A 10-year (1997–2006) reanalysis of quantitative precipitation estimation over France

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1. Introduction

In order to provide a common reference for hydrologists (e.g. for model calibration, assessing the value-added of inputting high space-time resolution data in hydrological models,...), the French national weather service has run a national collaborative project aiming at producing a 10-year reference database of Quantitative Precipitation Estimations (QPE). The initiation of that work stems back to the previous Weather Radar and Hydrology Conference (WRAH2008, Grenoble, 2008), where the need for reanalysis of QPE was clearly identified during a workshop (Delrieu et al. 2009). Similar projects have been conducted or are currently underway in the radar hydrometeorology community (e.g. Overeem et al. 2009, Nelson et al. 2010). The objective is to make optimum use of all available information in the operational archives in order to obtain the best surface precipitation accumulation estimation over France with no gaps and to provide associated uncertainties at the hourly time step and 1 km² spatial resolution. The various modules of the processing chain are described hereafter. The final product – 1 km² composite hourly accumulation maps – has been evaluated with independent rain gauge data over one year in southeast France.

2. Period of analysis and available data

Taking into account the evolution of the radar network, the availability of radar products and the need to cover a period of at least 10 years, decision was made to focus on the 1997-2006 time period. This time period will be extended to present time in the future. In 1997, the French operational network was based on 13 radars. 11 additional radars have been deployed over the 1997-2006 period, increasing the total number of operational radars up to 24 in 2006 (Fig. 1). The radar scan strategy over the considered time period typically consisted of 1 (flat areas) to 4 (mountainous areas) elevation angles revisited every 5 minutes.

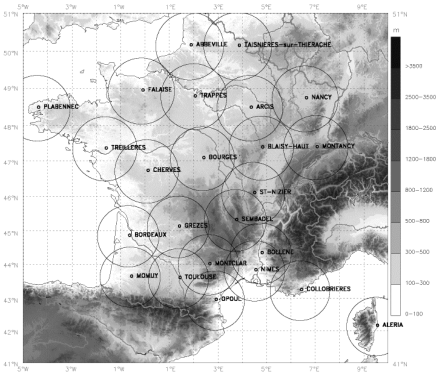

Fig. 1 French radar network in 2006.

Radar data that were used for the reanalysis are single-radar 5', 1 km², 512x512 km², pseudo-CAPPI reflectivity images. Those data are the only ones that have been continuously archived since 1997. They are not corrected for:

- partial beam blocking (referred to as PBB hereafter),
- vertical profile of reflectivity (VPR) effects,
- advection effects,
- attenuation by gases, precipitation or wet radome,
- clear-air (insects / birds / chaff).

Ground-clutter (hereafter referred to as GC) is theoretically corrected for, even though the state-of-the-art GC identification methods used at the beginning of the 1997–2006 period was not perfect. Reflectivity data are coded as follows: < 8 dBZ, 8-16 dBZ, 16-20 dBZ, 20-21 dBZ, 21-22 dBZ, … The coarse resolution of the coding at low levels is a limiting factor for the precise estimation of precipitation at low rain rates. On the rain gauge side, hourly and daily (from 6 UTC on one day to 6 UTC on the following day) data are available in the operational databases. Those data are routinely checked by experts and – if needed – corrected for. The typical number of hourly (resp. daily) rain gauge data over France (550 000 km²) is 1000 (resp. 4000). Fig. 2 shows the location of available hourly and daily rain gauges data in 2006.

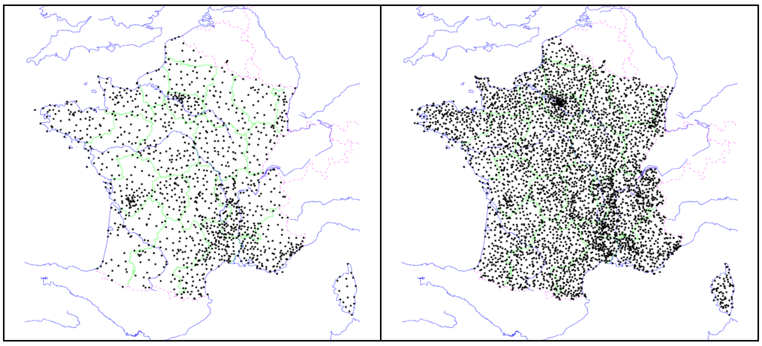

Fig. 2 Hourly (left) and daily (right) available rain gauges data in 2006

3. Radar data processing

Radar data pre-processing turned out to be absolutely necessary before considering merging them with rain gauge data. A number of modules have been developed – based upon the operational experience of radar data processing at Météo-France – to address the various error sources that have been identified on the data. The principles that governed the choice of the various algorithms are the following: simplicity, robustness (better discard a data rather than take the risk to keep a bad data), efficiency, interoperability. Because the project was working on a tight schedule – the aim being to deliver a first version of the reanalysis database by the first quarter of 2012 – limited time was available to specify and test each module. The assumptions and limitations of each algorithm are acknowledged and perspectives regarding their improvement mentioned.

4. Establishment of GC maps for all [radar; year] couples

Occurrence frequency maps are computed for each [radar; year] couple. The thresholds of 25 dBZ (S-band radars) and 15 dBZ (C-band radars) have been used to compute the occurrence frequency. Pixels having an occurrence frequency exceeding some threshold (determined subjectively by an expert, typically from 3 to 12%) are classified as GC and never used for the considered year. This may appear as a drastic approach but emphasis was laid on minimizing the rate of unfiltered clutter that may corrupt the radar – rain gauge analysis. Abnormal propagation GC is not filtered by the proposed approach, which is a problem for some radars (e.g. Bordeaux) of the network that are very frequently subject to abnormal propagation. The reason for re-establishing the GC map for each year stems from the fact that the scan strategy of the radar may have changed (faster antenna rotation rates, more elevation angles in the volume coverage pattern, …). GC maps could be updated more frequently but this would require more time and efforts. Fig. 3 shows an example of GC removal.

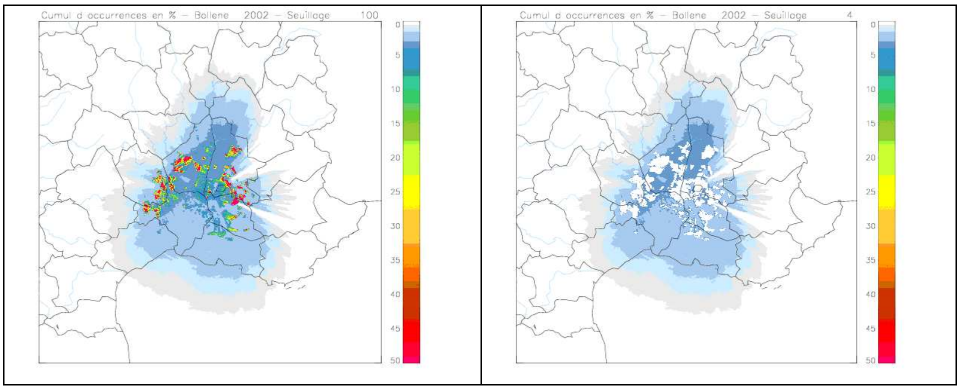

Fig. 3 Occurrence frequency map (512x512 km²) without (left) and with (right) application of a 4% threshold (512x512 km²) for Bollène radar in 2002.

5. Establishment of PBB maps for all [radar;year] couples

For each [radar; year] couple, a yearly rainfall accumulation map is computed using the GC-identified Cartesian pseudo-CAPPI reflectivity images converted into rainfall rates using the Marshall-Palmer Z-R relationship ($Z=200R^{1.6}$). This accumulation map is then converted into polar coordinates. Accumulation curves - functions of the azimuth – are then computed for various classes of distance (0-10 km, 10-20 km, etc). Those curves are then filtered with a moving 10° window that replaces each value by the upper 95% percentile value. Once this is done, the original curve is compared to the filtered curve and the PBB rate is obtained for each [distance; azimuth] couple. This procedure aims at identifying narrow masks, with the assumption that such masks have an extension lower than 10°. Wider masks (e.g. arising from mountains) will not be captured by this approach. However, wide masks are assumed to be identified and corrected for through the daily comparison with rain gauges and the daily calibration factor maps (see further down).

The retrieved PBB rates are converted into a 512x512 km² Cartesian map for further application to the raw 5' reflectivity pseudo-CAPPIs (see Fig. 4 for an example). This empirical approach to PBB was preferred over using a simulation tool (e.g. Delrieu *et al*. 1995) because it takes simultaneously into account orogenic and non-orogenic masks, potential biases in the antenna's pointing angles and coupling between PBB and Vertical Profiles of Reflectivity (VPR) effects (see quantification of that effect in Tabary 2007).

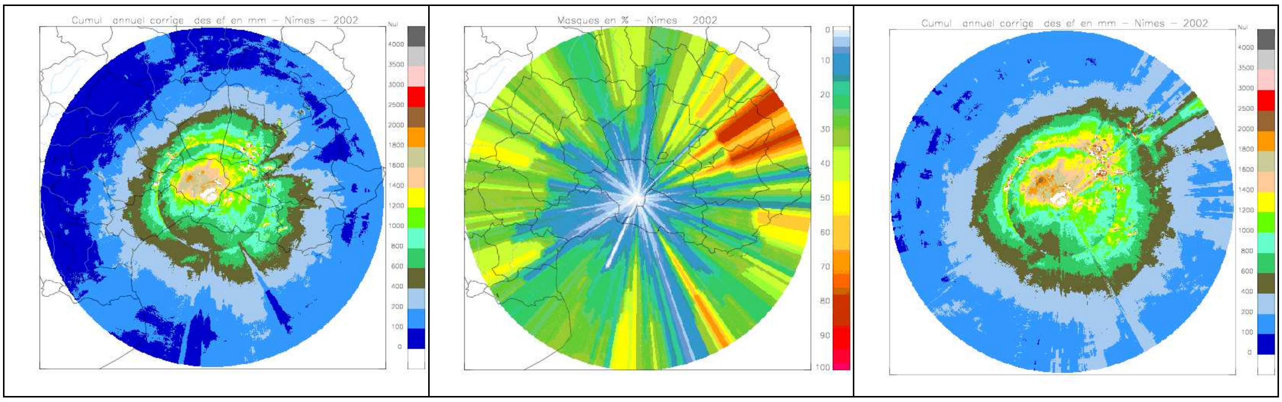

Fig. 4 Raw accumulation (left), PBB map (center) and corrected accumulation map (right) for Nîmes radar in 2002.

6. Clear-air / weak signals processing and computation of hourly radar rainfall accumulations

The approach that was taken to get rid of clear-air echoes (most likely birds and insects), whose frequency and intensity are known to be quite high on the S-band radars located in southern France during the fall and spring seasons, simply consists in keeping only radar pixels with a reflectivity above a certain threshold Z_{MIN}. Based upon operational experience, Z_{MIN} was taken equal to 20 dBZ at S-band and 16 dBZ at C-band. Notice that technologies such as polarimetry, volumetric scans, high-resolution and frequent (5') satellite imagery were not yet operationally available over the reanalysis period (1997 – 2006), hence the proposed – and rather brutal – approach. Pixels with a reflectivity value less than Z_{MIN} are considered as "weak" and their reflectivity is temporarily set to Z_{MIN} (i.e. the maximum value a "weak" pixel can take). At each pixel, the hourly radar rainfall accumulation of the "weak" values within the hour (ACC_{WEAK}) is then compared to the hourly accumulation of the "non-weak" values within the same hour (ACC_{NOWEAK}). If ACC_{WEAK} is found to be much smaller than ACC_{NOWEAK}, then ACC_{WEAK} is considered to be negligible and the hourly accumulation is taken equal to ACC_{NOWEAK}. Otherwise, the hourly accumulation is considered to be unavailable and set to WEAK_VALUE. In that case, the sum of ACC_{WEAK}+ACC_{NOWEAK} is kept in memory for further exploitation. In other words, the proposed approach is such that radar data are not used to provide the "no-rain" information.

Two-dimensional advection fields are then computed using a standard cross-correlation approach (as in Tuttle and Foote 1990) between two successive 5 minutes images. The advection fields are subsequently used to over-sample the rainfall rates maps (every minute) and produce smooth hourly accumulation maps (see Tabary 2007 for a detailed description of the approach).

7. Production of daily accumulations and computation of radar / rain gauge calibration factor map

The 512x512 km² radar hourly accumulations are subsequently accumulated over 24h (from 6 UTC to 6 UTC the following day). "Weak" and "no-weak" hourly accumulations are processed as in the hourly time step. The radar-based 24h rainfall accumulation map, wherever it is available (i.e. outside GC classified areas, high PBB areas and "weak" areas), is then confronted with 24h rain gauges. A radar / rain gauge calibration factor field is computed as follows:

1. A circular neighbourhood (with a radius of 30 km) is moved successively over each 1 km² pixel of the 512x512 km² radar domain.
2. For each new position of the neighbourhood, the rain gauges inside the neighbourhood having reported more than 0.6 mm in 24h are paired with the corresponding radar pixels (in cases where radar rainfall accumulation is not classified as GC, high PBB or weak).
3. A number N of [radar; rain gauge] 24h accumulations couples are established.
4. wherever N is higher than 3, the median value of the N radar / rain gauge ratios is computed and attributed to the central pixel of the neighbourhood.

The calibration factors are then applied to the daily radar accumulation, wherever possible. In the case of missing hourly radar accumulations, ordinary kriging of hourly rain gauges is used in the computation. The calibration factor is only applied to available radar data and the ordinary kriging accumulation corresponding to the hours of missing radar data is added to the result.

There are two important implicit assumptions:

- The daily [radar; rain gauge] ratio has – on average – a spatial correlation of several tens of kilometers. This assumption is needed to justify the use of a running 30km-radius circular neighbourhood when producing the daily [radar; rain gauge] calibration factor map.
- The [radar; rain gauge] ratio at a given point is – on average – constant over all 24h hours composing the day. This assumption is needed to justify the application of the daily [radar; rain gauge] calibration factor map to the 24 hours composing the day.

If the calibration factor cannot be computed, the resulting daily accumulation is given by ordinary kriging of daily gauges. See Fig. 6 for an illustration.

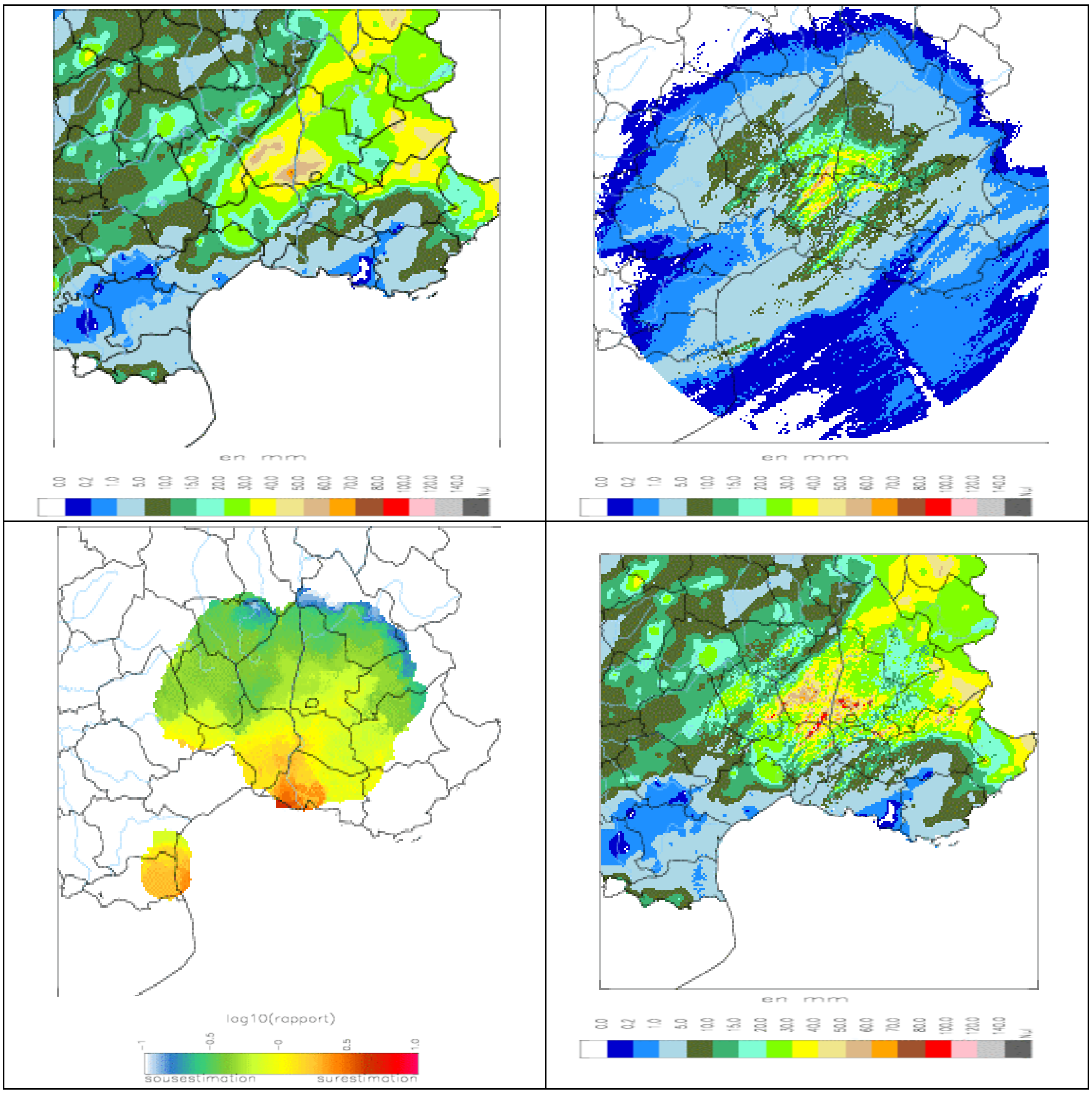

Fig. 6 Daily kriging accumulation (top left), raw radar accumulation (top right), calibration factor (log_{10}, bottom left) and calibrated radar accumulation (bottom right), for Nîmes radar (21/10/2002).

8. Generation of the best daily accumulation from radar and rain gauges over FRANCE

In order to obtain the best daily estimation of precipitation, an extra step consists in merging the calibrated daily radar accumulation map with daily rain gauges using kriging with external drift (KED). The description of KED equations can be found in Hengl *et al.* (2003) as well as the description of the regression-kriging method – the one used in the reanalysis – which are shown to lead to the same results.

Prior to this step, all calibrated radar accumulation maps are composited to obtain a map covering France. As KED requires the drift (the daily calibrated radar accumulation) to be available all over the domain, missing data are replaced by ordinary kriging of daily rain gauges. The rule used for compositing is to take the median value of the different available calibrated data. Different rules of compositing have not been studied and this choice could be subject to improvement.

This step aims at ensuring that the rain gauge accumulations are retrieved – at the location of the gauges – in the final result. It can also help in reducing the impact of some remaining radar artefacts, by smoothing the estimation (see Fig. 7).

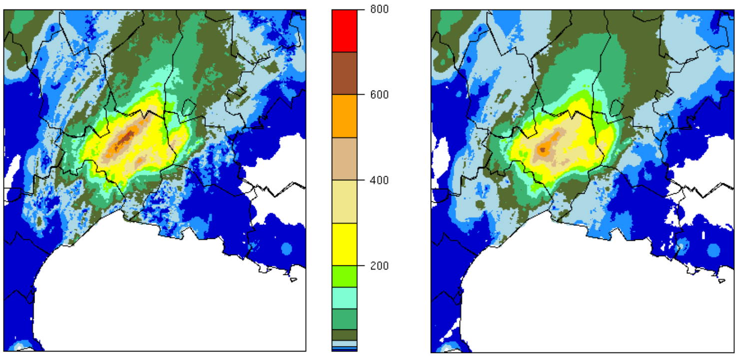

Fig. 7 Daily calibrated radar estimation (left) and best daily estimation (right) over the Nîmes area (08/09/2002).

9. Generation of the best hourly accumulations from radar and rain gauges over FRANCE

This step – temporal downscaling - consists in deriving hourly precipitation from the best daily precipitation accumulation estimation. This is achieved by distributing the 24h accumulation over the 24 hours composing the day as follows:

1. For each radar, hourly radar rainfall accumulations are first corrected using the calibration factors established earlier. Because of all the criteria that are imposed (on the number of reporting gauges, the quality of the radar data, etc), the calibration factors are not available everywhere. An extrapolation algorithm is therefore applied in order to propagate the values that could be computed all over the radar domain.
2. Hourly precipitation accumulation fields are then computed from available hourly (calibrated) radar and rain gauges data. The method used to compute those temporary fields is here again KED. As for the daily KED step, compositing of the different available calibrated radar data is done first, following the same rule. When no hourly radar data is available, the composite map is filled by ordinary kriging values of hourly rain gauges.
3. For a given point of the 1536x1536 km² composite domain, letting h_i ($i \in [1;24]$) be the hourly estimation derived from merging hourly radar and rain gauges data, σ_i the kriging estimation error, H the sum of the 24 h_i and D the best daily estimation of precipitation (see above), then we define the weight $w_i = h_i/H$ and the final hourly estimation $w_i.D$, with an uncertainty approximated to $\sigma_i.C/H$.

10. Results

In order to evaluate the final composite 1 km² hourly QPE, some rain gauges were removed from the whole process and left aside for independent validation purposes. Evaluation has been conducted considering only one set of data, corresponding to the [Bollène, Nîmes] couple (southeast France, see Fig. 1) for the year 2002. Fig. 9 shows the locations of the gauges used for evaluation and the two radars. The different gauges have been chosen at distances from the two radars lower than 100 km so that the radar impact can really be evaluated.

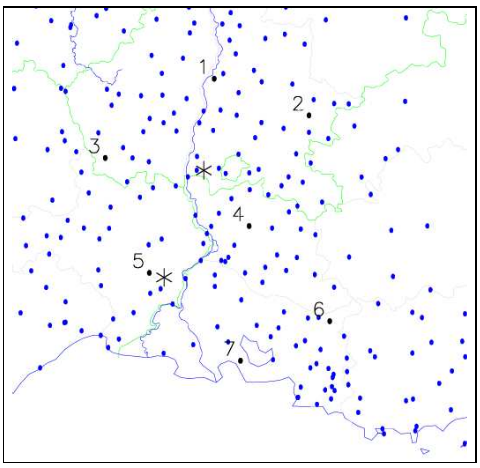

Fig. 9 Locations of reference gauges (black, 1 to 7) and used gauges (blue) and the radars of Nîmes and Bollène (*).

Table 1 presents correlation and normalised bias for various hourly rain gauges accumulations thresholds (0, 2 and 5 mm in 1 hour). Results are compared with the ones obtained with ordinary kriging of rain gauges and a version of the reanalysis not using any radar information. The difference of the latter with ordinary kriging is that it takes advantage of the temporal downscaling step, using the daily rain gauges information. This allows for a fair comparison with the reanalysis and better assessment of the influence of radar information. The normalized bias is defined here as the ratio of the total QPE accumulation over the total observed accumulation. Scores are computed for the whole year.

	Correlation HRG > 0 mm / HRG > 2 / HRG > 5 mm	Normalised Bias HRG > 0 mm / HRG > 2 / HRG > 5 mm
HRG	4117 / 993 / 337	4117 / 993 / 337
Ordinary Kriging	0,67 / 0,49 / 0,39	0,87 / 0,72 / 0,59
Reanalysis without radar	0,70 / 0,56 / 0,47	0,92 / 0,78 / 0,67
Reanalysis	0,80 / 0,70 / 0,61	0,94 / 0,85 / 0,78

Table 1 Correlation and normalised bias over the (Bollène,Nîmes) domain in 2002.

Both correlations and normalised biases show a better quality of the reanalysis over the two gauges oriented QPE. Whatever threshold is applied considering observed accumulations, correlations remain over 0.6, which is often assumed as the value over which correlations can be considered as good. However, normalised biases are all lower than 1 and tend to exhibit an underestimation, more and more as observed accumulations increase. Table 2 presents some statistical parameters of the distributions for rainfalls greater than 5 mm: Q10 (first decile), median and Q90 (last decile), mean and standard error.

HRG > 5 mm (337 obs)	Q10	Med	Q90	ME	SD
HRG	5,5	7,5	17,5	9,9	6,4
Ordinary Kriging	1,7	5,4	9,9	5,9	4,0
Reanalysis without radar	1,9	5,8	12,3	6,6	4,7
Reanalysis	2,7	6,2	14,7	7,7	6,1

Table 2 Statistical parameters for precipitation greater than 5 mm/h over the (Bollène,Nîmes) domain in 2002.

Table 3 is the same but related to error distributions. Both show the same results regarding the performance and the underestimation: the reanalysis distribution is closer to the observed one compared to ordinary kriging or the reanalysis without radar, and it is noticeable that it cannot reach the highest accumulations. The distribution of the errors confirms this underestimation with negative median and mean errors. It is not obvious to find a reason for that problem, which may lie in the temporal downscaling step, a smoothing effect of the hourly radar data occurring because of kriging.

HRG > 5 mm (337 obs)	Q10	Med	Q90	ME	SD
Ordinary Kriging	-11,2	-2,5	1,2	-4,0	6,1
Reanalysis without radar	-9,2	-2,1	1,3	-3,3	5,9
Reanalysis	-6,9	-1,8	2,4	-2,1	5,5

Table 3 Statistical parameters of error for precipitation greater than 5 mm/h over the (Bollène,Nîmes) domain in 2002.

11. Conclusions and outlook

A processing chain has been developed in order to produce a high-resolution (1 km²), 10-year reference database (1997-2006) of hourly QPE covering the French metropolitan territory with no spatial nor temporal gaps. The chain uses the individual 5' 512x512 km² pseudo-CAPPI radar reflectivity images of the French radar network and hourly and daily rain gauges. Simplicity, robustness, efficiency and interoperability are the principles underlying the decisions regarding the various modules. The chain consists in the following steps: pre-processing of radar data, production of the reference daily rainfall accumulation maps over France by combining pre-processed radar data and gauges, and production of the reference hourly rainfall accumulation maps by temporal downscaling. Several exercises have been performed to validate the various steps of the processing chain. In particular, the final product has been evaluated with independent rain gauges data over southeast France in 2002. Whatever score is considered, the final product over-performs ordinary kriging and a version of the reanalysis without radar data. However, the reanalysis tends to underestimate and may have problem in reaching the extreme values, a problem that may come from the temporal downscaling step and that would deserve special attention in order to improve the estimation. The first version of the database (1997 – 2006) has been delivered at the beginning of 2012. Later on, the database will probably be extended from 2006 onwards and improvements of several modules will be made.

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