Proceedings of ERAD (2004): 509–515 © Copernicus GmbH 2004

ERAD 2004

Some examples on the use of radar observations for the verification of NWP models in the Alpine region

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Abstract. Data from rain gauges, radar and two high resolution Numerical Weather Prediction (NWP) models are being analyzed. The accuracy of radar-derived precipitation amounts is verified during two consecutive days of heavy rain in the Alps. Good agreement is found between daily radar/gauges amounts. The average forecast of (alternatively) one of the two NWP models was in reasonable agreement with the average rainfall amounts derived from the observations. One NWP model failed in both days to predict the location of the intense cells: these were forecast "upstream", while they occurred "upslope". No matter what the representation may be ("point" measurements from rain gauges, radar estimates from a volume, NWP-values on a grid) both the geographic transformation and upscaling of the rainfall field for the comparison induces changes in the statistical as well as deterministic properties of the field.

1 Introduction

The scope of the present study lies within the "Approaches to verification" working area of the Working Group 2 of the COST 717 action, which is addressing the objective of "Using radar observations for parameterisation and validation of atmospheric models" (e.g. Fruhwald, 2000). Our efforts are towards the use of gauge-adjusted, radar-derived precipitation fields for comparison with Numerical Weather Prediction (NWP) models even in regions characterized by a complex orography, where the radar estimations are affected by several sources of error (e.g. Zawadzki, 1984; Koistinen et al., 1999) that are unfortunately particularly severe (e.g. Joss and Waldvogel, 1990; Germann and Joss, 2004). The case study presented here refers to an extreme event (October 13–16, 2000 Piedmont flood) that occurred over the southern side of the Western Alps (Gabella and Mantovani, 2001); the $\sim$12 000 km^2 study area is surveilled by a C-band weather radar and instrumented with a network of 70 telemetered rain gauges. Hence, the comparison will concern traditional, in situ, "point" measurements (rain gauges), remotely sensed, radar-derived areal estimates (derived from 3D data simply using the maximum echo along the vertical or by means of an identified average vertical profile of reflectivity (VPR), over cells with size of a few kilometers) and the outputs of NWP models over a grid with size of tens of kilometers. The comparison is presented on a daily basis for the two days that are characterized by the largest average precipitation (a volume of $\sim$0.82 and $\sim$1.31 km^3 of water(!) according to the 70 gauges) and is based on various points of view: A) For a given "alarm threshold" of daily rainfall, what is the size of the area that was hit? B) What is the amount of daily rainfall over a given area? C) What is the daily total volume of water? D) What is the size of the area where a given percentage of the total water fell? We will try to answer these questions in Sects. 4 and 5 (Sect. 2 describes the study area, the instrumentation and the data, Sect. 3 briefly summarizes the adjustment methods used.

2 Geographic, instrumentation and data description

The digital elevation map in Fig. 1 shows the area of the experiment, which is located in Northwest Italy within the Piedmont region (whose political boundaries are indicated with a black line). The white marks in Fig. 1 indicate the 70 rain gauges (tipping-bucket with 0.2 mm resolution) within the selected area of interest (a region of $\sim$12 000 km^2 shown in Figs. 2, 3 and 4). The rather asymmetrical distribution of the gauge altitudes is summarized in Table 1.

The Swiss C-band radar is located on top of Monte Lema at 1625 m a.s.l. (see the upper right part of Fig. 1). The statistical characteristics of the distances between the Monte Lema radar and the gauges are summarized in the first row of Table 1.

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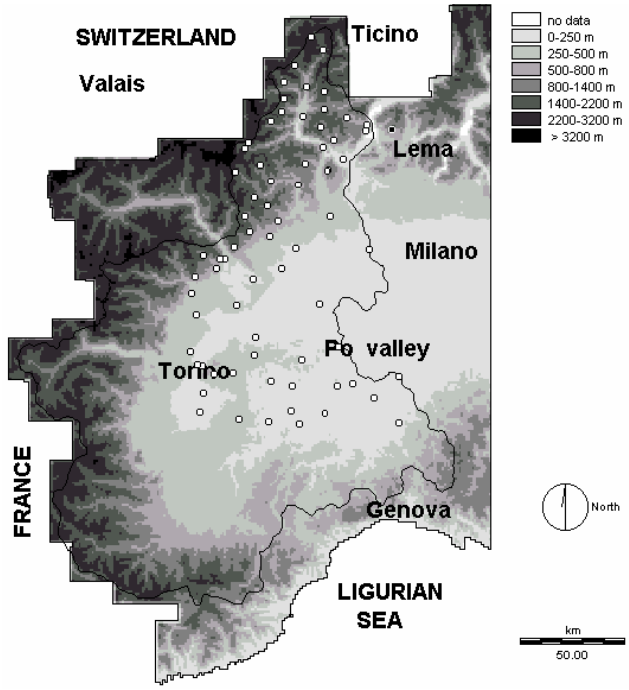

Fig. 1. Digital Elevation map of the northwestern part of Italy, political boundaries of Piedmont (black line), Monte Lema radar site (black mark) and location (white marks) of the 70 rain gauges.

The Monte Lema radar is a C-band Doppler radar. The full volume is scanned with a 1° beam at 20 elevations. This scanning is accomplished in two cycles with interleaved elevation angles; each cycle lasts 2.5 min. The $1° \times 1° \times 80$ m clutter-free range bins are averaged and re-sampled on a Cartesian grid. An OVERVIEW product that contains full volume reflectivity information is updated every 5 min. A 2D product that contains one projection of the maximum vertical reflectivity (MAXECHO) was used to derive "first-guess" daily rainfall amounts. However, it is well known that it is not sufficient to simply take reflectivity aloft and then use some Z-R relations to derive the rainfall rate on the ground (using for instance the MAXECHO product). The RAIN product is based on a more sophisticated concept that distinguishes between two "orthogonal" causes of error: (A) The horizontal contribution, which includes the effect of visibility, residual clutter and beam broadening with distance. In this contribution we include errors that, as a first approximation, are fixed for a given radar, which vary to a great extent in space but are almost independent of the weather. These errors are diagnosed and modeled using the WMR technique. (B) The vertical contribution to the error, which varies to a great extent in time and depends on the weather situation. Therefore, this component should be estimated and corrected – whenever feasible – using hourly estimates of the reflectivity profile from volume data (the different values of the daily WMR-derived coefficients are related to this variability).

The "best" estimate of precipitation at ground level stored in the RAIN product is derived from a weighted mean of the overlying estimates. Considering that the measurement error increases with the height of the radar observation, the weight is reduced with increasing distance (height) from the ground.

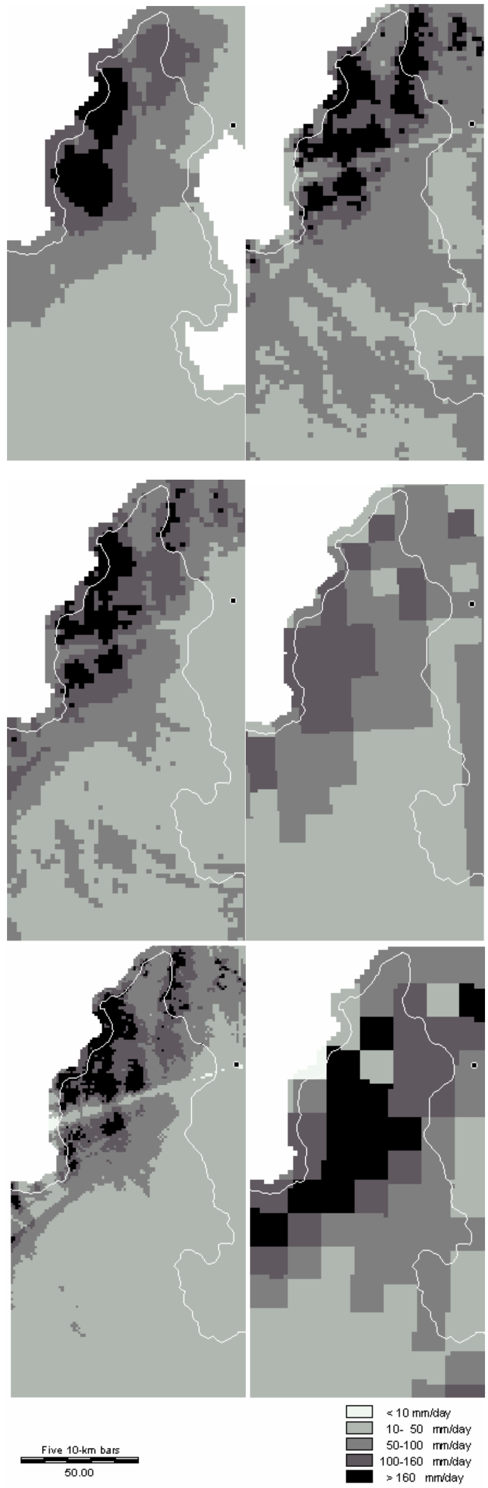

Fig. 2. October 14 daily precipitation: rain gauges (isohyets); bulk- and WMR- adjusted radar estimates (Max. Echo, $2 \times 2\,\text{km}^2$); "QBOLAM" NWP forecast; WMR-adjusted mean-VPR corrected radar estimates ($1 \times 1\,\text{km}^2$); "Swiss Model" NWP forecast.

Fig. 3. October 14 daily precipitation amounts: rain gauges (Thiessen); bulk- and WMR- adjusted radar estimates (Max. Echo, $2\times2\,km^2$); "QBOLAM" NWP forecast. Radar data have been upscaled to the NWP models grid by keeping the average.

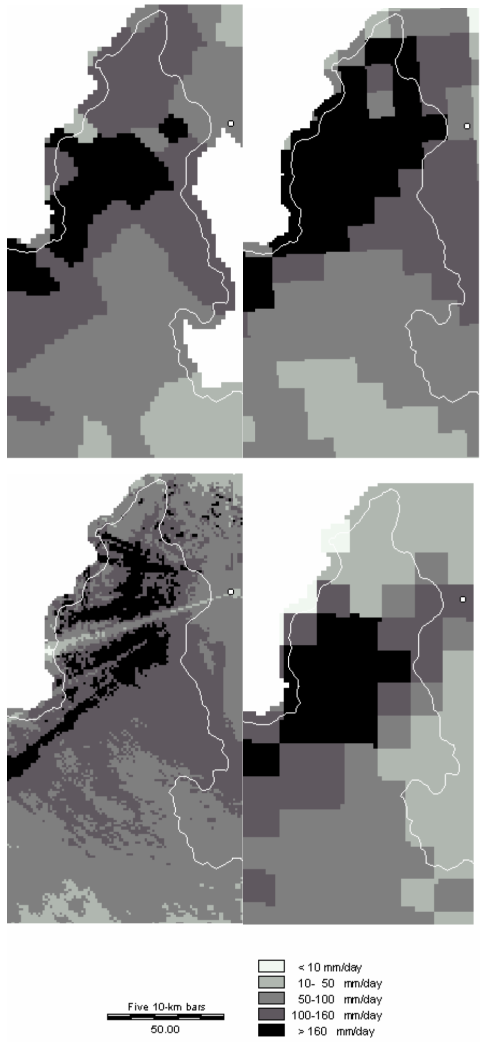

Fig. 4. October 15 daily precipitation: rain gauges (isohyets); "QBOLAM" NWP forecast; WMR-adjusted mean-VPR corrected (RAIN product) radar estimates ($1\times1\,km^2$); "Swiss Model" NWP forecast.

Consequently, it is hoped that a better estimate of the precipitation rate that reaches the ground can be recorded in the "RAIN" product than that recorded with the simpler MAXECHO product. All clutter-free reflectivity measurements along the vertical are converted into the equivalent rain rate using a simple $Z=a\cdot R^b$ relationship (b=1.5 and a=316) and then weighted with weights that are inversely proportional to the reflectivity heights in order to extrapolate the rain rate on the ground. A total of 288 MAXECHO and RAIN maps for each day were used to derive the daily radar amounts (raw data).

As far as the NWP models are concerned, the Swiss Model (SM) is a hydrostatic meso-"beta" scale numerical weather prediction model operationally used at the MeteoSwiss in the period 1994–2000. It has been developed in a joint effort of the Deutscher Wetterdienst (DWD) and MeteoSwiss, as a high-end resolution version of the DWD Europa Modell. In a slightly different configuration, the same model was operational at DWD till the end of 1999, under the name Deutschland Modell (DM). The reference grid is a latitude/longitude reference system (the grid mesh is about 14 km). The spin-up time used in this study is 24 h. The Bologna Limited Area Model (BOLAM) is a hydrostatic, primitive equation, grid-point meteorological model. The QBOLAM version

Table 1. Statistical attributes of the network of 70 gauges distributed in a region of about $12\,000\,km^2$ surveyed by the Lema radar: distance from the Swiss Lema radar, D, Height of the Gauges above sea level, HG, and minimum Height of Visibility, HVmin (it is the minimum height at which a meteorological target must reach to be visible to the radar).

	Mean	Median	Std	min	Max
D	85 km	80 km	41 km	11 km	157 km
HG	750 m	480 m	660 m	80 m	2820 m
HVmin	1060 m	660 m	880 m	80 m	2760 m

Table 2. October 14, 2000: percentage of area (within the selected ~12 000 km^2 region in Piedmont) covered by rainfall amounts larger than the "attention" and "alarm" thresholds that are indicated in columns 2 and 3.

	>70 mm/day	>150 mm/day
- Interpolation of 70 Gauges (Isohyets)	30%	8%
- Interpolation of 70 Gauges (Thiessen)	25%	8%
- Radar MAXECHO bulk-adjusted	33%	10%
- Radar MAXECHO WMR-adjusted	28%	7%
- Radar MAXECHO bulk-adjusted and upscaled ("NWP-like")	36%	10%
- Radar MAXECHO WMR-adjusted and upscaled ("NWP-like")	32%	10%
- 70 Gauges (equal weights)	39%	14%
- QBOLAM NWP forecast	28%	1%
- Swiss Model NWP forecast	51%	17%

Table 3. October 15, 2000: percentage of area covered by rainfall amounts larger than the "alarm" threshold shown in columns 2 and 3 within the selected ~12 000 km^2 area in Piedmont.

	>70 mm/day	>150 mm/day
- 70 Gauges	74%	21%
- Interpolation of 70 Gauges (Isohyets)	76%	14%
- Radar WMR-adjusted (1×1 km^2) RAIN product (VPR corrected)	77%	12%
- Swiss Model NWP forecast	55%	17%
- QBOLAM NWP forecast	63%	25%

Table 4. October 14, 2000: rainfall amounts that hit at least 50% and 16% of the selected ~12 000 km^2 area in Piedmont.

	~6000 km^2	1920 km^2
- Interpolation of 70 Gauges (Isohyets)	>40 mm/day	>105 mm/day
- Radar MAXECHO WMR-adjusted	>42 mm/day	>104 mm/day
- Radar MAXECHO bulk-adjusted	>54 mm/day	>113 mm/day
- Radar MAXECHO bulk-adjusted and upscaled ("NWP-like")	>55 mm/day	>122 mm/day
- 70 Gauges (equal weights)	>49 mm/day	>128 mm/day
- Swiss Model NWP forecast	>72 mm/day	>158 mm/day
- QBOLAM NWP forecast	>49 mm/day	>98 mm/day

Table 5. October 15, 2000: rainfall amounts that hit at least 50% and 16% of the selected ~12 000 km^2 area in Piedmont.

	~ 6000 km^2	1920 km^2
- Interpolation of 70 Gauges (Isohyets)	>109 mm/day	>143 mm/day
- Radar WMR-adjusted (1×1 km^2) RAIN product (VPR corrected)	>96 mm/day	>138 mm/day
- 70 Gauges (equal weights)	>115 mm/day	>161 mm/day
- Swiss Model NWP forecast	>81 mm/day	>156 mm/day
- QBOLAM NWP forecast	>91 mm/day	>183 mm/day

presented in this study represents its implementation on a Quadrix supercomputer, which is used operationally by the Italian Environmental Protection Agency (APAT) in Rome. The spin-up time used here is 12 h. Adding up, for our daily comparison of the model output with rain gauge and radar precipitation accumulation (synchronized at 00 UTC), we started the NWP model integration the previous day (namely, at 00 UTC for the SM and at 12 UTC for the QBOLAM).

For both the NWP models, the shape of the pixels reflects the conversion from lat/long to the conformal Swiss cartographic kilometric reference system using a nearest-neighbor resampling procedure.

3 Methods (adjusting radar-derived precipitation fields)

A well-known technique that has been used in Europe to combine radar and gauge data, particularly in complex orography regions, is that of a non-linear Weighted Multiple Regression (Gabella et al., 2001), which was developed in cooperation with radar-meteorologists from the Swiss Confederation and the Czech and Slovak Republics (Boscacci, 1999; Kracmar et al., 1999). The adjustment used in this study is thoroughly described by Gabella and Notarpietro (2004): in particular, the first day of the event is used for training the adjustment coefficient(s) and the next two days are used for the verification (Gabella, 2004).

4 For a given threshold, what is the size of the area?

Having at our disposal a spatial representation (i.e. an image) of the rainfall field, we can answer the question by looking at the intersection with the Cumulative Distribution Function (CDF) of a vertical line in correspondence with the given threshold. We start from the most traditional observational source, i.e. by using the available in situ measurements. Unfortunately, these are available only at several tens of points. There are simple methods that try to reconstruct from the "point" values the rainfall field spatial variability, for instance by giving weights that are inversely related to the distance from the in situ measurements (isohyets, top-left picture in Fig. 2) or by means of the Thiessen (1911) polygons (top-left picture in Fig. 3). Obviously, the spatial resolution of the reconstructed field (2×2 km^2 in this case) is somehow "artificial" since both methods are not able to "downscale" the precipitation field multifractal properties. For two exemplificative "attention" ($\geq$70 mm/day) and "alarm" ($\geq$150 mm/day) thresholds, the percentage of area (within the selected $\sim$12 000 km^2 region in Piedmont) that are characterized by values larger than these selected thresholds, are shown in the 1st and 2nd lines of Table 2: the order of magnitude is similar and consistent with the observations of an instrument that has unique capabilities in observing the spatial properties of the rainfall fields, i.e. the weather radar. From the CDF of the original MAXECHO radar data (a bulk-adjustment, being simply a multiplicative factor, does not affect the radar image CDF) it turns out that the percentages of area at hand is $\sim$33% and 10% (3rd line, Table 2). The corresponding bulk-adjusted radar image is shown in the top right picture of Fig. 2. The WMR-adjustment basically increases radar values at large distances or high altitude, while it reduces them at short distance and lower elevations (center-left picture in Fig. 2); this spatial modification has consequences on the CDF of the image: the areal percentages for the WMR-adjusted MAXECHO product are 28% and 7% (4th line, Table 2). The center-right and bottom-right pictures in Fig. 2 show the NWP forecast at a much coarser resolution than the radar (approximately 11 km grid for the QBOLAM and 14 km grid for the Swiss Model). The center-right picture shows the forecast from the QBOLAM on October 13, at 12 UTC+12 h+36 h (i.e. the "previous midday-forecast" accumulated daily over the next 12–36 h); the lower-right picture shows the forecasts from the Swiss Model (SM) on October 13, at 00 UTC+24 h+48 h (i.e. the "previous-day midnight-forecast" accumulated daily over the next 24–48 h). QBOLAM almost correctly displaces the most intense core, though it underestimates its value; SM correctly estimates the core intensity, though it is somehow shifted toward SE (it was forecast "upstream", while it occurred "upslope"). Not surprisingly, the corresponding percentages of area (see the last two lines in Table 2) are rather under-estimated by QBOLAM (28% and 1%) and overestimated by SM (51% and 17%). However, is it reasonable to compare the CDF at such different spatial resolutions? Should the radar observations be "upscaled" for the comparison at the scale of the NWP models resolution? Upscaling operations are related to problems, which we have to cope with, when dealing with the enormous variability of the rainfall field. Upscaling is the procedure to create from a number of smaller pixels (e.g. radar observations) a representative precipitation fields of what a low-resolution process (e.g. a NWP model) sees on a larger pixel. When passing from a higher resolution pixel to a lower resolution, we have to make a choice concerning the upscaling rule. The easiest way to do upscaling is to average daily rainfall amounts of all small (radar) pixels of which the center falls in the large (NWP) pixel. By way of example, Fig. 3 shows the upscaled bulk-adjusted (upper-right) and WMR-adjusted (bottom-left) radar observations (for the sake of comparison, the same QBOLAM picture as in Fig. 2 is shown again). The upscaling, certainly, makes the visual comparison easier. Nevertheless, it may change the percentages of area. In this case, the percentage of area has for instance increased to 36% and 10% (see Table 2, line 5). In other words, even though the upscaling preserves average areal precipitation amounts, the statistical properties (e.g. the CDF) are changed by the upscaling. This unwanted change in the statistical and deterministic properties of the precipitation fields may happen not only in cases where we luckily have a true 2D representation of the precipitation fields (like in this case thanks to the radar), but even with "point" measurements. For instance, if we give to all the rain gauges the same "weight", we get quite different values of percentages of area (it increases to 39% and 14%!). This is the consequence of assuming a regular spatial distribution of the gauge locations (average distance among gauges of $\sim$13 km). As shown in Table 3, similar results are obtained for October 15. For the sake of brevity, not all the cases shown for October 14 are here reported (e.g. for radar data, only the "best" image, i.e. the one that contains VPR

Table 6. Total amount of precipitated water over the selected area (∼12 000 km^2) as derived from approximately a hundred of observations (gauges or radar) and forecast values on a grid (NWP models).

	Day	Total amount
- 70 Gauges	October 14	0.89 km^3
- 70 WMR-adj. Radar estimates aloft	October 14	0.99 km^3
- 70 bulk-adj. Radar estimates aloft	October 14	1.05 km^3
- Swiss Model NWP forecast	October 14	1.05 km^3
- QBOLAM NWP forecast	October 14	0.74 km^3
- 70 Gauges	October 15	1.31 km^3
- 70 WMR-adj. Radar estimates aloft	October 15	1.15 km^3
- 70 bulk-adj. Radar estimates aloft	October 15	1.22 km^3
- Swiss Model NWP forecast	October 15	1.17 km^3
- QBOLAM NWP forecast	October 15	1.31 km^3

Table 7. October 14, 2000: surface extension where 50% and 16% of the total water fell (within the selected ∼12 000 km^2 region in Piedmont).

	50%	16%
- Interpolation of 70 Gauges (Isohyets)	3540 km^2	830 km^2
- Radar MAXECHO WMR-adjusted	3800 km^2	780 km^2
- Swiss Model NWP forecast	4000 km^2	970 km^2
- QBOLAM NWP forecast	4740 km^2	1180 km^2

corrected and WMR-adjusted estimates is shown). The corresponding pictures are shown in Fig. 4. QBOLAM agrees with observations better than SM, both in terms of intensity and displacement. SM again failed to position the embedded convection cells so deep within the Alpine chain.

5 For a given area, what is the rainfall amount?

For every "image" of the precipitation field (no matter if it comes from radar, gauges or NWP), we can answer the question by looking at the intersection with the Cumulative Distribution Function (CDF) of a horizontal line in correspondence with the given percentage of area. By way of example, we choose half (∼6000 km^2) and 16% (∼1920 km^2) of the study area. Table 4 shows the values for October 14, Table 5 for October 15 (for the sake of conciseness, not all the images CDF intersections are shown).

On October 14, half of the area receives more than 40 mm/day, according to the gauges. Similar values are obtained from the radar. As in the previous section, the upscaling changes the CDF and causes increased values of precipitation amounts. Similar characteristics are found, if the analyzed area is restricted to 1920 km^2 (16% of the study area). In both cases, the SM heavily overestimates rainfall amounts, while QBOLAM does not. Higher values are also found if equal weight is given to all gauges.

Also on October 15, rain gauge reconstructed and adjusted radar observations agree quite well. Again, higher values are found if equal weight is given to all gauges.

6 What is the total daily water?

To compute the total amount of precipitated water, we need to determine the average rainfall amount over the study area. Unfortunately, the characteristic spatial resolution of rain gauges, NWP grid and radar observations is too different for such a direct comparison. To homogeneize the situation, we have here selected 70 radar echoes above the gauges only: one advantage is that, given their number, it was feasible to check them against 10 min gauge tips and assure their quality (see e.g. the Appendix A of Gabella and Notarpietro, 2004). In Table 6, we have averaged 70 "point" in situ measurements, the corresponding 70 radar estimates aloft and 61 (99) forecast from the SM (QBOLAM) NWP models. Radar and NWP models underestimated the extreme amount of October 15.

7 What area was hit by half of the total water?

The area contributing to half (or 16%) of the rain amount can be derived from the transformed CDF of the previously shown images; the "transformation" consists of weighting each pixel with the corresponding daily rainfall amount.

In other words, let $\mathrm{P}(D)$ be the probability distribution function of the Daily rainfall amounts; in the two previous sections, the analysis was based on the integral of $\mathrm{P}(D)\ \mathrm{d}D$, while here we use the integral of $D{\cdot}\mathrm{P}(D)\ \mathrm{d}D$. For October 14, the results are shown in Table 7. According to the gauges and the (WMR-adjusted) radar, ∼30% of the area contributed to half the total water, while for the SM and QBOLAM models the contributing area is 33% and 39%.

Also on October 15 (Table 8), the estimate by gauges and radar of the area that was hit by half of the total water is similar (around 47%). This is not true for the NWP models, especially the SM (29%). Within the selected ∼12 000 km^2 area, it has probably been the day with the largest precipitated water in the last century (and the median of the 70 gauge daily amounts is larger than the average!)

8 Summary and conclusions

The precipitation field, although widely used in operational meteorology, is extremely variable in time and space and complex: it is the product of an atmospheric water transformation involving processes that are characterized by a wide range of space-time scales. The ability in comparing various estimates of the precipitation field is beginning to

Table 8. October 15, 2000: surface extension where 50% and 16% of the total water fell within the selected ∼12 000 km^2 region in Piedmont.

	50%	16%
- Interpolation of 70 Gauges (Isohyets)	5580 km^2	1420 m^2
- Radar WMR-adjusted (1×1 km^2) RAIN product (VPR corrected)	5630 km^2	1340 km^2
- Swiss Model NWP forecast	3530 km^2	970 km^2
- QBOLAM NWP forecast	4510 km^2	1150 km^2

play a central role in the structure of modern systems of observation, assimilation, forecast and verification. The procedures needed to bring different variables into the "comparison space" (and back from it) are complex and various sources of deterministic and/or statistical error appear at each step. In this study, the comparison between numerically modeled and observed ("point" and remotely-sensed volumetric) rainfall amounts has been analyzed from various perspectives: as expected, the agreement between observations is much better than between observations and forecast.

Acknowledgements. We would like to thank Francis Schubiger (MeteoSwiss) for the "Swiss Model" and Christophe Accadia (APAT, Agenzia per la Protezione dell'Ambiente e per i servizi Tecnici) for the "QBOLAM" NWP forecasts. Radar data were provided by MeteoSwiss, gauges data by Regione Piemonte. This work was supported in part by the European Commission under the Contract (EVK2-CT-2002-00155) VOLTAIRE (more info at the page http://www.voltaireproject.org/).

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