjusted by a mean field bias correction. Then, for each gauge location the residual mean bias of the 24h radar accumulation is estimated. A spatialized local bias is then obtained through an ordinary kriging. The local bias correction has been calculated for the year 2005 using gauge observations of the RMI climatological network and applied to the radar data collected in 2006. This correction is applied before a range dependent adjustment.

5.4 Brandes spatial adjustment (BRA)

This is the spatial method developed by Brandes (1975). The assessment factors from each raingauge are interpolated on the whole radar field following the Barnes objective analysis scheme based on a negative exponential weighting. The smoothing is controlled by a parameter linked to the density of the network. This approach is valid here because the gauge network is sufficiently homogeneous.

5.5 Ordinary kriging (KRI)

This is a geostatistical method for the spatial interpolation of a random field (precipitation) from observations at several locations (raingauges). It requires the definition of a variogram describing the spatial variability of the field. The kriging estimation is the best linear unbiased estimator assuming a constant unknown mean across the field. In this study, we use only the 20 nearest points to reduce the computational cost. The model variogram, assumed isotropic, is a first order linear function of the distance. This method, based only on raingauges, is tested to evaluate the added value of merging methods.

5.6 Kriging with external drift (KED)

This is a geostatistical method that uses the radar as secondary information. This is the same as ordinary kriging except that the mean of the estimated precipitation field is a linear function of the radar field. Here we use a first order function with two unknown parameters. Additional constraints ensure that the predictor is not biased.

5.7 Kriging with radar-based error correction (KRE)

This method proposed by Sinclair and Pegram (2004) uses the radar field to estimate the error of the ordinary kriging method based on raingauges. Radar values at each gauge site are used to produce a radar-based kriging field. This field is then subtracted from the original radar field and added to the gauge-kriged field.

A long-term evaluation of these methods and the sensitivity to the density of the gauge network used for merging with radar is presented in the next section.

6. Long-term verification

The performance of the merging has been evaluated by comparing the adjusted 24h precipitation accumulations to the measurements of the climatological gauge network. Only pairs with both values larger than 1mm and days allowing an adjustment (i.e. with at least 10 valid pairs) are taken into account. The gauge data used for the adjustment and for the verification are independent.

Several quality parameters are found in the literature. The Root Mean Square Error (RMSE) is the most common parameter used in verification studies. However, the Mean Absolute Error (MAE) is less sensitive to large errors and it will be used here as first quality parameter. A standard for objective judgement of radar performance is proposed in Germann et al. (2006). The mean bias, the error distribution and the scatter as defined in that paper are also used in the present study. The mean bias is the total precipitation as seen by the radar divided by the total precipitation measured by the gauges. The error distribution is the cumulative contribution to total rainfall as a function of the radar-gauge ratio. The scatter is half the distance between the 16 % and 84 % percentiles of the error distribution.

6.1 Advection correction

We have tested the impact of the advection correction over a long period. The raw data (ORI) have been corrected (ADV) for the year 2006. We have also applied the mean field bias correction on the original and corrected fields (MFB and AMB respectively).

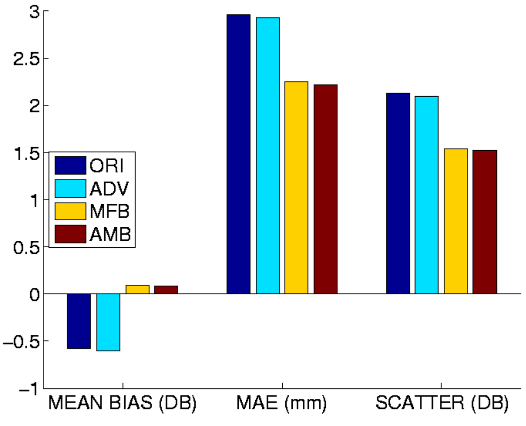

Fig. 3. Verification statistics for 2006: impact of the advection correction and of the mean-bias adjustment.

Fig. 3 shows several global quality parameters in order to compare the 4 fields. As expected, the advection correction hardly affects the mean bias. The effect is positive but very small for the MAE and the Scatter. This is probably due to the fact that the time sampling problem affects only a limited number of days and limited geographical areas. This kind of error is also probably small compared to other sources of error. The mean field bias correction gives a significantly better improvement.

6.2. Radar-gauge merging

We examine in this section different quality parameters to compare the different merging methods.

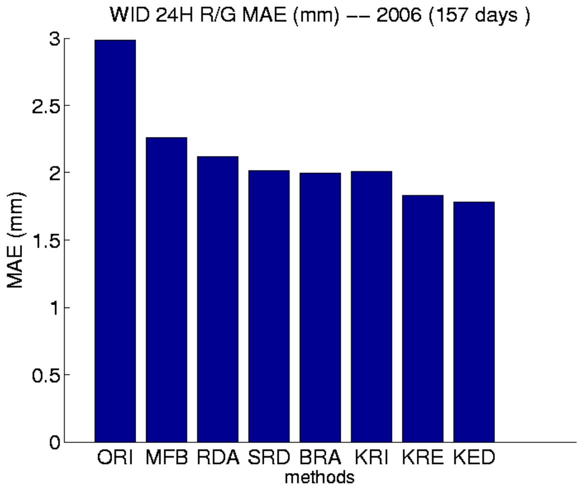

Fig. 4. MAE score for different merging methods based on all valid pairs during the year 2006.

As shown in Figure 4, the MAE significantly decreases for all methods compared to the original data (ORI). A simple mean field bias correction reduces the error by 25 %. Using the range dependent adjustment (RDA) allows a small additional improvement. A similar improvement is obtained when a static local bias (SRD) correction is added. The performance of this method is similar to the Brandes one (BRA), which is also a spatial method. The ordinary kriging method (KRI), using only gauge data, gives a similar score. This good result is due to the high density of the raingauge network. The two geostatistical methods (KRE, KED) using both radar and gauges perform best for this quality parameter. When using the kriging with external drift, the error decreases by 40 % with respect to the original data.

When we look at the Scatter score (Fig. 5), the results are the same except that the Brandes method is slightly better. It seems that this method can lead to large errors that are taken into account for the computation of the MAE but not for the Scatter.

We can see in Figure 6 the error distribution for 4 methods of increasing complexity. The vertical line divides the R/G ratios set in underestimation (left) and overestimation (right). A perfect match should give a step function, with a mean bias and a scatter equal to zero. The original radar data (ORI) reveal a significant underestimation with a mean bias of -0.58 dB. The mean field bias correction (MFB) succeeds in balancing the error distribution. The range-dependent adjustment (RDA) reduces the overestimation while the most sophisticated geostatistical method (KED) further decreases the error.

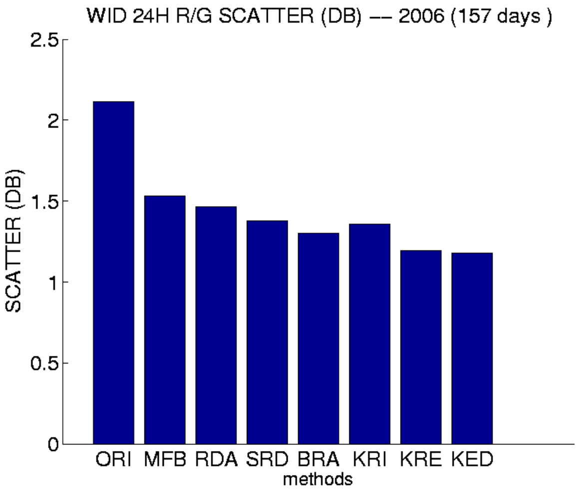

Fig. 5. Scatter score for different merging methods based on all valid pairs during the year 2006.

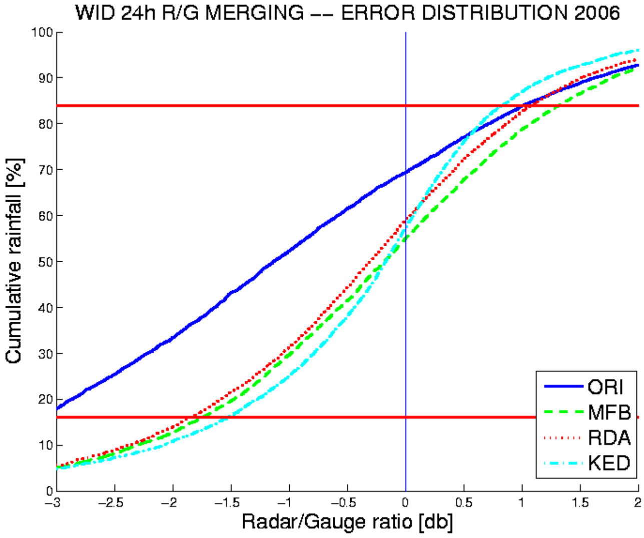

Fig.6. Error distribution of 24 h R/G ratios based on all valid pairs during the year 2006 for 4 different methods. The horizontal lines mark the 16% and 84% percentiles.

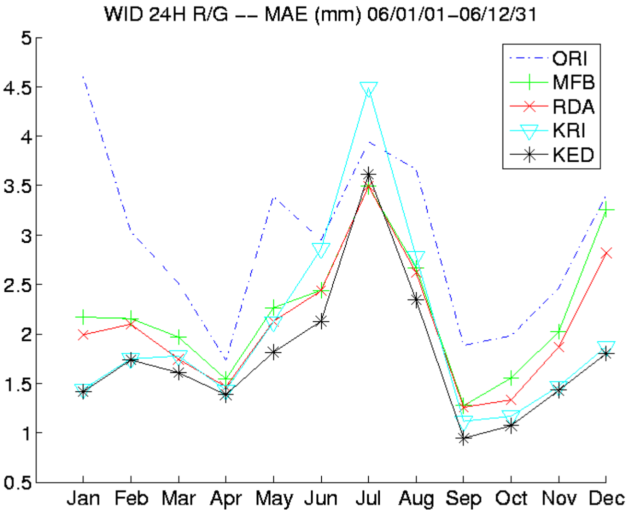

Fig. 7. Monthly evolution of the MAE for several merging methods.

It is also interesting to analyse the seasonal variation of the performance. Fig. 7 shows that the ranking of the methods slightly varies along the year. We first note that the estimation from the gauges only (KRI) is relatively bad in the summer, being worse than the radar in July. This behavior also affects the kriging with external drift (KED), which is not the best method for that month. In the winter, the ordinary kriging is better and very close to the KED.

6.3 Sensitivity to gauge network density

We analyse here the effect of gauge density on the performance of the merging methods. For this purpose, we remove raingauges from the network in such a way that it remains as homogeneous as possible. At each step, we compute for all points the sum of the inverse of the distance to the 4 nearest points. Then the point with the maximum value is removed.

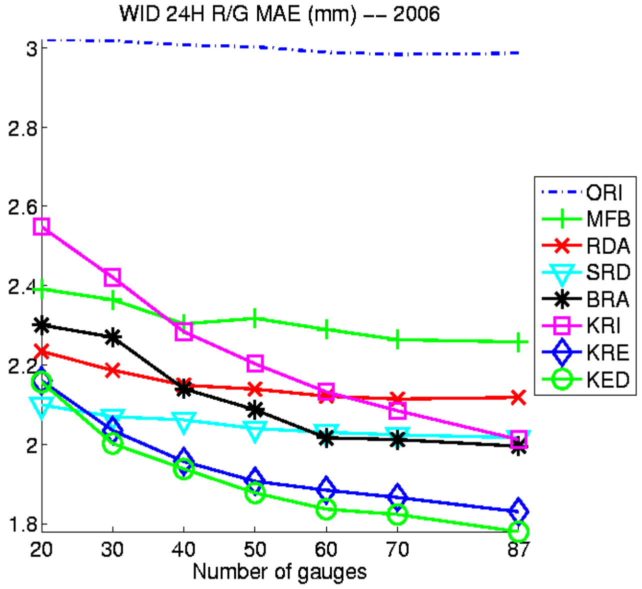

Fig. 8. MAE score for different merging methods in function of the gauge density of the adjustment network from 20 gauges (1 per 842 km^2) to 87 gauges (1 per 194 km^2).

Figure 8 shows the evolution of the MAE in function of the number of gauges. The score of the original data (ORI) varies because the number of valid days for adjustment decreases with the network density. We can see that the simple methods (MFB, RDA, SRD) are not very sensitive to the gauge density and the performance remains acceptable even for a low density. As expected, the ordinary kriging is the most sensitive to the density becoming the worst method for a network of less than 40 gauges. The MAEs of the two other kriging methods (KED, KRE) rise when the density of the network decreases. However, these two methods remain the best except for very low density. Very similar results are obtained with the other quality parameters.

Corresponding address: Laurent Delobbe,
Royal Meteorological Institute of Belgium,
laurent.delobbe@oma.be.

7. Conclusions

Different corrections for improving the quantitative precipitation estimation from the radar have been developed. The advection correction succeeds in removing the ripple effect due to the sampling problem. A long-term verification with rain gauges based on 24h accumulation maps has shown a small improvement of the statistics. The VPR correction has been tested for a couple of days. The rings of enhanced reflectivity due to the bright band effect are partially removed. The verification with gauges shows an improvement of the statistics for half of the tested cases. Further work is needed to improve this correction.

Several methods merging radar and rain gauges have also been implemented and evaluated. The verification over the year 2006 against an independent gauge network allowed comparing them using some appropriate statistics. Our results show that the radar-gauge merging methods based on kriging are the most effective according to most quality parameters. The impact of the density of the gauge network used for the adjustment has been evaluated. It was found that the radar-gauge kriging methods outperform the other methods except for very low gauge densities and that the benefit of these methods increases with the gauge density.

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References

Delobbe, L., D. Dehem, , P. Dierickx, E. Roulin, M. Thunus, and C. Tricot, 2006: Combined use of radar and gauge observations for hydrological applications in the Walloon Region of Belgium. Proceedings of ERAD 2006, ERAD Publication Series, 3, 418-421.

Delobbe, L., G. Bastin, P. Dierickx, E. Goudenhoofdt, G. Leclercq, L. Moens, and M. Thunus, 2008: Evaluation of several radar-gauge merging techniques for operational use in the Walloon region of Belgium. *Proceedings of WRaH 2008, Grenoble, France.*

Germann, U., G. Galli, M. Boscacci, and M. Bolliger, 2006: Radar precipitation measurements in a mountainous region. *Q. J. R. Meteorol. Soc.*, **132**, 1669-1692.

Brandes, E.A, 1975: Optimizing rainfall estimates with the aid of RADAR. *J. Appl. Meteor*, 14, 1339-1345.

Sinclair, S., G. Pegram, 2005: Combining radar and rain gauge rainfall estimates using conditional merging. *Atmospheric Science Letters*, **6**, 1, 19-22.

Michelson, D., T. Anderson, J. Koistinen, C.G. Collier, J. Riedl, J. Szturc, U. Gjertsen, A. Nielsen, and S. Overgaard, 2000: BALTEX radar data centre products and methodologies. SMHI Reports Meteorology and Climatology No. 9.

Mohymont, B., and L. Delobbe, 2008: Analysis of the mean and the variability of the vertical profile of reflectivity over Belgium. Proceedings of ERAD 2008.