Twelve years of operational real-time hourly precipitation estimation in the Alps: better performance of the radar-only and radar-gauge products in recent years

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Abstract

In the present communication we describe the performance of the two MeteoSwiss radar-derived precipitation products (radar-only and radar-gage merging) from 2005 to 2017 using as a reference the same set of 68 in situ measurements available during such a long observation period. Hourly amounts have been put together in a unique seasonal pool and the agreement is characterized in terms of dispersion of the weighted multiplicative error (scatter in dB). As far as radar-only estimation is concerned, the typical **scatter** in summer for hourly accumulation is **3.0**±0.1 **dB** (from 2005 to 2013); in the following two years, after the installation of a fourth weather radar in Wallis, the scatter is 2.8 dB and 3.1 dB. After the installation of a fifth radar in Grison, it decreases to (2.75 dB) **2.70 dB** in (2016) **2017**. The radar-only estimates at gauge locations are certainly not affected by the amounts measured by the gauges. On the contrary, the radar-gage merging (CombiPrecip) values are affected. That is why a cross-validation approach has been used in the verification: the typical CombiPrecip cross-validation scatter in summer is **2.44**±0.12 dB (2005-2013). Thanks to the continuous increase in the number of rain gauges in the automatic tele-metered network (as well as the 4th radar), the scatter decreases to 2.20 and 2.35 dB in the following two years. With more than 260 gauges and five radars, the scatter in the same 68 sites decreases to (2.0) **1.9 dB** in (2016) **2017**. This quantitative estimate of the agreement in summer between in situ measurements and remotely sensed estimates is representative for most of the hourly estimates, but certainly not all of them; the last section shows how problematic could be the quantitative characterization of an extreme event, since it evolves very rapidly in space and time. In such cases, the spatio-temporal resolution of our monitoring system becomes the limiting factor.

1. Introduction

Real-time quantitative precipitation estimation (QPE) in mountainous terrain is important in several applications: monitoring and nowcasting precipitation, river flow and lake level forecasting, hydro-geological risk management, precipitation extremes, urban and water management, civil protection for human outdoor activities. Yet, neither conventional in situ measurements (rain gauges) nor remotely sensed observations from weather radars are able alone to provide an adequate answer. That is why the problem of the optimal combination of rain gauge point measurements and radar precipitation estimates has been thoroughly investigated at MeteoSwiss, among other weather services and research institutes.

2. Methods

At MeteoSwiss a method has been developed (Sideris et al., 2014) that attempts to generalize well-established geostatistical techniques, such as kriging with external drift, and operationally produces effective real-time merging of data coming from the MeteoSwiss gauge and weather radar networks, which have been recently renovated and enlarged. This innovative, multi-sensor, precipitation product (CombiPrecip) has been operationally running since 2012; furthermore, a reprocessing of the period 2005-2010 has been run.

In the following Sec. 3 and 4 we aim at characterizing the performance of the two MeteoSwiss radar-derived products (radar-only and CombiPrecip) from 2005 to 2017 using as a reference the same set of in situ measurements available during this long period. We have tried to reduce the enormous and challenging differences in the sampling modes of the two instruments (radar versus gauges) by averaging the precipitation rates over one hour. All seasonal hourly amounts are then put together in the same pool. The disagreement is characterized in terms of dispersion of the weighted multiplicative error around the mean (scatter in dB, see Germann et al., 2006), in addition to the obvious mean under- or over-estimation. The radar-only precipitation estimates at gauge locations are obviously not affected by the amounts measured by the gauges. On the contrary, the CombiPrecip (CPC) values are. That is why a cross-validation approach has been used in the verification: each validation gauge is excluded when predicting the "CPC Cross-Val" hourly precipitation amounts at that site.

3. Data

The observation period consists of 12 years: six years (2005-2010) with the previous generation of weather radars and other six years (2012-2017) with the current state-of-the-art weather radar network. In 2011, in fact, MeteoSwiss has started the renewal and enlargement of its (Doppler, analogue-receiver) radar network (Rad4Alp project): it now consists of five dual-polarization, Doppler, C-band radars. Antenna-mounted, fully-digital receivers have been introduced into the current new generation: each system has two receiving channels, which are able to measure orthogonal polarizations. Three of these radars are located near the political borders of Switzerland (to control fronts and detect perturbations in the largest possible range) and close to highly populated areas and large airports; these locations are the same as in the previous network. Two additional radars have been installed, by necessity, at high altitudes (3000 m), to improve the coverage in the inner parts of the Alps. The 4th system, which is located near Crans-Montana, is operational since 2014; the 5th one, near Davos, is operational since 2016. Switzerland has also a long tradition of in situ observations of precipitation based on hundreds of daily-measuring gauges. For the present study, which is focused on hourly amounts, only the telemetered network equipped with 68 automatic rain gauges could be used; in this case rain amounts are recorded every ten minutes and transmitted, in real time, to the operation center in Zurich. The resolution is 0.1 mm. Starting from 2012, such a network has been increasing in size to reach its current extension of 268 gauges in the last years.

4. Results

At MeteoSwiss considerable efforts are spent in calibration, adjustment and monitoring activities so that the systematic error of the (radar and) CombiPrecip products over one year and the whole Country is small enough, e.g. less than ±0.5 dB. As a consequence, the goal of the present evaluation is to assess the dispersion of the error around such small average error. For this purpose a score that is orthogonal to the mean error has been conceived: it is called scatter and it is a measure of the dispersion of the weighted multiplicative error (see Germann et al., 2006).

4.1 Quantitative Precipitation Estimation: best performances in summer

This subsection is devoted to results obtained during the summer season (June-July-August), which is, as expected, the one easiest to be interpreted and with the best performance. Since in summer most of the precipitation is liquid, at least at the ground level, it is also the most significant for comparing precipitation amounts. Table 1 presents the dispersion of the (dis-)agreement with respect to the 68 gauges for the radar-only (1st line) and the CPC Cross-Validation precipitation estimates. For each 2-year period, two values of scatter have been used to derive an average value (±1_deviation). The first three columns refer to the previous radar network, the last three columns to the state-of-the-art, dual-polarization network equipped with three (column 4), four (column 5*) and five (column 6**) radars. For what concerns the radar-only QPE, no general improvement can be seen in 2012-2013, despite the improvement in hardware (better sensitivity) and scan program (an additional antenna rotation with angle of elevation of 1°). The scatter remains of the order of 3 dB, as obtained in the 2005-2010 period as well as in Southern Switzerland during six “mild” months (see Fig. 2, page 450, in Germann et al., 2006). A small improvement in the 2-year average is observed in 2014-2015. On the contrary, the performance are better in 2016-2017. It is worth to remind that the clutter suppression algorithm has been improved during 2013 thanks to dual-polarization information. It is concluded that the breakthrough in terms of the selected verification score is mainly caused by the improvement in visibility and coverage thanks to the installation of the (4th and) 5th radar(s).

Table 1: Performance of MeteoSwiss precipitation products during summer. The analysis is based on hourly amounts evaluated in the same 68 sites during six two-year periods. The tables shows the 2-year seasonal average value(±1_deviation) of the scatter in dB.

Product	2005-2006	2007-2008	2009-2010	2012-2013	2014*-2015	2016**-2017
Radar-only	**3.1**±0.12 dB	**3.0**±0.15 dB	**3.0**±0.15 dB	**3.0**±0.15 dB	**2.9**±0.25 dB	**2.7**±0.04 dB
CPC Cross-Val.	**2.5**±0.16 dB	**2.4**±0.13 dB	**2.4**±0.10 dB	**2.4**±0.13 dB	**2.3**±0.11 dB	**2.0**±0.07 dB

Similar conclusions can be obtained by looking at the (obviously better) performance of CPC Cross-Val: the first 8 years are characterized by a scatter of 2.4 dB; during the next two-year period (4 radars) the small improvement is still undistinguishable in terms of deviation. Thanks to the 5th radar, the scatter results to be as low as 1.96 dB in 2016-2017 (±0.07 dB deviation).
What would one obtain, if he used the hourly amounts stored in the CombiPrecip product? Obviously, a much smaller scatter, simply because each prediction is based also on the gauge amount used in the evaluation! For this reason, the “temporal trend” is the interesting part of the story (while the values per se are less significant and certainly too optimistic): with the old radar network (2005-2010), the scatter of CombiPrecip results to be around 1.6 dB. In 2012-2013, probably thanks to the installation of new rain gauges (this is at least, our interpretation), it decreases to 1.3 dB. Finally, the scatter decreases to 0.9(±0.03) dB and 0.7(±0.04) dB in the last two two-year periods: it is argued that this is caused by both the increased number of gauges and the two additional high-altitude radars in Wallis and Grisons.
It is important to underline that the Scatter is derived using a double conditional approach: a threshold of 0.3 mm/h is applied to BOTH conventional AND non-conventional estimates.

4.2 Quantitative Precipitation Estimation: performances in winter (and other seasons)

The agreement of the two gridded precipitation products (radar-only and CPC) during the other three seasons are, as expected, considerably worse. This is mainly caused by the fact that the retrieval of precipitation rates when the majority of the hydrometeors are in the (water) solid phase is much more difficult and uncertain than the case with liquid rain drops. By way of example, a characterization of the performance during the winter season is shown in Table 2.

Table 2: Same as in Table 1 but during winter (December-January-February).

Product	2005-2006	2007-2008	2009-2010	2012-2013	2014*-2015	2016**-2017
Radar-only	**3.3**±0.26 dB	**3.1**±0.05 dB	**3.2**±0.22 dB	**3.3**±0.28 dB	**2.9**±0.15 dB	**3.3**±0.07 dB
CPC Cross-Val.	**2.8**±0.35 dB	**2.5**±0.03 dB	**2.4**±0.24 dB	**2.5**±0.40 dB	**2.0**±0.16 dB	**2.1**±0.08 dB

As expected, the performance of CPC Cross-Val are better than the radar-only product. It is also worth noting that in a statistical sense (the CPC Cross-Val performance in winter (2nd row, Table 2) are considerably better than radar-only performance in summer (1st row, Table 1).
For what concerns the radar-only QPE, on the one hand winter performance are worse than in summer, on the other hand there is no beneficial trend caused by the two additional high-altitude radars (1st row, Table 2). However, at least the CPC Cross-Validation evaluation (see the 2nd row of Table 2) performance (as well as the CombiPrecip values) are positively affected by the presence of the two new radars.

If someone used the hourly amounts stored in the CombiPrecip product (instead of the Cross-val. values), he would get a scatter of ~1.6 dB with the old radar network (2005-2010), ~1.3 dB in 2012-2013, and (0.9) 0.8 dB in (2014-2015) 2016-2017.

5. Examples of precipitation estimation in extreme conditions: Lausanne 11.6.2018

The methodology used in this extended abstract is valid and representative for most of the hourly (conventional and remotely sensed) estimates, but certainly not all. This Sec. 5 shows how problematic could be the quantitative characterization of extreme events, since they evolve too rapidly in space and time for our observing systems. As an example we briefly present an **extreme event** that hit the Lausanne urban area on June 11,2018. A MeteoSwiss automatic rain gauge located downtown at 601m altitude has measured between 21 and 21:10 UTC an impressive **10-min** amount of **~40.9 mm**. A gauge network is seldom dense enough so that at least one in situ device is not too far from the maximum in deep convection. On the contrary, in this case the gauge amount is likely not too far from the real maximum amount: as it will described below, the absolute precipitation maximum of the storm in term of polarimetric signature was a value slightly larger than 15 degree/km of the specific differential propagation phase delay; the spectral signature of the sampling volume containing the hydrometeors (and many others!) subsequently reaching the gauge was instead 14 degree/km (see Fig. 1, right picture).

Figure 1 shows a vertical cut of the temporal evolution of the summer storm (so-called Time Height Indicator, THI) at a "specific site close to" the LSN rain gauge as seen by the Dole radar at ~42 km range: each rectangular cell represents a polar volume of approximately 750×750×83.3 m (elevation, azimuth, range resolution) sampled every 5 minutes. Hence, twelve radar observations per hour are recorded and displayed. The time scale, which ranges from 20 to 22 UTC, is shown on the abscissa: each black vertical line is every 15 minutes. The altitude above sea level is shown on the ordinate (black horizontal line every 1km), which spans from 1.5 to 10.5 km. Twelve acquisitions at 12 different angles of elevation are shown on the ordinate: the interleaved nature of the Swiss scan program (see e.g., the Figure at page 45 in Germann et al., 2015). Consecutive odd (and even) lines are, in fact, more correlated simply because they are closest in time. The "semi-quantitative" color palette is related to the intensity of the polarimetric radar observables.

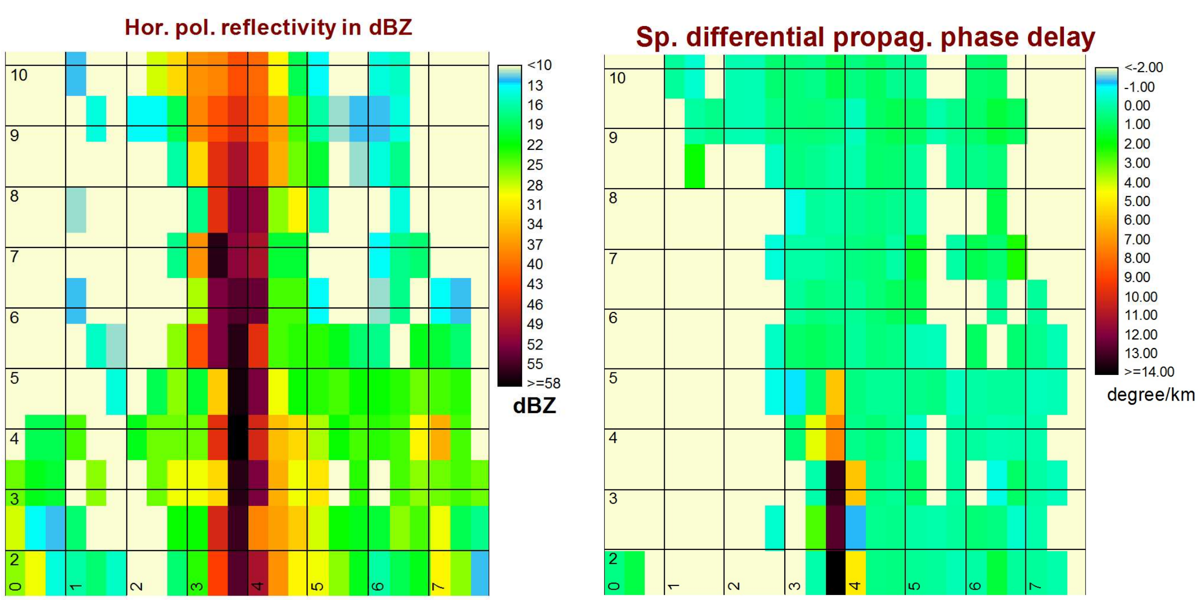

Figure 1: Time Height Indicator (THI) of radar reflectivity in dBZ (left picture) and specific differential propagation phase delay in degree per km (right picture) in correspondence of the LSN rain gauge. The temporal scale on the abscissa spans two hours (24 radar samples, one every 5 minutes; black vertical lines every 15 minutes).

Why to look at a "specific site close to" the gauge but not exactly above it? Because this is the place where we presume most of the rain drops aloft have subsequently reached the LSN gauge. During this windy event, in fact, the horizontal velocity of rain drops can be even (much) larger than the vertical terminal fall velocity of the drops themselves (e.g., ~4 m/s for a 1 mm drop). Hence most of the drops subsequently reaching (21:00-21:10 UTC) the gauge are probably located above this site at the twelfth time frame (20:55-21:00 UTC, that is just before the vertical line #4) at altitudes (depending on the size of such drops) between 1.5 and 4.25 km.

The left picture shows the Log-transformed value of the radar reflectivity, Z, which ranges over a bit more than six orders of magnitude. At the twelfth time frame (just before 21 UTC) the reflectivity of the four lowest radar sampling volumes (~50×10^6 m^3) is 59, 56, 55 and 54 dBZ, respectively (from top to bottom, dark red). If most of precipitating hydrometeors in the radar backscattering volume were spherical raindrops (not true in this case!) and the drop size distributions (DSD) could be described by an exponential DSD, then a simple power-law would relate Z to the instantaneous rain rate, R. The first ever exponential DSD presented in a peer-reviewed paper and probably the most quoted is the Marshall-Palmer distribution. The power law derived using the exponential fit proposed in Eq. (1) and (3) of the famous paper by Marshall and Palmer (1948) is $Z=296\times R^{1.47}$. This would mean 216, 134, 115 and 98 mm/h respectively (neglecting attenuation and the presence of hail). The LSN gauge has measured the amazing values of 23.7 mm between 21:00 and 21:05 and 17.2 mm five minutes later; this corresponds to an equivalent hourly rain rate of 284.4 and 206.4 mm/h.

The right picture shows the values of the specific differential propagation phase delay, K_{dp}, which represents a much better radar-derived estimator of the instantaneous rain rate in such extreme conditions (deep convection). Except in heavy rain, it is relatively small and difficult to be estimated accurately given that it is a derivative (in range) of a difference (in polarization). It is, in fact, defined as the one-way increase of the differential propagation phase between the radar and the observed target and is typically expressed in degree/km. Just before 21 UTC, two (near-in-time) K_{dp} values are as large as 13 and 14! degree/km. As it can be seen in the companion extended abstract by Wolfensberger et al. (UrbanRain18), the K_{dp}-R conversion should be implemented not using the ordinary Swiss power law but rather the extraordinary "tropical rain" power law. Indeed, the fact that such polarimetric radar signatures aloft a few minutes before 21 UTC subsequently resulted in approximately twenty litres per square meter at the ground, is an indirect confirmation of its "rare tropical nature".

6. Conclusions

A large Swiss data set evaluation here presented shows that the agreement between non-conventional hourly precipitation estimates and in situ measurements has in general improved remarkably in recent years. As far as extreme events are concerned, e.g. the one that hit the urban area of Lausanne on June 11, how to tackle the emerging need for improved low-altitude coverage and high temporal resolution weather radars? A possible remedy is represented by portable, low-range, small, X-band radar with adaptive scan program integrated in an operational thunderstorm tracking context and tailored to the monitoring of individual cell (e.g., Grazioli et al., 2018).

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