A 10-year (1997–2006) reanalysis of Quantitative Precipitation Estimation over France: methodology and first results

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Abstract In order to provide a common reference for hydrologists (e.g. for calibrating model parameters, assessing the added value of inputting high space-time resolution data in hydrological models), Météo France is currently running a national collaborative project aimed at producing a high-resolution (1 km^2), 10-year reference database (1997–2006) of hourly Quantitative Precipitation Estimations (QPE) covering the entire French metropolitan territory with no spatial nor temporal gaps. The input data that are used are the individual 5 min 512 × 512 km^2 pseudo-CAPPI radar reflectivity images of the French radar network and quality-controlled hourly and daily (from 6 UTC to 6 UTC) raingauges. Several validation exercises have been performed to validate the various steps of the processing chain. In particular, the final product – 1 km^2 composite hourly accumulation maps – has been evaluated with independent raingauge data over one year in two different geographical / meteorological contexts.

Key words radar Quantitative Precipitation Estimation; kriging; radar–raingauge merging

INTRODUCTION

In order to provide a common reference for hydrologists (e.g. for calibrating model parameters, assessing the added value of inputting high space-time resolution data in hydrological models), the French national weather service is currently running a national collaborative project aimed at producing a 10-year reference database of Quantitative Precipitation Estimations (QPE). The initiation of this 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 km^2 spatial resolution. The various modules of the processing chain are described hereafter. The final product – 1 km^2 composite hourly accumulation maps – has been evaluated with independent raingauge data over one year in two different geographical / meteorological contexts.

DATA USED AND PERIOD OF ANALYSIS

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, a decision was made to focus on the 1997–2006 time period. This time period will be extended to current time in the future. In 1997, the French operational network consisted of 13 radars. A further 11 radars have been deployed over the period 1997–2006, raising the total number of operational radars to 24 in 2006. The very large variation over time of the radar coverage is one of the numerous reasons why dynamic quality codes are so important. The scan strategy of the radars over the considered time period typically consisted of 1 (flat areas) to 4 (mountainous areas) elevation angles revisited every 5 minutes.

Radar data that are used for the reanalysis are single-radar 5 min, 1 km^2, 512 × 512 km^2, pseudo-CAPPI reflectivity images. These data are the only ones that have been continuously archived since 1997. They are not corrected for (1) partial beam blocking (referred to as PBB

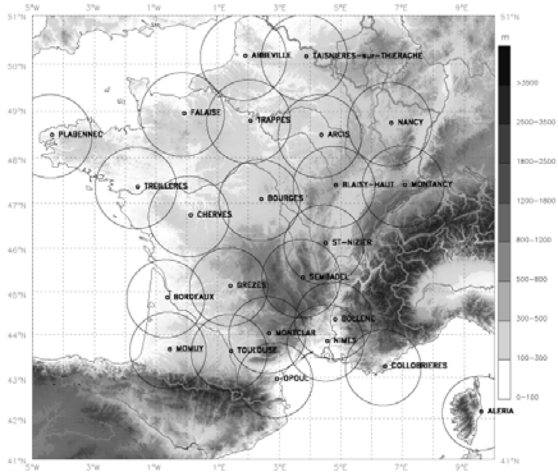

Fig. 1 French radar network in 2006.

hereafter), (2) vertical profile of reflectivity (VPR) effects, (3) advection effects, (4) attenuation by gases, precipitation or wet radome, (5) 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 time 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 raingauge side, hourly and daily (from 6 UTC on one day to 6 UTC on the following day) data are available in the operational databases. These data are routinely checked by experts and – if needed – corrected for. The typical number of hourly raingauges over France (550 000 km^2) is 1000, compared to 4000 daily.

RADAR DATA PROCESSING

Radar data pre-processing turned out to be absolutely necessary before considering merging them with raingauge 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 with the data). The principles that governed the choice of the various algorithms are the following: simplicity, robustness, efficiency, interoperability. Because the project is working on a tight schedule (the aim being to deliver a V1 version of the re-analysis 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 are mentioned.

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 3–12%) are classified as GC and *never* used for the considered year. This may appear as a drastic approach, but emphasis was put on minimizing the rate of unfiltered clutter that may corrupt the radar–raingauge analysis ("better have no data than risk introducing bad data"). Notice that anomalous 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 anomalous 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, etc.). GC maps could be updated more frequently, but would require more time and effort.

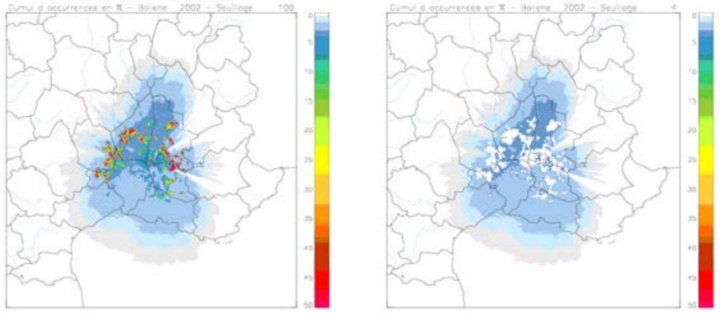

Fig. 2 Bollène (S-band) radar 2002: occurrence frequency map (512 × 512 km^2) without (left) and with (right) application of a 4% threshold (512 × 512 km^2).

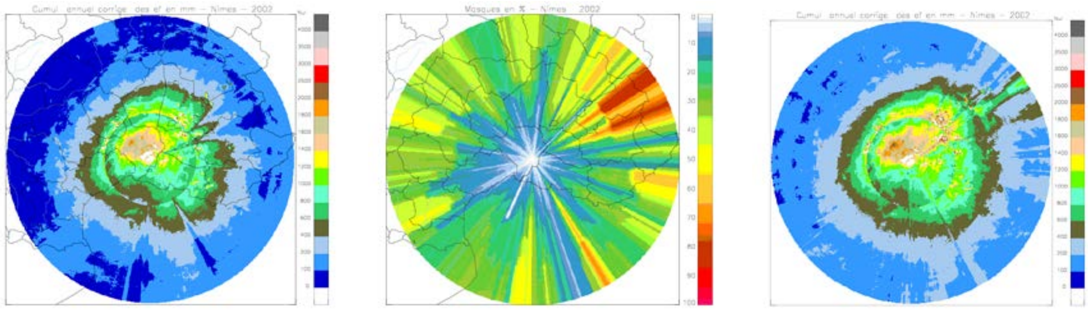

Fig. 3 Nîmes (S-band) radar 2002: raw yearly accumulation (left), PBB map (centre) and corrected yearly accumulation map (right).

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 distances (0–10 km, 10–20 km, etc.). These curves are then filtered with a running 10° filter that replaces each value with 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. The aim of this procedure is to identify narrow masks, with the assumption that such masks have an extension that is less 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 raingauges and the daily calibration factor maps (see further down). The retrieved PBB rates are converted into a 512 × 512 km^2 Cartesian map for further application to the raw 5 min reflectivity pseudo-CAPPIs. This empirical approach to PBB was preferred over using a simulation tool (e.g. Delrieu *et al*., 1995) because it takes into account simultaneously 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)).

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

The approach that was taken to eliminate 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 autumn 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 min) satellite imagery were not yet operationally available over the considered time period of re-analysis (1997–2006); hence the proposed (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 (see next sub-section). In other words, the proposed approach is such that radar data are not used to provide the "no-rain" information. The 5-min, 512 × 512 km^2 Cartesian reflectivity pseudo-CAPPI are converted into rainfall rate maps using Marshall-Palmer. Two-dimensional advection fields are then computed using a standard cross-correlation approach (as in Tuttle & Foote (1990)) between two successive images, spaced apart by 5 minutes. 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).

Production of daily accumulations and computation of radar/raingauge calibration factor map

The 512 × 512 km^2 radar hourly accumulations are subsequently accumulated over 24 h (from 6 UTC to 6 UTC the following day). The exact same approach is taken as at the hourly time-step to process "weak" and "no-weak" hourly accumulations. The radar-based 24 h rainfall accumulation map, wherever it is available (i.e. outside GC classified areas, high PBB areas and "weak" areas), is then confronted with 24 h raingauges. A radar/raingauge calibration factor field is computed as follows:

– a circular neighbourhood (with a radius of 30 km) is moved successively over each 1 km^2 pixel of the 512 × 512 km^2 radar domain;
– for each new position of the neighbourhood, the raingauges inside the neighbourhood having reported more than 0.6 mm in 24 h are paired with the corresponding radar pixels (in cases where radar rainfall accumulation is not classified as GC, high PBB or weak);
– a number N of (radar, raingauge) 24 h accumulations couples are established; wherever N is higher than 3, the median value of the N radar/raingauge 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. Where the calibration factor cannot be computed, the resulting daily accumulation is given by ordinary Kriging of daily raingauges.

GENERATION OF THE BEST DAILY ACCUMULATION FROM RADAR AND RAINGAUGES OVER EACH RADAR DOMAIN

In order to obtain the best daily estimation of precipitation, an extra step consists in merging the calibrated daily radar accumulation map with daily raingauges using Kriging with external drift (KED). The calibrated radar accumulation (the external drift) in itself is already a good estimation of daily precipitation. The main goal of this step is to ensure that the raingauge accumulations are retrieved (at the location of the gauges) in the final result.

The description of KED equations can be found in Hengl *et al.* (2003), as well as the description of the regression-Kriging method that is the one actually used in the project, which is shown to lead to the same results.

GENERATION OF THE BEST HOURLY ACCUMULATIONS FROM RADAR AND RAINGAUGES OVER EACH RADAR DOMAIN

This step (temporal disaggregation) consists in deriving hourly precipitation from the best daily precipitation accumulation estimation. This is achieved by distributing the 24 h accumulation over the 24 h composing the day as follows:

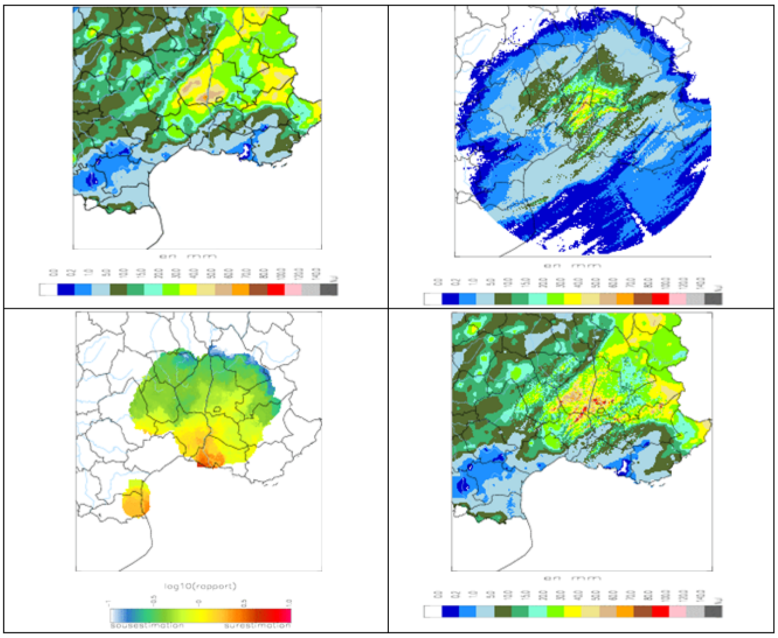

Fig. 4 Nîmes (S-band) – 21 October 2002 –24 h accumulation map from Kriged raingauges (top left), raw radar rainfall accumulation (top right), radar/raingauge calibration factor map (expressed in log10, bottom left) and calibrated radar rainfall accumulation map (bottom right).

– Hourly radar rainfall accumulations are first corrected using the calibration factors established in part 3. 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.
– Hourly precipitation accumulation fields are then computed from available hourly (calibrated) radar and raingauge data. The method used to compute these temporary fields is here again KED. As KED requires the drift (the hourly radar accumulation) to be available all over the domain, missing radar data are replaced by hourly ordinary Kriging values.

For a given point of the 512 × 512 km^2 radar domain, letting h_i (i∈[1;24]) be the hourly estimation derived from merging hourly radar and raingauge 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 $\sigma_i.D/H$. Special attention is paid to some particular cases (where $H = 0$).

RADAR COMPOSITING AND GENERATION OF THE BEST HOURLY COMPOSITE ACCUMULATION MAP OVER FRANCE

The final step is to generate a map all over France by compositing the different local estimates of precipitation, which are available on Cartesian 512 × 512 km^2 domains centred on the available radars. Notice that because of the size of each individual radar domain (512 × 512 km^2) and the number and location of radars in operation at any time between 1997 and 2006, this approach allows a complete coverage of the French territory. The estimation of hourly precipitation and its uncertainty for one point can be provided by different local estimates. It has been decided to use the uncertainties as weights in the combination of estimations in overlapping areas.

For a given point, letting h_i and e_i be the hourly rainfall estimation (in mm) and its uncertainty (also in mm) given by an individual estimation i, then the result of the weighted linear combination is (in terms of hourly QPE H (in mm) and uncertainty E (in mm)):

$$H = (h_1/e_1 + h_2/e_2 + ... + h_n/e_n) / (1/e_1 + 1/e_2 + ... + 1/e_n) \quad (1)$$

$$E = (\sqrt{n}) / (1/e_1 + 1/e_2 + ... + 1/e_n). \quad (2)$$

Table 1 Left: Reanalysis *vs* ordinary Kriging over the (Abbeville,Arcis,Trappes) domain in 2001. Nearly 57 000 observations were used to compute the scores. Right: Reanalysis *vs* ordinary Kriging over the (Bollène,Nîmes) domain in 2002. Nearly 34 200 observations were used to compute the scores. HRG: hourly raingauge accumulation (mm).

(Abbeville,Arcis,Trappes) domain in 2001	CORR HRG > 0 mm / HRG > 2 / HRG > 5 mm	NB HRG > 0 mm / HRG > 2 / HRG > 5 mm	(Bollène,Nîmes) domain in 2002	CORR HRG > 0 mm / HRG > 2 / HRG > 5 mm	NB HRG > 0 mm / HRG > 2 / HRG > 5 mm
Ordinary Kriging	0.67 / 0.40 / 0.27	0.78 / 0.58 / 0.43	Ordinary kriging	0.69 / 0.53 / 0.38	0.82 / 0.67 / 0.57
Re-analysis	0.73 / 0.56 / 0.45	0.84 / 0.69 / 0.59	Reanalysis	0.75 / 0.63 / 0.54	0.87 / 0.75 / 0.68

RESULTS

In order to evaluate the final composite 1 km^2 hourly QPE, some raingauge data have been removed from the whole process and left aside for independent validation purposes. At the current state of the project, only two different sets of data have been produced. The first one corresponds to the [Abbeville,Arcis,Trappes] radar triplet (north of France, see Fig. 1) for the year 2001, the second one to the [Bollène,Nîmes] couple (southeast of France, see Fig. 1) for the year 2002.

Table 1 presents some first results (correlation CORR and normalised bias NB = $\Sigma QPE_i / \Sigma HRG_i$) for various hourly raingauge accumulation thresholds (0, 2 and 5 mm in 1 hour), in comparison with ordinary Kriging of raingauges on the same domains. The normalized bias is defined here as the ratio of the total QPE accumulation over the total observed accumulation.

CONCLUSIONS AND OUTLOOK

A processing chain has been developed in order to produce a high-resolution (1 km^2), 10-year reference database (1997–2006) of hourly Quantitative Precipitation Estimations (QPE) covering the entire French metropolitan territory with no spatial or temporal gaps. The chain uses the individual 5-min 512 × 512 km^2 pseudo-CAPPI radar reflectivity images of the French radar network and quality-controlled hourly and daily (from 6 UTC to 6 UTC) raingauges as inputs. Simplicity, robustness, efficiency and interoperability are the principles that have governed the decisions regarding the various modules. Several validation exercises have been performed to validate the various steps of the processing chain. In particular, the final product – 1 km^2 composite hourly accumulation maps – has been evaluated with independent raingauge data over one year in two different geographical / meteorological contexts. The V1 of the database (1997–2006) is expected to be delivered by the end of the first quarter of 2012. Later on, the database will probably be extended from 2006 onwards and improvements will be made to several modules.

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