Preparation and evaluation of a Dutch-German radar composite to enhance precipitation information in border areas

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ABSTRACT

The Dutch weather radars in De Bilt and Den Helder have only limited coverage in the Dutch-German border area in the north-eastern part of the Netherlands, whereas the German radar in Emden is just across the border. For many years, local water authorities have been looking for a better quantitative precipitation estimate(QPE) for this region. Recently, a German water-management consultancy: *hydro & meteo* and a Dutch one: *HydroLogic* have jointly taken up the challenge to develop a completely new precipitation radar composite for this part of the Netherlands. The new composite uses the basic polar radar products (volume data) of the two national weather bureaux. The composite should be able to meet precipitation-information requirements of operational water managers; in other words it should be able to provide QPE in real time. The present case study of an interesting rainfall event demonstrates the capabilities of the new composite tool. The rainfall event was used to evaluate various filtering and correction algorithms. QPE results were verified against independent rain-gauge data. On average, the results of the new composite were found to be similar to the Dutch weather bureau's QPE for the entire Netherlands. However, the new composite yielded a much better QPE for the north-eastern part of the country, as a result of the addition of the Emden radar data. The algorithms we developed are ready to be applied in operational water-management by water boards and municipalities in the north-eastern part of the Netherlands.

INTRODUCTION

Weather radar networks are generally optimized for national monitoring requirements. However, coverage can be incomplete in some border areas, whereas elsewhere coverage extends beyond the national borders. Compositing radar information from bordering countries can be used to fill in the gaps in coverage by adding cross-border measurements. Dutch weather radars have incomplete coverage along the Dutch-German and the Dutch-

Belgian borders. Coverage of the north-eastern part of the Netherlands, in particular the province of Groningen, is currently far from optimal. The quantitative precipitation estimate (QPE) data are frequently found to have underestimated the observed rainfall and also prided wrongly shaped precipitation curves. Local water boards have been looking for a solution to this problem for many years.
The German national weather bureau DWD [Deutscher Wetterdienst] and the Dutch KNMI [Royal Netherlands Meteorological Institute] are currently not planning to improve operational cross-border coverage. Therefore,a German water-management consultancy: hydro & meteo of Luebeck (www.hydrometeo.de) and a Dutch one: HydroLogic of Amersfoort (www.hydrologic.com) decided to take up the challenge of studying and developing the required radar composite. We planned to develop a Dutch-German weight-based compositing algorithm that is capable of producing precipitation information with a high resolution in time and space (5 minutes and 1x1 km). We used online ground measurements to adjust radar data in order to create a good QPE for the entire Netherlands, on the basis of the original Dutch polar volume data, with a performance similar to that of the Dutch KNMI. Subsequently, we investigated whether the radar measurements for the north-eastern part of the country could be improved by adding the Emden radar data.

The Dutch weather bureau KNMI provides an adjusted composite for water management purposes with a time resolution of 3 hours. Actual precipitation figures become available every hour, approximately 1.5 hours after the last radar measurement. A non-adjusted 5-minute composite is available after approximately 7 minutes. Adjustment is performed by an average correction for the entire country, based on hourly monitoring data. A 24-hour adjusted composite is available approximately 36 hours after the last radar measurement. The latter is spatially adjusted on the basis of daily monitoring data. All these composites are provided in 1x1 km grids.
To enable the Dutch and German radar data to be merged, we used research datasets with volume data made available by the KNMI and the DWD. Our data sets include the original 5-minute polar information from two Dutch radars: De Bilt and Den Helder; and from one German radar: Emden.
We used the SCOUT software package, developed by hydro & meteo over many years (hydro & meteo, 2009). This software enables checking, cleaning, compositing and adjusting radar data by comparing these with measurements from rain gauges on the ground. In the present paper “adjustment” denotes the procedure to adjust the radar data to the measurements of the rain-gauge network.
The software includes a set of different adjustment algorithms and thus creates a numeric spatial data set of the precipitation at the interval of radar measurements integrating the point measurements.

RESEARCH DATA AVAILABLE

Rain gauges

The Netherlands is covered by a wide network of meteorological monitoring stations, partly national and partly owned by local water authorities. The KNMI operates two high-quality precipitation-monitoring networks: an automated network consisting of 32 continuous synoptic gauges and a network consisting of 325 daily gauges that are daily read manually by volunteer meteorologists throughout the country.

- Continuous gauges
  For an interesting rainfall event of 11 and 12 May 2010, hourly rain gauge data from32 automatic weather stations are available on the KNMI website (http://www.knmi.nl/klimatologie/uurgegevens/). These data were used in the radar/rain-gauge adjustment carried out by the SCOUT software. In the remainder of this paper we refer to these rain gauges as 'Synops KNMI'.
- Daily gauges
  These gauges are read manually every day at 08:00 UTC. After having been validated by the KNMI, these data are also published (http://www.knmi.nl/klimatologie/monv/reeksen/). The data from these rain gauges were used as independent gauges in the analysis to verify the compositing result. Data were available for 295 of the 325 daily gauge locations in the smaller composite area and for 319 stations in the larger composite area. Only the latter measurements were used in the analysis.

Figure 1 presents a map showing the locations of the rain gauges and the coverage of the radars.

Radar products

Radar data from three radars located in De Bilt, Den Helder, and Emden were available for the period from 00:00 UTC on 11 May 2010 to 24:00 UTC on 12 May 2010.

- KNMI polar radar data
  The Dutch KNMI radar data for De Bilt and Den Helder were provided as a volume scan with 14 elevations, performed every 5 minutes. To prepare the composite, we first used the same elevation angle of 0.8° for all three radars. Later, we discovered that the best option was to use an elevation angle of 0.4° for the Den Helder radar, maintaining 0.8° for the De Bilt radar. Data resolution was 1° x 1 km for a range of 240 km. The KNMI data were pre-processed for clutter and anaprop (anomalous propagation) before using SCOUT.
- German DX radar product
  The DX product of the German DWD is a one-elevation measurement at an 0.8° elevation angle and has a range of 128 km with a spatial resolution of 1° x 1 km. Measurements are taken every 5 minutes. The data were pre-processed by us for clutter using a statistical clutter filter.

DATA-PROCESSING SEQUENCE

Data pre-processing

- Speckle filter
  A speckle filter (Golz et al., 2006) eliminates items up to a defined size. Here, a limit of 16 pixels was selected so that ships could be deleted on the radar images. This means that radar echoes up to 16 connected pixels are eliminated since most of these echoes are caused by non-meteorological targets.

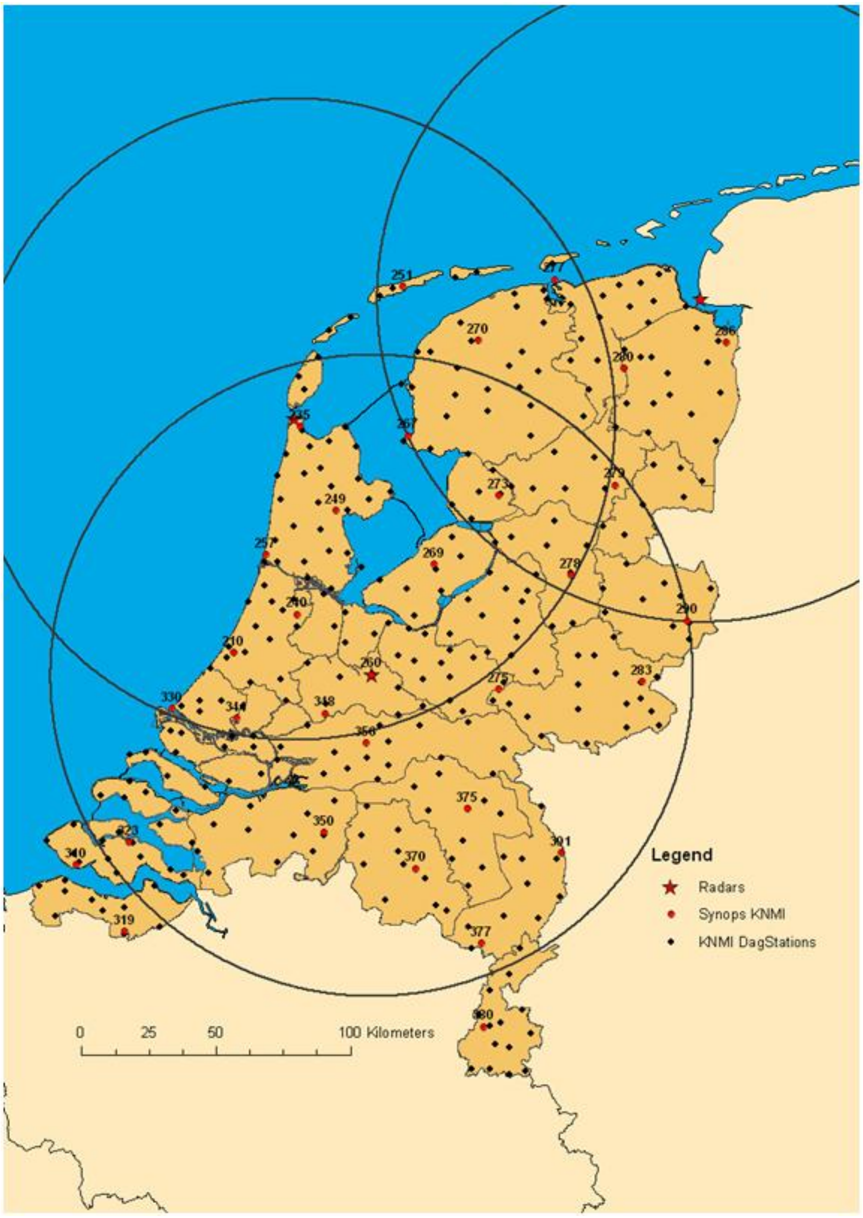

Figure 1: Map showing the rain-gauge locations and the radars' ranges. The red stars indicate the radar sites, the red dots indicate the 32 Synop KNMI raingauges (hourly data), and the small black dots indicate the 325 independent rain gauges (daily data).

- Gabella filter

  The texture-based filter (Gabella and Notarpietro 2000) smoothens out extreme peaks in the image, e.g. caused by ground clutter in a rain field. The filter computes the local gradient and smoothens out very local peaks taking into account the surrounding measurements and their statistics.

- Bright Band filter

  The bright-band filter used in our research is a further development of the one presented by Golz et al. (2006). It uses image-processing techniques, combined with a temperature bandwidth to allow elimination of bright bands. Measurements beyond the bright-band distance are corrected using the reflectivity-intensity relationship for snow.

Data compositing

Several approaches were tested for compositing the data from the three radars: the basic methods that apply the maximum approach and the weight-based method. These are explained below. Furthermore, either the full 240-km range of the Dutch radars could be used or it could be reduced to a hydrologically useful range of 120 km. Finally, the optimal elevation angle for the Dutch radar data was determined.

- Maximum versus weight-based compositing

  The maximum compositing method uses the maximum values of all the radars for every composite pixel. This creates sharp edges at the boundaries of the radar range. An alternative, but more complex method, is the weight-based method: a weight matrix is created that describes the impacts of the values originating from the various radars in the resulting composite:

$$C = \sum_{i=1}^{k} w_i * R_i$$

  C : composite image
  w_i : relative weight matrix for radar i
  R_i : measurement of radar i

  The weights are calculated by

$$w_i = \frac{Q_i}{Q_0}$$

  Q_i : weight matrix for each radar i
  Q_0 : cumulated weight matrix,

  where Q_0 is defined as

$$Q_0 = \sum_{i=1}^{k} Q_i$$

  and the individual weight factors as simple distances from the radar:

$$Q_i(j,k) = r_i - dist(R_i(j,k), Rad_i)$$

  Rad_i: location of radar i on image
  r_i : range of radar i

  This method provides numerical composite images that are continuous and smooth and the resulting adjustment yielded better results in the verification than the maximum approach. Moreover, the composite allows rain-cell tracking which is useful for developing a nowcasting product, another interesting data set for local water-management authorities.

- Using a 120 km versus a 240 km radius

  Although data beyond approximately 120 km from the radar are hardly useful for quantitative precipitation estimates, the results for the 240 km-range application were better than the ones of the 120 km-range application. The reason for this apparent discrepancy is that when the larger range was used, a few more rain gauges could be used for radar adjustment, yielding a radar result that is closer to the verification rain gauges.

- Elevation angle
  The Emden radar produces data at a fixed elevation angle 0.8° only. At first, this was also used as a starting point for all the Dutch radars. Better results could, however, be obtained by using an elevation of 0.4° for the Den Helder radar and of 0.8° for the De Bilt radar. The reason for this was a clutter region close to the De Bilt radar while there was no clutter in the vicinity of the Den Helder radar. In general, for hydrological purposes, the lowest undisturbed radar beam is the best for measuring rainfall close to the ground. These lowest elevations of the radar measurement without beam blockage and with minimum clutter effects have been used.

Data adjustment

The reflectivity to intensity conversion of the radar data was performed using the Z-R relationship $Z=200\ R^{1.6}$. The adjustment procedure is then modifying this relationship based on local fitting at the rain gauge locations.
For the case study, a single correction factor field was calculated for the entire event. In the SCOUT software, adjustment with the correction field values is based on inverse distance interpolation of the rainfall at the nearest four rain gauges (Wilson and Brandes 1979).
In our approach, all the rain gauges and radar cells with a measured precipitation of less than 0.3 mm were automatically excluded from the computation of the correction factor. Rain gauges with gaps in the data were also excluded from the computation, in which case other stations were used to replace the missing ones. A correction factor field was calculated and used for every single day. The maximum distance for interpolation of correction field values was set at 200 km.
The rain gauges used for this computation were the gauges in the online KNMI network-— the Synops stations in Figure 1 - to resemble near-real time compositing.

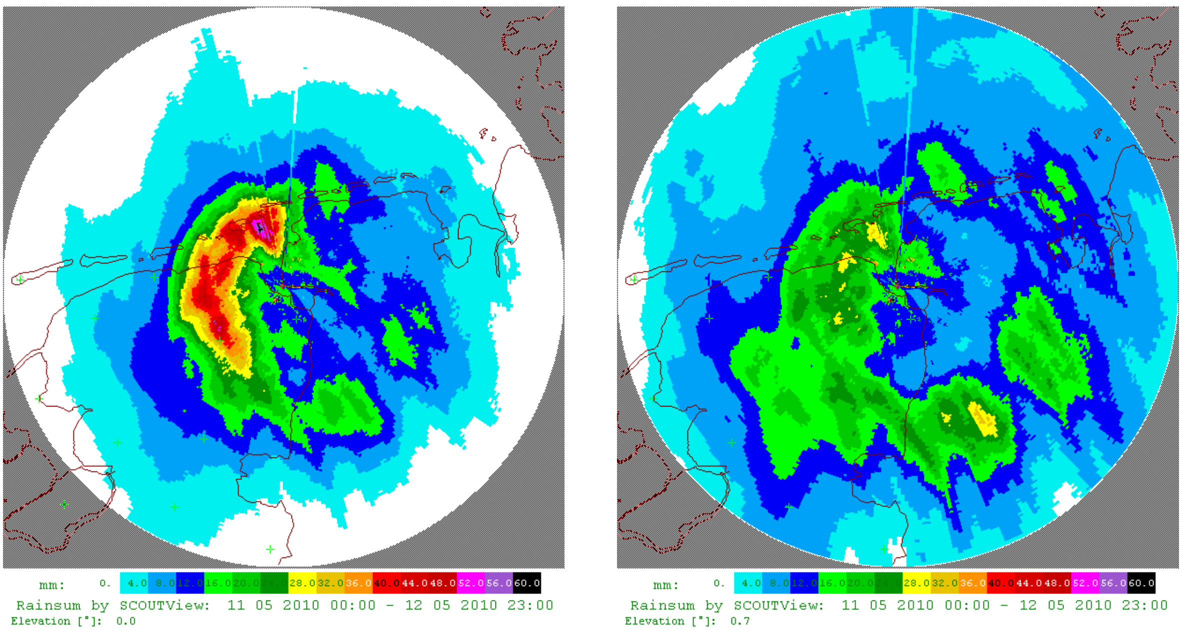

Figure 2: Effect of bright-band correction: image before (left) and after (right) correction.

RESULTS

Application of the above correction procedures substantially improved the quantitative precipitation estimate of the radar data in comparison with the raw incoming volume data. Figure 2 shows the reduction of the bright-band effect for the Emden radar, and Figure 3 presents the final QPE results after compositing and adjustment.

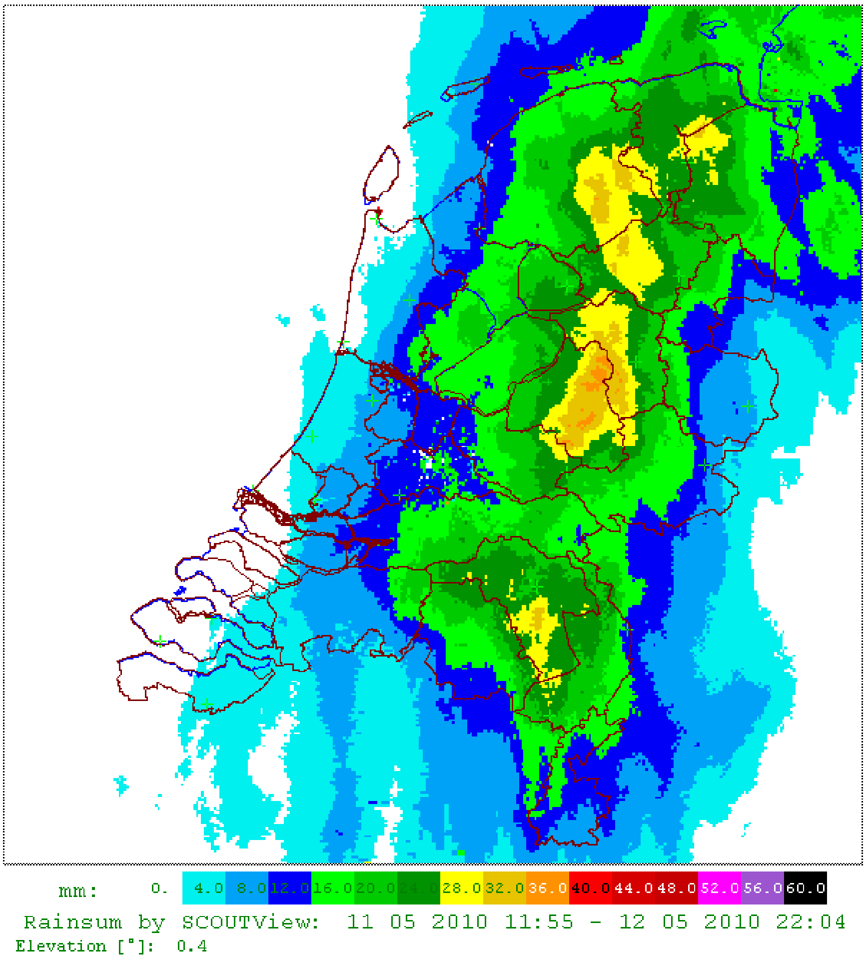

Figure 3: Final daily rainfall figures after compositing and adjustment.

VERIFICATION OF THE RESULTS

Area covered by only the Emden radar

We performed an analysis using only the Emden radar data to prove the quality of the SCOUT approach in the north-eastern part of the Netherlands. The analysis' QPE results were compared with the QPE results of the KNMI composites of the 3-hour and 24-hour data. A local correction was performed with the Synop rain gauges and validation was performed with 98 independent, daily measured rain gauges located within 128 km from the Emden radar. The SCOUT composite QPE was then compared with KNMI's standard 3-hour QPE composite (KNMI 3h), with KNMI's 24-hour daily adjustment (KNMI 24h), and with the daily rain gauges (RG).

Table 1: Verification of SCOUT results with the KNMI products for the region close to the Emden radar.

only Emden	*KNMI 3h*	*KNMI 24h*	*SCOUT*	*RG*
correlation with RG	**0.54**	**0.70**	**0.65**	**-**
mean error [mm]	**-1.82**	**-0.15**	**1.08**	**-**
RMSE	**5.57**	**3.04**	**4.13**	**-**
mean rainfall [mm]	**18.60**	**20.30**	**21.50**	**20.40**

The verification shown in Table 1 demonstrates that the QPE information for the area covered by this radar is clearly better when only the Emden radar data are used. The SCOUT results are better than the comparable KNMI 3h results: correlation between radar and rain gauges is better (0.65 versus 0.54); the absolute mean error (or mean bias) is less (1.1 mm versus 1.8 mm) and the root mean square error (RMSE) is less (4.13 versus 5.57). The 24-hour data are fully corrected by KNMI to correspond to the daily rain gauges and are therefore always very close to the 24-hour rain-gauge result (RG).
Table 2 presents the number of stations where the radar-derived rainfall deviates more than the threshold values of 5 mm and 10 mm from the rain-gauge measurements. The results support the above findings: KNMI 3h shows a clear weakness in performance in the north-eastern part of the Netherlands, in the vicinity of the Emden radar. This table also shows that KNMI's 24-hour fully corrected data are best. However, these data are not independent, only become available after 36 hours and are therefore not suitable for use in near-real time applications.

Table 2: Number of deviations of radar rainfall from gauge rainfall, larger than 5 mm and 10 mm, for the region close to the Emden radar

only Emden	*KNMI 3h*	*KNMI 24h*	*SCOUT*
number with D > 10mm	**10**	**2**	**1**
number with D > 5mm	**40**	**7**	**16**

The entire Netherlands

The new composite's good performance close to the Emden radar was shown above. We now compare the new composite's QPE using all three radars with the existing rain gauges for the entire Netherlands. The new composite's QPE adjustment produced by using the 32 continuous stations was verified with 319 independent rain gauges (locations given in Figure 1). The results thus achieved were compared again with the two standard QPE products: KNMI 3h and KNMI 24h. SCOUT obtained slightly better results than KNMI 3h (Table 3). SCOUT's mean error is lower than that of KNMI 3h (0.76 mm versus 1.64 mm). SCOUT's RMSE is lower than that of KNMI 3h (3.66 versus 4.36). SCOUT's correlation factor outperforms both KNMI products for this event (0.83 versus 0.75 for KNMI 3h and 0.83 for KNMI 24h).These results allow us to conclude that SCOUT obtained a better overall result than KNMI 3h.

Table 3: Verification of adjustment results for SCOUT and KNMI methods.

	KNMI 3h	*KNMI 24h*	*SCOUT*	*RG*
correlation RG/Radar	**0.75**	**0.82**	**0.83**	**-**
mean error [mm]	**-1.64**	**-0.29**	**-0.76**	**-**
RMSE	**4.36**	**2.71**	**3.66**	**-**
mean rainfall [mm]	**15.50**	**16.30**	**15.90**	**16.70**

A similar conclusion is reached when looking at a point-wise comparison of radar and gauge values for KNMI 3h (Figure 4) and for SCOUT (Figure 5). The correlation is higher for SCOUT results and the spread lower than with KNMI 3h data. In particular the overestimations by KNMI 3h data for the high values above 30 mm daily sum are less pronounced with the SCOUT results.

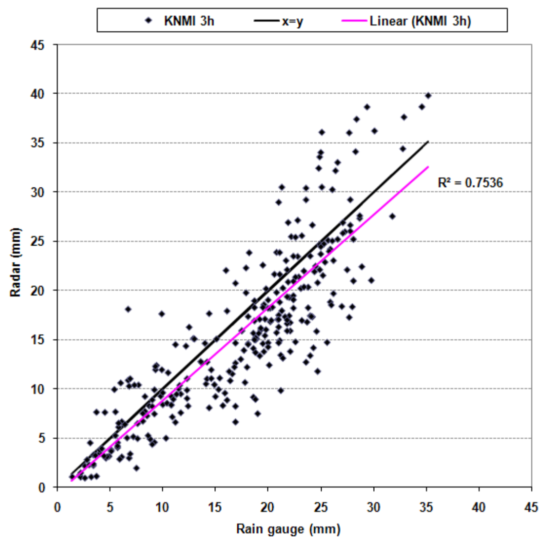

Figure 4: Comparison of rain-gauge measurements to KNMI 3h results (precipitation figures for entire event).

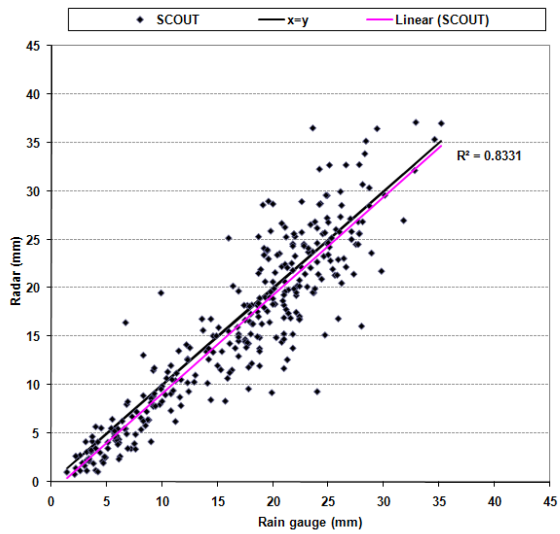

Figure 5: Comparison of rain-gauge measurements to SCOUT results (precipitation figures for entire event).

As we did in the Emden analysis, we again compared the composite QPE with the rain-gauge station measurements for the entire event, using threshold values of a 5 mm and a 10 mm difference. The analysis shows that the quality of the results obtained by SCOUT are close to that reached by KNMI 24h for the large deviation of 10 mm, and is in between the KNMI 3h and KNMI 24h results for deviations larger than 5 mm (Table 4).

Table 4: Number of deviations of radar rainfall from gauge rainfall, larger than 5 mm and 10 mm, for the entire Netherlands

	KNMI 3h	*KNMI 24h*	*SCOUT*
number with D > 10mm	**11**	**3**	**4**
number with D > 5mm	**78**	**12**	**46**

Influence of the Emden radar

Comparison of tables 2 (Emden results only) and 4 (results for the entire Netherlands) demonstrates that including the measurements based on the Emden radar improves the Dutch composite QPE (Table 5). This table shows the analysis result for the areas covered by the Dutch radars, but not covered by the Emden radar. The verification analysis was performed using 319 rain gauges. The performance of the KNMI 3h product is slightly better than that of SCOUT for the 10 mm threshold. For the 5 mm threshold it is slightly worse however. The results indicate that the performances of SCOUT and KNMI 3h are similar.
The results described in this section and the previous two sections permit the conclusion that the better performance of the SCOUT QPE in comparison to KNMI 3h in Tables 2 and 4 is mainly due to the addition of the Emden radar data to the composite of the two Dutch radars.

Table 5: Deviation of radar data from rain-gauge values in areas *without* Emden radar coverage

not Emden	*KNMI 3h*	*KNMI 24h*	*SCOUT*
number with D > 10mm	1	1	3
number with D > 5mm	38	5	30

CONCLUSIONS

The case study presented here proves that the addition of the German Emden radar data helps significantly in producing better quantitative precipitation estimates for the north-eastern part of the Netherlands. On the basis of the available radar data, including bright-band errors, data from the two Dutch radars were composited with the Emden radar data. The composited result was adjusted using data measured by 32 Dutch rain gauges. We explained our choice of compositing strategies as well as the corrections that need to be applied to the data.
The outcome was verified by comparing it with the measurements from 319 independent rain gauges. Results were also compared with the current standard operational water-management practice in the Netherlands: the online adjustment based on a 3-hour composite which is available after approximately 1.5 hours. Compositing was performed using different methods (maximum and weight-based methods) as well as different radar elevations and ranges in order to obtain an optimal result. The weight-based composite method was found to be capable of improving the composited QPE data in terms of mean bias as well as in terms of regression, when compared with the 319 available independent control gauges. The weight-based method has the potential to incorporate - when available - different quality factors for the choice of composite values, yielding a composite data set in which measurement points with higher quality scores are selected instead of those with lower scores.
The result is now ready for use in near-real time hydrological applications in urban hydrology, as well as in pluvial and fluvial hydrology. This is of particular interest to water boards and municipalities in the border region.

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