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Quantitative precipitation estimation in the Alps: where do we stand?

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Abstract. Quantitative precipitation estimation in a mountainous region is of high practical use. Think of hydrogeological risk management, hydroelectric power, road maintenance, and tourism. Yet, neither gauge networks nor weather radars give a perfect answer. Gauge observations in a mountainous region such as the Swiss Alps suffer from severe errors because of wind, snow-drift and spatial variability. Radar scientists and engineers, on the other hand, are faced with severe beam shielding, strong ground clutter, and difficult operating conditions. A sophisticated elimination of ground clutter, and automatic robust algorithms to correct for shielding and profile effects are a must if one needs quantitative estimates of precipitation amounts in a routinely manner. At MeteoSwiss many efforts went into the optimisation of hardware stability and data processing of the radar network in order to obtain quantitative precipitation estimates that meet both the meteorologist's and the hydrologist's requirements. Recent modifications in the correction schemes of the operational radar product RAIN, the best radar estimate of surface precipitation over Switzerland, resulted in a significant reduction of bias, scatter and false alarms.

1 Introduction

MeteoSwiss has more than fourty years of experience with the operation of weather radars in a mountainous region. Many efforts went into the optimisation of hardware stability (Cavalli, 1998) and data processing of the radar network (Joss and Waldvogel, 1990; Joss et al., 1998) in order to obtain quantitative precipitation estimates that meet both the meteorologist's and the hydrologist's requirements. One of the results of these efforts is the MeteoSwiss operational radar product RAIN, a two-dimensional map with the best radar estimate of surface precipitation over Switzerland. The main challenge in a mountainous region is the elimination of ground clutter (Lee et al., 1995; Germann and Joss, 1999b, 2004), and the correction for shielding and profile effects (Joss and Lee, 1995; Germann, 1998; Germann and Joss, 1999a; Vignal et al., 2000; Pellarin et al., 2002; Germann and Joss, 2002). In Switzerland about two thirds of all radar measurements are made in the snow.

Although of minor relative importance in a mountainous context also attenuation (Delrieu et al., 1991; Germann, 1999), and variations in the drop size distribution (Joss and Zawadzki, 1997; Smith and Joss, 1997; Lee and Zawadzki, 2003) introduce significant uncertainties in deriving precipitation rates from radar reflectivity.

Recent modifications in the correction schemes of the radar product RAIN (Germann and Joss, 2002; Germann et al., 2003; Germann and Joss, 2004) resulted in a significant reduction of bias, scatter and false alarms (Bolliger et al., 2004, and this paper).

On the use of weighted multiple regression analysis to correct for residual errors and as a quality check see Gabella et al. (2004), this conference.

2 Outline

This paper, first, briefly describes recent modifications in radar data processing for quantitative estimates of surface precipitation in Switzerland, and, second, presents an objective evaluation based on measurements of 3 radars, 58 automatic gauges and 7 years of data. For details the reader is referred to the literature.

3 Recent improvements

This is a list of the major recent modifications in radar data processing for quantitative estimates of surface precipitation in Switzerland.

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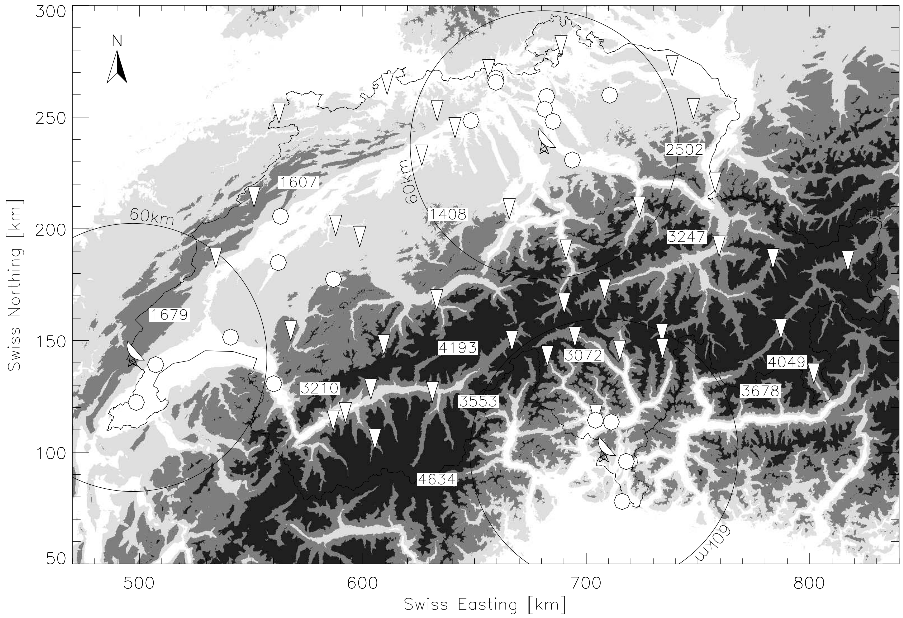

Fig. 1. Network of automatic gauges used for evaluation (both triangles and circles), and for long-term adjustment (circles only). Levels of shading correspond to terrain height below 500 m (white), between 500 and 1000 m (light grey), between 1000 and 2000 m (dark grey), and above 2000 m (black). Highest peak in Switzerland is 4634 m above sea level.

Modification A:. (spring/summer 1997) Introduction of radar visibility map to correct for partial and total shielding (Joss and Lee, 1995; Germann and Joss, 2004).

Modification B:. (spring 1999) Modification of operational clutter elimination algorithm (Germann, 2000; Germann and Joss, 2004).

Modification C:. (early 2001) Introduction of meso-beta profile to obtain more robust estimate of vertical reflectivity profile (Germann and Joss, 2002).

Modification D:. (early 2003) Long-term adjustment of radar constants, and modification in the meso-beta profile correction algorithm (Germann et al., 2003).

Modification E:. (early 2004) Long-term adjustment of radar constants.

A general discussion of the MeteoSwiss concepts of automatic hardware calibration, multi-parameter ground clutter elimination, visibility and profile corrections, and long-term radar-gauge adjustment can be found in Germann and Joss (2004).

4 Evaluation

A scheme for an objective evaluation of the radar product RAIN has been designed. The goal is twofold: First, to quantify the accuracy of radar precipitation estimates in the Swiss Alps. This is mandatory information for any type of application of the product RAIN. Second, we need an objective basis to track the progress of applied research, that is, to decide whether or not a modification of the system did improve the results. The statistics help to judge step by step the value of modifications made in the operational radar data processing chain.

We like to get an answer to the following four questions:

1. What is the overall bias of radar estimates with respect to ground truth?
2. How much does the ratio between the radar estimate and ground truth vary from day to day?
3. How reliable is the radar to detect precipitation (probability of detection)?
4. How often does the radar indicate precipitation in non-precipitation situations (false alarm rate)?

Of course, we do not know ground truth. But, we have a network of automatic gauges. The evaluation presented here is based on measurements of 58 gauge stations more or less evenly distributed over whole Switzerland , and observations of 3 radars located on mountain tops close to Zurich, Lugano and Geneva (925 m, 1625 m, and 1675 m above sea level, respectively), see Fig. 1.

To answer the four questions listed above we defined the following parameters:

Bias:. The bias is defined as the total of precipitation as seen by the radar divided by the total of precipitation measured by the gauges. A positive bias in dB thus indicates that the radar overestimates ground truth, while a negative bias in dB corresponds to underestimation.

Scatter:. To determine the scatter we first calculate daily radar-gauge ratios of all 58 gauge stations for days with gauge>2 mm,

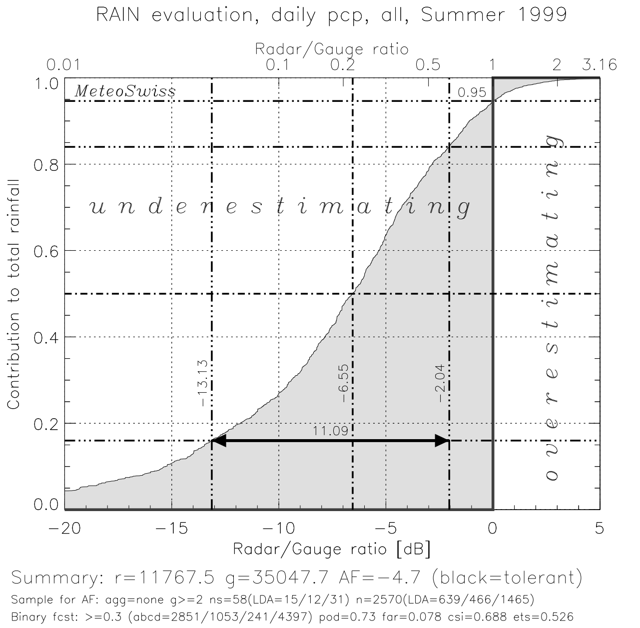

Fig. 2. Cumulative contribution to total rainfall as a function of radar-gauge ratio for daily precipitation >2 mm of summer 1999.

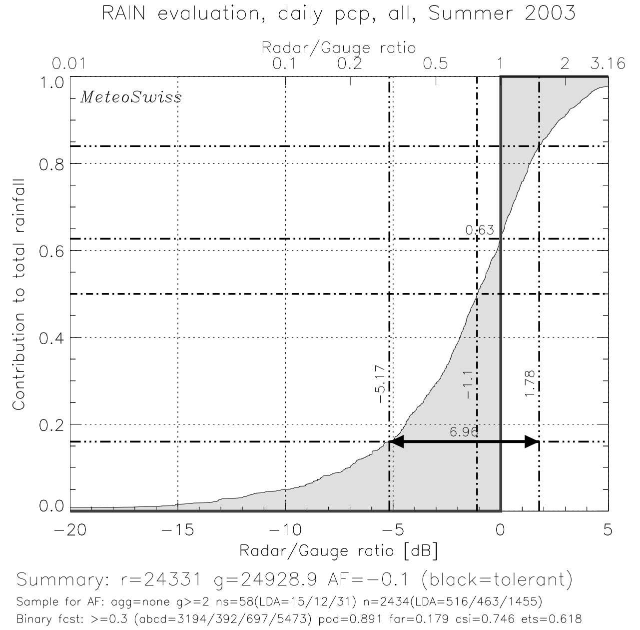

Fig. 3. Same as Fig. 2, summer 2003. Note the considerable reduction of the overall bias and scatter with respect to 1999 (Fig. 2).

and plot the cumulative contribution to total rainfall as a function of the ratio. Examples of such a diagram are shown in Figs. 2 and 3. We then determine the 16% and the 84% percentiles, and take half the distance between the two as a measure of the variability of individual radar-gauge ratios.

POD:. Probability of detection with respect to daily totals of 0.3 mm.

FAR:. False alarm rate with respect to daily totals of 0.3 mm.

CSI:. Critical success index with respect to daily totals of 0.3 mm.

ETS:. Equivalent threat score with respect to daily totals of 0.3 mm. For a definition of POD, FAR, CSI and ETS see Wilks (1995) and Germann and Zawadzki (2002). Both, CSI and ETS are a combination of POD and FAR, and describe the skill of observing the occurrence of precipitation above a given threshold rate, here 0.3 mm per day. We prefer the ETS to the more common CSI for the following reasons: the ETS is 0 for constant radar estimates of either category as well as for random radar estimates, while a perfect radar estimate gets a value of 1. The CSI may be non-zero even for constant or random radar estimates.

5 Benchmark

Tables 1 and 2 and Figs. 2 and 3 show the statistics defined above for precipitation in the summer months May-October from 1997 till 2004. Perfect agreement between radar and gauge would result in a 0 dB bias, 0 dB scatter, 1.0 probability of detection (POD), 0.0 false alarm rate (FAR), 1.0 critical success index (CSI), and 1.0 equivalent threat score (ETS).

Table 1. Bias between radar and gauge measurements as evaluated over those gauges that are used for long-term adjustment of the radar constants (circles in Fig. 1). Summer 1997 till 2004. Note that for summer 2004 only May and June data was available.

Year	Bias [dB]	Bias [%]
RAIN 1997	−2.0	−37
RAIN 1998	−1.2	−24
Modification B: changes in the operational clutter elimination		
RAIN 1999	−3.9	−59
RAIN 2000	−2.9	−49
Modification C: introduction of meso-beta profile		
RAIN 2001	−3.8	−58
Modification D: long-term adjustment and modification of profile correction		
RAIN 2003	1.0	26
Modification E: long-term adjustment		
RAIN 2004	0.4	10

A realistic target for the Swiss Alps is

- a bias close to zero in Table 1 [0 dB ±0.5 dB],
- a small negative bias in Table 2 [around -1 dB],
- low scatter in Table 2 [3 dB],
- a high POD in Table 2 [above 0.8],
- and a low FAR in Table 2 [below 0.2].

Table 2. Bias, scatter, probability of detection (POD), false alarm rate (FAR), critical success index (CSI) and equivalent threat score (ETS) of radar estimate of daily precipitation for summer half-year from 1997 till 2004. The radar-gauge comparison is made for 58 automatic gauge stations in whole Switzerland, see triangles and circles in Fig. 1. The bias is defined as the total of precipitation as seen by the radar divided by the total of precipitation measured by the gauges. The scatter is a measure of the variability of individual radar-gauge ratios of daily precipitation, and is defined as half the distance between the 16% and the 84% percentile of cumulative contribution to total rainfall diagrams as shown in Figs. 2 and 3. For bias and scatter only days with gauge$>$2 mm are considered. POD, FAR, CSI and ETS are calculated for a threshold of 0.3 mm using all days of the given period. Note that for summer 2004 only May and June data was available.

Year	Bias [dB]	Bias [%]	Scatter [dB]	POD [0..1]	FAR [0..1]	CSI [0..1]	ETS [0..1]
RAIN 1997	−3.0	−50	4.4	0.84	0.34	0.59	0.40
RAIN 1998	−2.0	−37	4.2	0.87	0.30	0.63	0.39
Modification B: changes in the operational clutter elimination							
RAIN 1999	−4.7	−66	5.5	0.73	0.08	0.69	0.53
RAIN 2000	−3.7	−57	5.2	0.74	0.11	0.68	0.52
Modification C: introduction of meso-beta profile							
RAIN 2001	−4.4	−64	3.1	0.75	0.08	0.71	0.57
Modification D: long-term adjustment and modification of profile correction							
RAIN 2003	−0.1	−2	3.5	0.89	0.18	0.75	0.62
Modification E: long-term adjustment							
RAIN 2004	−0.8	−17	3.2	0.85	0.16	0.73	0.58

6 Discussion

By analysing the numbers in the figures and tables presented here we come to the following four conclusions:

1. The bias indicated in Table 1 was never so close to zero than in 2004 (0.4 dB). Adjustment of the radar constants is based on long-term radar-gauge comparison at locations with good visibility and high spatial resolution at short ranges from the radar (circles in Fig. 1). As a logical consequence, it is this set of gauges for which the bias should converge to zero.

2. When comparing 1997 with 2004 all statistics of Table 2 except for the POD show a significant improvement. The POD remains virtually unchanged. Whereas, generally speaking, the reduction of an overall bias may be straightforward, the simultaneous reduction of bias, scatter and FAR is not!

3. The modifications in the operational clutter elimination decision tree (modification B) resulted in a considerable reduction of false alarms (Table 2).

4. The introduction of the meso-beta profile correction (modification C) helped to reduce the scatter, a challenging task (Table 2).

Unfortunately we do not have the data that would be necessary to calculate the statistics for 1996. Therefore, we can not examine the success of the introduction of the visibility map mentioned in modification A, above.

Of course, one could “find” a much better agreement between radar and ground truth (here gauge observations) by subjectively selecting the events and stations to be considered. But this was not our intention. We like to obtain an objective evaluation of operational quantitative radar estimates of surface precipitation over whole Switzerland, including severly shielded valleys at relatively far ranges and including all events in a given period regardless of radar performance. We thus get an overall assessment of radar estimates over the whole territory including all types of summer precipitation. A next step will be the stratification according to location, weather, season, etc.

Note that the disagreement found between the two types of observations results from the superposition of gauge and radar errors. Therefore, the numbers presented here overestimate the true uncertainty of radar estimates.

If the user needs areal averages of precipitation amounts, as is the case for most hydro(geo)logical and industrial applications, then several radar measurements can be averaged and the stochastic part of the radar error decreases by the square root of the number of samples. Gauge measurements, on the other hand, may then suffer from severe representativeness errors caused by the spatial variability of precipitation (Germann and Joss, 2001). It is unknown which of the two instruments gives the better estimate in a particular situation. For a robust combination one needs to know the error structure of all measurements to be considered.

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