Improving the precipitation accumulation analysis using lightning measurements and different integration periods

E. Gregow[1], A. Pessi[2], A. Mäkelä[1] and E. Saltikoff[1]

[1]Finnish Meteorological Institute, P.O. Box 503, FIN-00101 Helsinki, Finland

[2]Vaisala, 3 Lan Dr., Westford, MA 01886, USA

Correspondence to: E. Gregow (erik.gregow@fmi.fi)

Abstract. The focus of this article is to improve the precipitation accumulation analysis, with special focus on the intense precipitation events. Two main objectives are addressed: (i) the assimilation of lightning observations together with radar and gauge measurements and (ii) the analysis of the impact of different integration periods in the radar-gauge correction method. The article is a continuation of previous work in the same research-field, by Gregow et al. (2013).

A new Lightning Data Assimilation (LDA) method has been implemented and validated within the Finnish Meteorological Institute (FMI) - Local Analysis and Prediction System (LAPS). Lightning data does improve the analysis when no radar is available, and even with radar, lightnings have a neutral to positive impact on the results.

The radar-gauge assimilation method is highly dependent on statistical relationships between radar and gauges, when performing the correction to precipitation accumulation field. Here we investigate the usage of different time integration intervals: 1, 6, 12, 24 hours and 7 days. This will change the amount of data used and affect the statistical calculation of the radar-gauge relations. Verification shows that the real-time analysis using the 1 hour integration time length gives the best result.

1 Introduction

Accurate estimates of accumulated precipitation are needed for several applications, such as flood protection, hydropower, road- and fire-weather models. In Finland, one of the economically most relevant users of precipitation is hydropower industry. Between 10 and 20% of Finnish annual electric power production comes from hydropower, depending on the amount of precipitation and water levels in dams and water reservoirs. In order to maintain correct calculation of the energy supplied to customers and to avoid (or at least minimize) the environmental risks and economical losses during extreme precipitation and flooding events, a profound analysis of the expected water amounts in dams and reservoirs from catchment-areas is needed. The current hydropower strategy of Finland is to increase capacity by improving the efficiency of existing plants through technical adjustments. The maintenance and planning of proper dam structures need the most up-to-date information about the rain rates to be able to adjust the regulation functions of the dams, both for the current and the changing climatic conditions (IPCC-AR5, 2013).

Often, the accumulated precipitation values are based on pure radar analysis, unless there exists a surface gauge observation in the immediate surroundings. Radar echoes are related to rainfall rate and thereafter transformed into accumulation values. However, such conversions are based on general empirical relations, which are not suitable for all meteorological cases (e.g. depending on precipitation type; Koistinen and Michelson, 2002). Radar reflectivity can in some cases suffer from poor quality, resulting from electronic mis-calibration, beam blocking, clutter, attenuation and overhanging precipitation (Saltikoff et al., 2010). In some cases the radar can even be missing, due to upgrading or technical problems. Thunderstorms add probability of many of these problems in form of interruptions in electicity and telecommunications, and attenuation due to intervening heavy precipitation. In general, combining radar and rain gauge data is very difficult in the vicinity of heavy, local rain cells (Einfalt et al., 2005).

The research of combining radar and surface observations, to perform corrections to precipitation accumulation, is well explored. Many have made developments in this field and much literature is available, for example Sideris et al. (2014), Schiemann et al. (2011) and Goudenhoofdt and Delobbe (2009). Recently, Jewell and Gaussiat (2015) compared performances of different merging schemas, and noted a large difference between convective and stratiform situations. In their study, the non-parametric kriging with external drift (KEDn)

outperformed other methods in accumulation period of 60 minutes. Wang et al (2015) developed a sophisticated method for urban hydrology, which preserves the non-normal charactersitics of the precipitation field. They also noticed that common methods have a tendency to smooth out the important but spatially limited extremes of precipitation.

Comparing radars and gauges, an additional challenge arises from the different sampling sizes of the instruments. Radar measurement volume can be several kilometers wide and thick (one degree beam is approximately 5 kilometres wide at 250 kilometres), while the measurement area of a gauge is 400 cm^2 (weighing gauges) or 100 cm^3 (optical instruments). Part of the disparateness of radar and gauge measurements is due to variability of the raindrop size distribution within area of a single radar pixel. Jaffrain and Berne (2012) have observed variability up to 15% of the rainrate in a 1x1 km pixel, with timesteps of 1 minute. Gires et al (2014) have shown that the scale difference has an effect in verification measures (such as normalized bias, e.g. RMSE) but it decreases with growing accumulation time (e.g. from 5 to 60 minutes). In our study, the 60 minutes accumulation period is smoothing some of the differences.

Lightning is associated with convective precipitation, but in areas where a large portion of precipitation is stratiform, lightning data alone is not adequate for precipitation estimation. However, lightning has been used to complement and improve other datasets. Morales and Agnastou (2003) combined lightning with satellite-based measurements to distinguish between convective and stratiform precipitation area and achieved a remarkable 31% bias reduction, compared to satellite-only techniques. Lightning has also been assimilated to numerical weather prediction models to improve the initialization process of the model. This can be done by blending them with other remote sensing data to create heating profiles (e.g. estimating the latent heat release when precipitation is condensed). Papadopulos et al. (2005) used lightning data to identify convective areas and then modified the model humidity profiles, allowing the model to produce convection and release latent heat using its own convective parameterization scheme. They combined lightning with 6-hourly gauge data, within a mesoscale model in the Mediterraiean area, and showed improvement in forecasts up to 12 hours lead time.

Our situation is different from the above mentioned experiments because lightning activity is usually low in Finland, compared to warmer climates (Mäkelä et al., 2011). Also, our analysis area already has a good radar coverage and relatively evenly distributed network of 1 hour

gauge measurements. However, if we want to enlarge the analysis area, we will soon go to either sea areas or neighbouring countries where availability of radar data and frequent gauge measurements is low. Our principal goal is to have as good analysis as possible, which is different from having a best analysis to start a model.

Gregow et al. (2013) has proven that there is a benefit of assimilating various sources of data to estimate the precipitation accumulation (e.g. combining radar and gauge data via the Regression and Barnes method). It was also shown, that the largest uncertainties took place during heavy rainfall (i.e. convective weather situations), situations when lightning is likely to take place. To improve the precipitation analysis new methods are adopted to enable estimation of accumulated precipitation in a spatially precise and timely manner (i.e. near real-time). This is done by using weather radar, lightning observations and rain gauge information in novel ways. This leads to better possibilities in estimating extreme rainfall events (i.e. > 5 mm/h) and the accumulated precipitation, for the benefit of hydropower management and other related application areas. The work reported here has been performed using the operational Local Analysis and Prediction System (LAPS), which is used in the wether service of Finnish Meteorological Institute (FMI). Testing new approaches in an operational system has its limitations in e.g. excluding independent reference stations. Also the possibilities to rerun cases with different settings have been limited. The benefit of the approach is that we can be sure that we only use data which is operationally available.

In this article the observational datasets are described in chapter 2. New methods on how to calculate the precipitation accumulation is handled in chapter 3, and the results and discussion are shown in chapters 4 and 5, respectively.

2 Observations and instrumentation

Here we describe the three data sources employed in this study: rain gauge observations, radar and lightning observations.

2.1 Rain gauge observations

Rain gauges provide point observations of the accumulation. They are usually considered more accurate than radar, as point values, and are frequently used to correct the radar field

(Wilson and Brandes, 1979). The surface precipitation network (in total 472 stations) consists of standard weighting gauges and optical sensors mounted on road-weather masts. Since 2015, FMI manages 102 stations instrumented with the weighting gauge OTT Messtechnik Pluvio2. The Finnish Transport Agency (FTA) runs 370 road-weather stations with optical sensor measurements (Vaisala Present Weather Detectors models PWD22 and, to some extent, PWD11). The precipitation intensity is measured in different time intervals which are summed up to 1 hour precipitation accumulation information. Uncertainties and more detailed information can be found in Gregow et al. (2013). If measurements consistently indicate poor data quality, either manually identified from station error-logs or by inspecting the data, those stations are blacklisted within the LAPS process and do not contribute to the precipitation accumulation analysis. Hereafter in this article, the weighting gauges and road-weather measurements are indistinctly called gauges and their placement in Finland is shown in Fig. 1a.

2.2 The radar data

As of summer 2014, FMI operated eight C-band Doppler radars (two more were added to the network late 2014 and autumn 2015). All but one in Vimpeli (western Finland; see Fig. 1b) are dual-polarization radars. At the moment, the quantitative precipitation estimation based on dual-polarization is not used operationally in FMI, but the polarimetric properties contribute to the improved clutter cancellation (i.e. removal of non-meteorological echoes, especially sea clutter, birds and insects). In southern Finland, the distance between radars is 140–200 km, but in the north, the distance between Luosto and Utajärvi is 260 km. The location of the radars and the coverage is shown in Fig. 1b. As Finland has no high mountains, the horizon of all the radars is near zero elevation with no major beam blockage, and, in general, the radar coverage is very good except in the most northern part of the country. The Finnish radar network does have a very high system utilization rate (e.g. no interruption). During year 2014 and 2015 the utilization rate was > 99%. Further details of the FMI radar network and processing routines are described in Saltikoff et al. (2010).

The basic radar volume scan consists of thirteen PPI sweeps. The FMI operated LAPS version (hereafter FMI-LAPS) is using the six lowest elevations: 0.3 (alternative 0.1 or 0.5 depending on site location), 0.7, 1.5, 3.0, 5.0 and 9.0, which are scanned out to 250 km, and repeated

every 5 minutes. These radar volume scans are further used in LAPS routines for the rain-rate calculations but also, as proxy data to the LDA method (see Sect. 3.2).

2.3 The Lightning Location System (LLS)

The Lightning Location System (LLS) of FMI is part of the Nordic Lightning Information System (NORDLIS). The system detects cloud-to-ground (CG) and intracloud (IC) strokes in the low-frequency (LF) domain. Finland is situated between 60–70°N and 19–32°E and thunderstorm season begins usually in May and lasts until September. During the period 1960–2007, on average, 140'000 ground flashes occurred during approximately 100 days per year (Tuomi and Mäkelä, 2008). The present modern lightning location system (LLS) was installed in summer 1997 (Tuomi and Mäkelä, 2007; Mäkelä et al., 2010; Mäkelä et al., 2016). The system consists of Vaisala Inc. sensors of various generations, and the sensor locations in 2015 and the efficient network coverage area can be seen in Fig. 2. Lightning location sensors detect the electromagnetic (EM) signals emitted by lightning return strokes, measure the signal azimuth and exact time (GPS). Sensors send these information to the central processing computer in real time which combines them, optimises the most probable strike point and outputs this information to the end user. More detailed information of LLS principles are described in Cummins et al. (1998). The lightning information used for the LAPS LDA-method is the location data (e.g. time, longitude and latitude) for each CG lightning stroke.

3 Methods

The systems used to assimilate radar, gauge and lightning measurements are described in Sect. 3.1-3.2. The impact of different integration time periods on the Regression and Barnes (RandB)-method is shown in Sect. 3.3 and, finally, the verification methods in Sect. 3.4.

3.1 The Local Analysis and Prediction System (LAPS)

The LAPS produces 3D analysis fields of several different weather parameters (Albers et al., 1996). LAPS uses statistical methods to perform a high-resolution spatial analysis where observational input, from several sources, are fitted to a coarser background model first-guess

field (e.g. ECMWF forecast model). Additionally, high resolution topographical data are used when creating the final analysis fields. The FMI-LAPS products are mainly used for now-casting purposes (i.e. what is currently happening and what will happen in the next few hours), which is of critical interest for end-users who demand near real-time products.

The FMI-LAPS use a pressure coordinate system including 44 vertical levels distributed with a higher resolution (e.g. 10 hPa) at lower altitudes and decreasing with height. The horizontal resolution is 3 kilometres and the temporal resolution is 1 hour. The domain used in this article covers the whole Finland and some parts of the neighbouring countries (Fig. 1b). LAPS highly relies on the existence of high-resolution observational network, in both space and time, and especially on remote sensing data. The FMI-LAPS is able to process several types of in-situ and remotely sensed observations (Koskinen et al., 2011), among which radar reflectivity, weighting gauges and road weather observations are used for calculating the precipitation accumulation. The Finnish radar volume scans are read into LAPS as NetCDF format files, thereafter the data is remapped to LAPS internal Cartesian grid and the mosaic process combines data of the different radar stations (Albers et al., 1996). The rain-rates are calculated from the lowest levels of the LAPS 3D radar mosaic data, via the standard Z-R formula (Marshall and Palmer, 1948), which is then used for precipitation accumulation calculations (see Sect. 3.2). Other information on observational usage, first-guess fields, the coordinate system etc. is described in Gregow et al. (2013).

In this study the lightning data are ingested into the FMI-LAPS. Modifications have been made to the software, in order to use it together with FMI operational radar input data and the new lightning algoritms.

3.2 The LAPS Lightning Data Assimilation (LDA) method

A Lightning Data Assimilation (hereafter LDA) system has been developed by Vaisala and distributed as open and free software (Pessi and Albers, 2014). The LDA-method is constructed to build up statistical relationships between radar and lightning measurements. LDA counts the amount of CG lightning strokes and converts lightning rates into vertical radar reflectivity profiles, within each LAPS grid-cell. The radar reflectivity-lightning (hereafter Rad-Lig) relationship profiles may differ depending on the local geographical regime and climate. A set of default profiles are included within the LDA package, profiles

that were derived over the eastern United States with the use of radar data from NEXRAD network and lightning data from GLD360 network (Pessi, 2013 and Said et al., 2010). These profiles can be used as a first guess, if profiles for the local climate are not available.

For this study over Finland, climatological Rad-Lig reflectivity relationship profiles were estimated using NORDLIS-LLS lightning information and operational radar volume data from Finland area, during summer 2014. A total of approximately 220'000 lightning strokes were used for this calibration. The FMI-LAPS LDA is using 5 minutes interval of lightning- and radar data, within a LAPS grid-box of resolution 3*3 km. The collected strokes are divided into binned categories using an exponential division (i.e. $2^n...2^{n+1}$), following the same method used in Pessi (2013). This result in 6 different lightning categories (e.g. with 1, 2-3, 4-7, 8-15, 16-31 and 32-63 strokes) for the NORDLIS-LLS dataset. For each of these 6 categories, the average radar reflectivity profile is calculated and gives the Average Rad-Lig profiles (Fig. 3a), which is the baseline method. We extend this method to also calculate the 3'rd Quartile (i.e. 75%-percentile) and a Variable Quartile Rad-Lig profiles. The Variable Quartile method uses a range between 50%-percentile (for the lower dBZ values) up to the 95%-percentile (for the highest dBZ values). The Rad-Lig profiles have been manually smoothed (i.e. removing peaks in the generated profiles), especially the highest profiles where there are less data available. There is a good correlation (R^2=0.95) between the maximum reflectivity of profile and number of lightning strokes (Fig. 3b; results shown for the Average Rad-Lig profiles).

The Rad-Lig reflectivity profiles can be used either independently, or merged with the radar data, in the LAPS accumulation analysis. When merging the two sources, radar and lightning reflectivity values are compared at each grid-point, both horizontally and vertically. The data source giving the highest reflectivity value will be used in that LAPS grid-point. The logic behind this is that the radars are more likely to underestimate, than overestimate the precipitation (due to attenuation, beam blocking or the nearest radar missing from network; e.g. Battan, 1973 and Germann, 1999), especially in thunderstorm situations. LAPS then uses the generated 3D volume reflectivity field in a similar manner as it would use the regular volume radar data, for example, to adjust hydrometeor fields and rainfall.

The reflectivity (Z) parameter measured by the radar, or estimated by LDA-method, is converted to precipitation intensity (R; mm/h) within LAPS, using a pre-selected Z-R equation (Marshall and Palmer, 1948) as of the type:

$$Z = A \cdot R^b \quad (3)$$

Where A and b are empirical factors describing the shape and size distribution of the hydrometeors. In FMI-LAPS's implementation A=315 and b=1.5 for liquid precipitation, which is relevant in this study carried out during summer period. These static values introduce a gross simplification, since the drop size and particle shapes vary according to weather situation (drizzle/convective, wet snow/snow grain). Challenging situations include both convective showers, with heavy rainfall, and the opposite case of drizzle, with little precipitation (Uijlenhoet, 2008). Although convective events contribute only a fraction of the annual precipitation amount, they might be important during flooding events. On the other hand, the same static factors have been used for many years in FMI's other operational radar products, and looking at long-term averages, the radar accumulation data does match the gauge accumulation values within reasonable accuracy (Aaltonen et al., 2008). The intensity field (R; Eq. 3) is calculated at every 5 minutes and the 1 hour accumulation is thereafter obtained by summing up over the 5 minutes intervals.

The following FMI-LAPS precipitation accumulation products are calculated based on Radar- (hereafter Rad_Accum), LDA- (hereafter LDA_Accum) and the combined radar and LDA- (hereafter Rad_LDA_Accum) precipitation accumulation.

3.3 The FMI-LAPS Regression and Barnes (RandB) analysis method

The FMI-LAPS RandB-method corrects the precipitation accumulation estimates using radar and gauges datasets. The first step in this method is to make the radar-gauge correction using the Regression method. Data of hourly accumulation values are derived from the gauge-radar pairs within the LAPS grid (i.e. from same location and time), and from this a linear regression function can be established. The corrections from Regression method is applied to the whole radar accumulation field and thereafter used as input for the second step, the Barnes analysis. Within LAPS routines the Barnes interpolation converge the radar field towards gauge accumulation measurements at smaller areas (i.e. for gauge station surroundings). Several iterative correction steps are performed within the Barnes analysis, adjusting the final accumuation. The FMI-LAPS RandB-method is described in more details in Gregow et al. (2013).

In this article, the RandB-method is used to calculate the precipitation accumulation with the use of radar, ligthning and the combination of radar-lightning. This gives the additional three FMI-LAPS accmulation products: Rad_RandB, LDA_RandB and Rad_LDA_RandB, respectively.

3.3.1 RandB-method and the integration time period

The original FMI-LAPS RandB-method uses radar and gauge data from the recent hour. Using only the latest hour, the gauge observational dataset can suffer from too few observations and thereby affect to the quality and robustness of the Regression- and Barnes calculations. As a further investigation in this article we use a selection of longer time periods (e.g. the previous 6, 12, 24 hours and 7 days of data) in order to build up a larger radar-gauge dataset. These datasets are thereafter used to make the correction within the RandB-method.

We have limited our studies to compare how the occurring synoptic weather situation, i.e. frontal or convective situation (1 to 12 hours), and the medium time-range information (24 hours to 7 days) impact on the accumulation analysis. The longer integration time, the less information on the situational weather occurring at analysis time, i.e. the dataset is getting more smoothed and extremes might disappear.

Verification was done for the summer period 2015, using the input from radar and lightning, and gives the following resulting accumulation products: Rad_LDA_RandB (i.e. dataset collected within the last 1 hour), Rad_LDA_RandB_6hr, Rad_LDA_RandB_12hr, Rad_LDA_RandB_24hr and Rad_LDA_RandB_7d, respectively.

3.4 Verification methods

The verification periods consists of one long period ranging from 1 April to 1 September, 2015 (i.e. to avoid the winter season and snow precipitation). This dataset includes many precipitating cases without lightning and therefore, the effective impact by lightning is diluted (e.g. no influence by the LDA-method). Therefore, a subset of 25 days with frequent lightning (e.g. > 100 CG strokes/day) were selected from summer 2015. Additionally, in order to perform several autonomous experiments with the FMI-LAPS LDA system, a dataset consisting of four days with heavy rain and strong convection were used: 03, 23, 24 and 30 of

July 2014 (hereafter 4-days period). These were the 4 days with highest lightning intensity (e.g. > 100 strokes/day) in Finland, during year 2014.

The hourly accumuation results have been verified against surface gauge observations, both dependent and independent stations. The dependent station data are included into the FMI-LAPS analysis calculating the 1 hour precipitation accumulation, i.e. the analysis is depending on the station information used as input. There are 7 independent stations which are excluded from the LAPS analysis. In this study we apply a filter to the verification datasets, where hourly accumulation data less than 0.3 mm are discarded (due to the lowest threshold value of surface gauge measurements from FMI real-time database).

The validation of the different analysis methods are based on the logarithmic standard deviation (STDEV; Eq. 4), root-mean-square deviation (RMSE; Eq. 5), and Pearson's correlation coefficient (CORR; Eq. 6):

$$STDEV = \frac{1}{N-1}\sum_{i=1}^{N}\left(\log\left(\frac{Analysis}{Gauge}\right)_i - \overline{\log\left(\frac{Analysis}{Gauge}\right)}\right)^2 \quad (4)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}\left|\left(Analysis - Gauge\right)_i\right|^2}{N-1}} \quad (5)$$

$$CORR = \frac{\sum_i \left|\left(Gauge_i - \overline{Gauge}\right)\left(Analysis_i - \overline{Analysis}\right)\right|}{\sqrt{\sum_i \left(Gauge_i - \overline{Gauge}\right)^2 \sum_i \left(Analysis_i - \overline{Analysis}\right)^2}} \quad (6)$$

STDEV quantifies the amount of variation (i.e. spread) of a dataset. A low STDEV indicates that the data points tend to be close to the mean value of the dataset. Here we use the logarithm of the quotients, in order to get the datasets closer to be normally distributed. RMSE is a quadratic scoring rule, which measures the average magnitude of the error. Since the errors are squared before they are averaged, RMSE gives a relatively high weight to large errors. CORR gives a measure of the linear relationship (both strength and direction) between two quantities.

4 Results and verification

Results using lightning data is presented in Sect. 4.1 and the impact from different integration time intervals in Sect. 4.2.

4.1 FMI-LAPS LDA results

A slight improvement in the accumulation analysis, using lightning information, can be seen in the RMSE from the 25 days dataset of frequent thunderstorms (Table 1; compare Rad_Accum and Rad_LDA_Accum). The effect is only visible when comparing with the dependent gauges, as no thunderstorms occurred at the seven independent stations. When the verification period is extended to the entire summer of 2015 (i.e. including days with no thunderstorms) the independent stations show some improvement (Table 2). The correlation (i.e. CORR) is higher for the Rad_LDA_Accum independent data (compared to Rad_Accum), and even though the RMSE is higher, the STDEV has been improved. The overall impact for the dependent stations is neutral (Table 2 and Fig. 4; compare Rad_Accum and Rad_LDA_Accum). For both the 25 days and whole summer period the Rad_RandB and Rad_LDA_RandB give the best results, with similar scores.

Comparing the accumulation results from the 4-days period for radar alone (i.e. Rad_Accum; black markers in Fig. 5) and lightning alone (i.e. LDA_Accum; red markers in Fig. 5), it is clear that the use of LDA_Accum is less accurate than Radar_Accum results. Figure 5 also show that the Rad_LDA_Accum estimates (using the baseline method, with Average Rad-Lig profiles) are amplified over the whole range of precipitation values, compared to Rad_Accum (Fig. 5; compare the blue with the black markers). For the high accumulation values (> 5 mm/h) this is a positive effect, while in lower range (< 5 mm/h) there is an overestimation of the results. Note that the plot uses log-scale at each axis.

Figure 6 show the results using different Rad-Lig profiles, i.e. Average-, 3'rd Quartile- and Variable Quartile profiles. The results are validated against Rad_Accum. The precipitation accumulation estimates are improved at high accumulation values (> 5 mm), using either 3'rd- or Variable Quartile profiles. Simultaneously, they both does add to the overestimate in low accumulation values (< 5 mm). Note the use of log-scale, which enlarges the differences in the range of low values and reduces it in high ranges. The 3'rd Quartile profiles gives the largest overestimate, over the whole accumulation scale.

4.2 RandB-method and impact from different integration periods

The plotted results of different time sampling periods are seen in Fig. 7, with verification against the independent stations. The Rad_LDA_RandB (i.e. using observations from the latest 1 hour) does give the best result, when compared to Rad_LDA_Accum, Rad_LDA_RandB, Rad_LDA_RandB_6hr, Rad_LDA_RandB_12hr, Rad_LDA_RandB_24hr and the Rad_LDA_RandB_7d output. The statistical scores shown in Table 3 also imply the same result. Note that Rad_LDA_Accum (e.g. a method not using RandB, as an reference) is included when comparing the results of different integration periods.

Discussions and conclusions

The aim of this article is to describe new methods on how to improve the hourly precipitation accumulation estimates, especially for heavy rainfall events (> 5 mm) and, if possible, also the low-valued ranges (< 5 mm) or at least leave them as unaffected as possible.

The strength of the LDA-method is that the radar and lightning information can be merged and complement each other. This is especially important in areas of poor, or even none, radar coverage, where the lightning information will improve the hourly precipitation accumulation analysis. The results in this article are limited to Finland but considering extending this area to include Scandinavia, the LDA-method will become even more useful. The long verification period (i.e. summer 2015) had fewer days of lighting compared to other years (on average) and therefore, the verification dataset was limited. Nevertheless, the summer period and the subset of 25 lighting instense days show neutral to positive impact in the reuslts, using the LDA-method (Table 1-2 and Fig. 4). One reason we don't see larger impact by LDA-method could be that the Finnish radar network does have a very high quality and system utalization rate and therefore less impacted by the LDA-method.

The accumulation products generated from RandB-method are corrected using gauge information. This process is influencing the final accumulation results much more than the contribution from the LDA-method (seen in Fig. 4 results from dependent dataset, where a, c and b, d panels, respectively, are almost identical). The same result was seen for the independent dataset. Even though, we have proven that in case there would be no radar data (for example if the radar is malfunctioning), precipitation accmulation information would be available from lightning data (i.e. through the LDA-method) and add value to the final

product. This is visualized through the example in Fig. 8, where the radar- and Rad-Lig lowest reflectivity fields are plotted for one analysis time: 16 UTC, 30 July 2014, and for which, accumulation would be generated from the LDA-method. In the RandB-method the Regression is used to correct for large-scale multiplicative biases between radar and gauge data. In this article we introduce lightning into the RandB-method, as an additional data source. However, lightning errors are likely to be different from those of radar and gauges and this could have an effect on the methodology used here. In future developments, after collecting longer time series to quantify the nature of uncertainty of lightning-based precipitation estimates, we intend to improve the analysis in this direction.

New methods to calculate the Rad-Lig profiles reveal that the Variable Quartile method improve the estimates for the large accumulation (i.e. > 5 mm), though with some overestimation in low accumulation (Fig. 6). The 3'rd Quartile approach gives the highest impact to the whole accumulation field, which results in large overestimates for the low accumulation values (i.e. between 0-5 mm). The Average method smoothens out the small-scale variances, which is observed in heavy convection. Hence, the collected radar reflectivity profiles are less representative and, therefore, the calculated Rad-Lig profiles will have too low values in these cases. As a result, the Average method will give low impact to the final precipitation accumulation estimates, compared to the use of 3'rd Quartile- and Variable Quartile method (Fig. 6). One should also mention that there is an overall uncertainty due to instrumental errors and the collocation between observations, within the LDA-method. This could potentially result in dislocation and bad quality of the received radar- and lightning measurements, which would affect to the calculated Rad-Lig profiles. For example in case of radar attenuation, where strong rainfall weakens some part of the reflectivity field. Here the collected radar profiles will have too low reflectivity values and give underestimated Rad-Lig profiles, especially when using the Average method. In upcoming version of FMI-LAPS the calculated Rad-Lig profiles, using Variable Quartile method, will be implemented and verified for a long period. Also, for verification purposes, inclusion of areas with poor (or none) radar coverage where gauges are available, will be studied.

For the near real-time accumulation product, data used from the recent hour of analysis time does give the best precipitation accumulation result (Table 3 and Fig. 7). We see correlation peeking at 1 hour integration period and decreasing already for the 6 hours period. Therefore, according to the result in this study, the use of long time integration periods for the RandB-

method (up till 7 days in this case) does not improve the hourly precipitation accumulation analysis. Berndt et al (2014) compared data resolutions from 10 minutes to 6 hours and reported a large improvement in the correlation (10 minutes to 1 hour the correlation increased 0.37 to 0.57). From 1 hour to 6 hours the corresponding increase was 0.57 to 0.62, respectively. In Norway, Abdella and Alfredsen (2010) have shown that the use of average monthly adjustment factors leads to less than optimal results. One could speculate that there is an intermediate choice of temporal resolution that would improve the results in this article. For example, there could be better results using periods of 2 to 5 hours. This has not been investigated in this article but will be considered in future studies.

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Table 1. Precipitation accumulation results, using radar (Rad_Accum) and radar merged with lightning dat (Rad_LDA_Accum), together with and without RandB-method (Rad_RandB and Rad_LDA_RandB, respectively). Verification both for the dependent and independent stations dataset, for a period of 25 intensive lightning days (e.g. > 100 CG strokes/day) during summer 2015.

	Rad_Accum	Rad_LDA_Accum	Rad_RandB	Rad_LDA_RandB
Dependent				
Nr of observations	3206	3332	3822	3823
STDEV (log(R/G))	0.27	0.27	0.12	0.12
RMSE	1.66	1.64	0.76	0.76
CORR	0.67	0.67	0.93	0.93
Independent				
Nr of observations	0	0	0	0

Table 2. Precipitation accumulation results, using radar (Rad_Accum) and radar merged with lightning dat (Rad_LDA_Accum), together with and without RandB-method (Rad_RandB and Rad_LDA_RandB, respectively). Verification was performed against both the dependent and independent stations datasets, for whole summer period 2015.

	Rad_Accum	Rad_LDA _Accum	Rad_RandB	Rad_LDA _ RandB
Dependent				
Nr of observations	14414	14420	17724	17725
STDEV (log(R/G))	0.25	0.25	0.13	0.13
RMSE	1.25	1.24	0.54	0.54
CORR	0.64	0.65	0.93	0.93
Independent				
Nr of observations	1694	1102	1402	1402
STDEV (log(R/G))	0.39	0.25	0.15	0.15
RMSE	1.28	1.44	0.69	0.71
CORR	0.71	0.72	0.92	0.92

Table 3. Impact of the integration time length on RandB-method, for the dependent and independent stations datasets, during summer 2015. Note that Rad_LDA_Accum (e.g. a method not using RandB, as an reference) is included when comparing the results of different integration periods.

	Rad_LDA_Accum	Rad_LDA_RandB_1hr	Rad_LDA_RandB_6hr	Rad_LDA_RandB_12hr	Rad_LDA_RandB_24hr	Rad_LDA_RandB_7d
Dependent						
Nr of observations	13200	16311	10956	10917	10915	11033
STDEV (log(R/G))	0.25	0.13	0.13	0.13	0.14	0.14
RMSE	1.20	0.52	0.67	0.71	0.72	0.72
CORR	0.64	0.93	0.91	0.90	0.89	0.89
Independent						
Nr of observations	1177	1492	1028	1013	1005	1014
STDEV (log(R/G))	0.25	0.15	0.22	0.22	0.22	0.22
RMSE	1.38	0.68	1.16	1.23	1.24	1.24
CORR	0.39	0.92	0.79	0.77	0.77	0.77

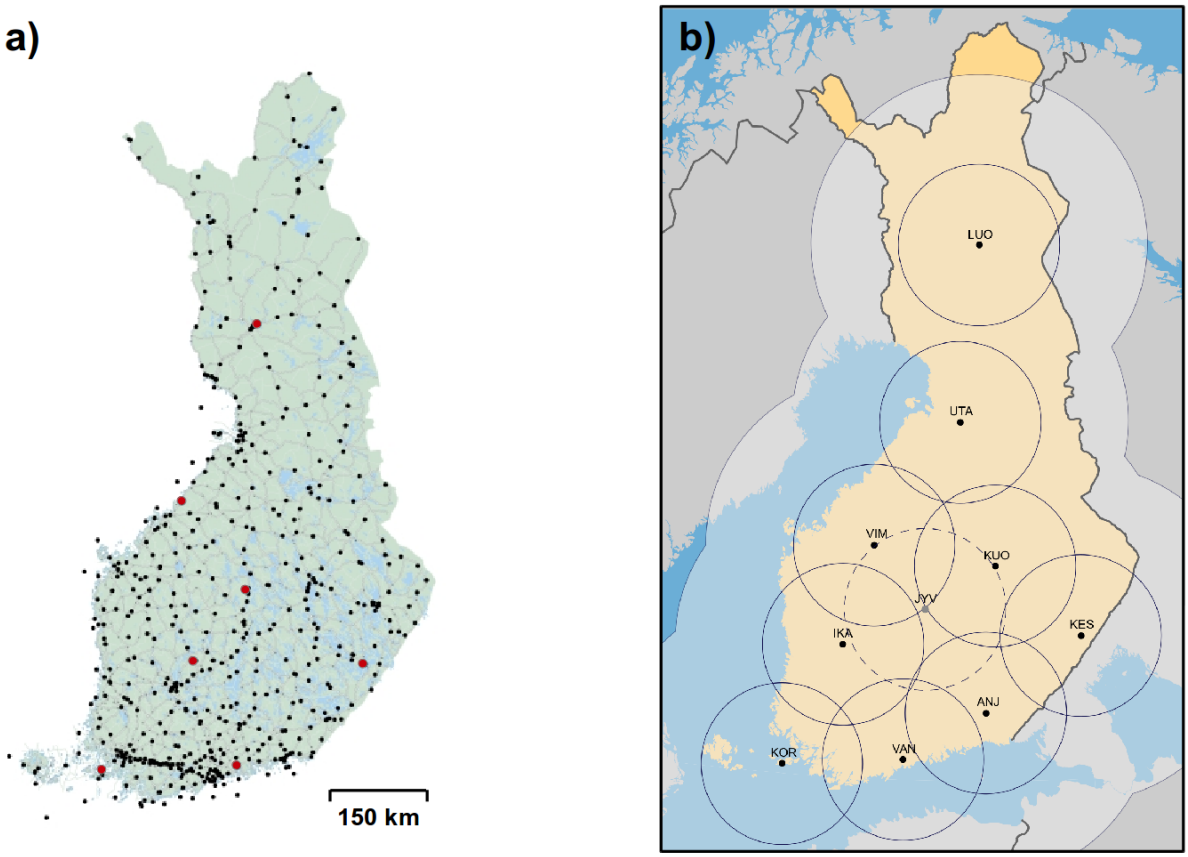

Figure 1. In (a) the Finnish surface gauge stations are shown (as dots on the map), these are used to measure the hourly precipitation accumulation. The red dots indicate the position of the 7 independent stations used for the verification. In (b) the outer rectangular frame of the map depicts the LAPS analysis domain. The black dots represent the 10 Finnish radar stations and the outer, black curved lines display their coverage. The thin circles surrounding each radar represent the areas where measurements are performed below 2 km height.

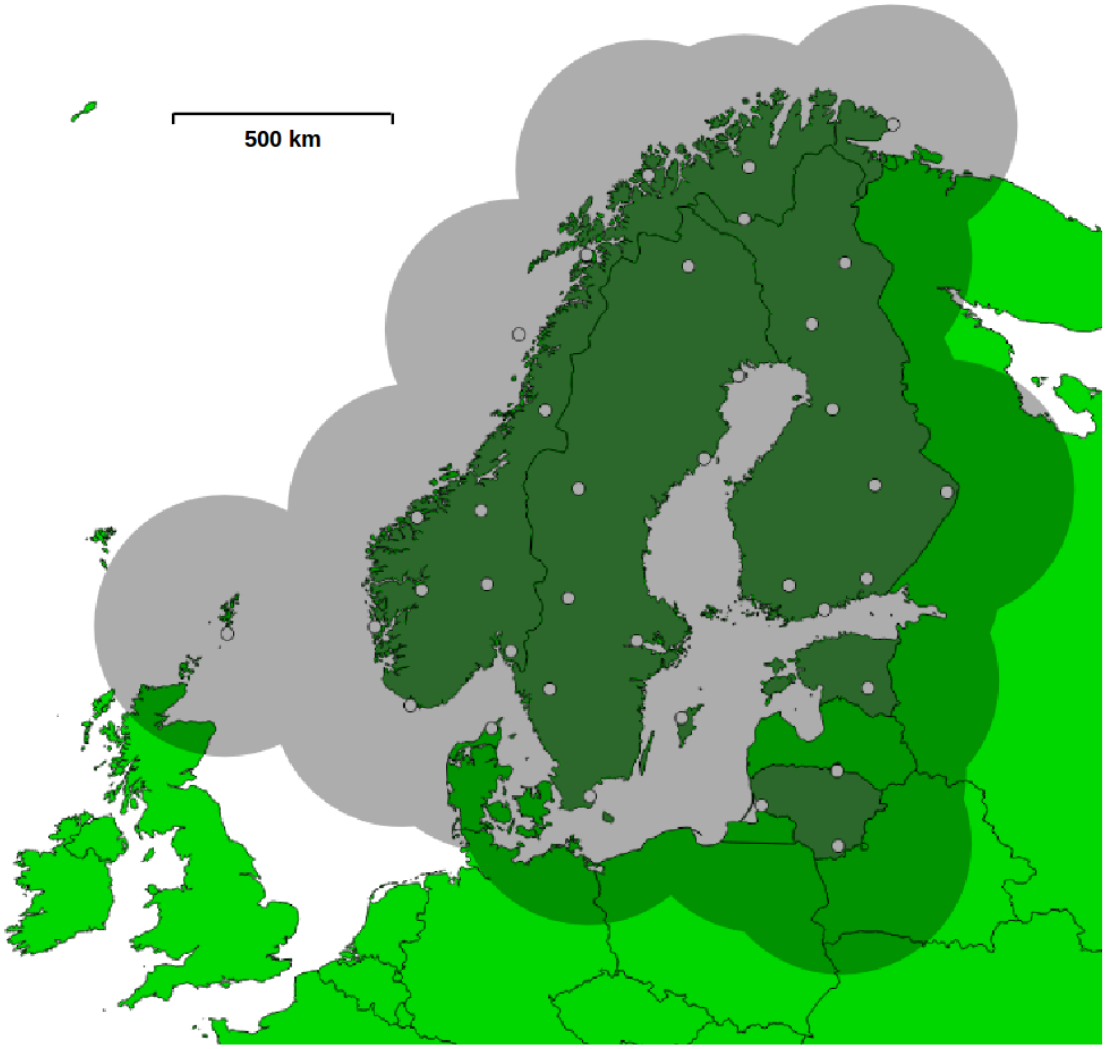

Figure 2. The LLS sensor locations (white dots) and coverage (grey circular areas), as of year 555 2015.

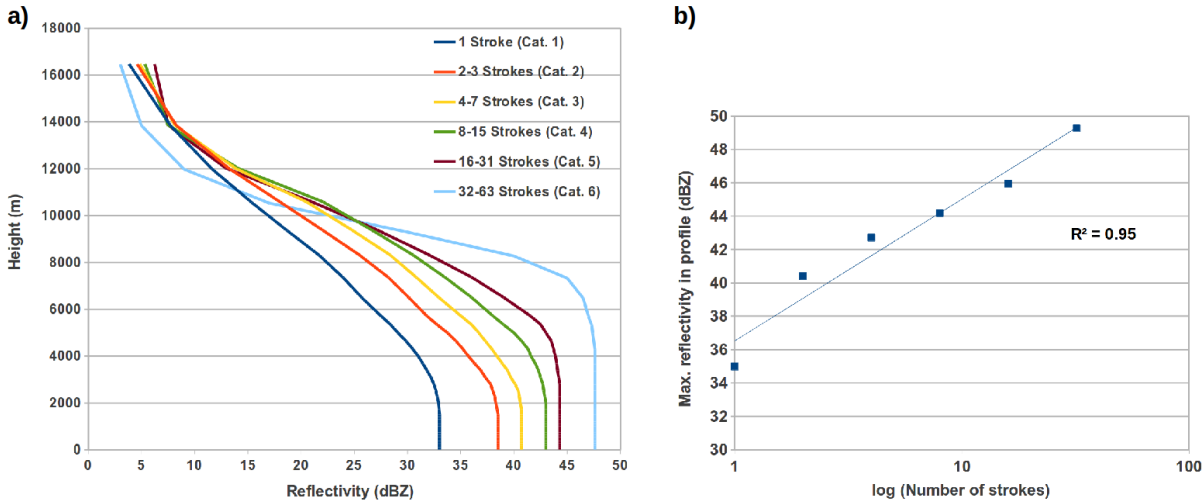

Figure 3. In a) Rad-Lig relationship profiles (smoothed) from Finland NORDLIS-LLS, calculated using dataset from summer 2014. Profiles are divided into binned categories of strokes, with temporal resolution of 5 minutes and spatial resolution of 3 km. In b) profile's max reflectivity values versus lightning rate (logarithmic-scale of bins).

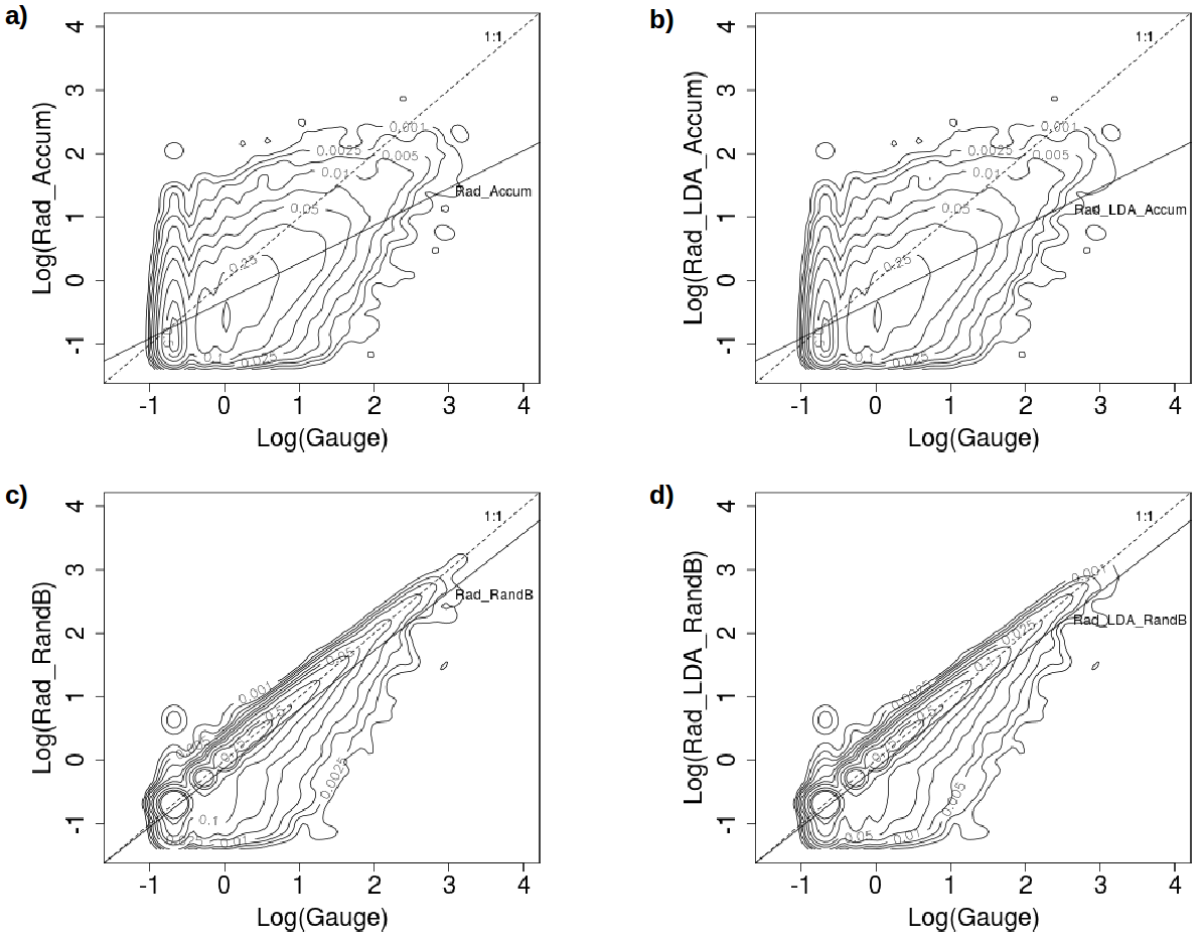

Figure 4. The FMI-LAPS precipitation accumulation (described in plots with density iso-lines of hourly accumulation values, in mm and log-scale) calculated using 4 different methods: a) Rad_Accum, b) Rad_LDA_Accum, c) Rad_RandB and in d) Rad_LDA_RandB. Results are from the dependent gauge dataset during summer 2015. Shown is also the best fit line (1:1).

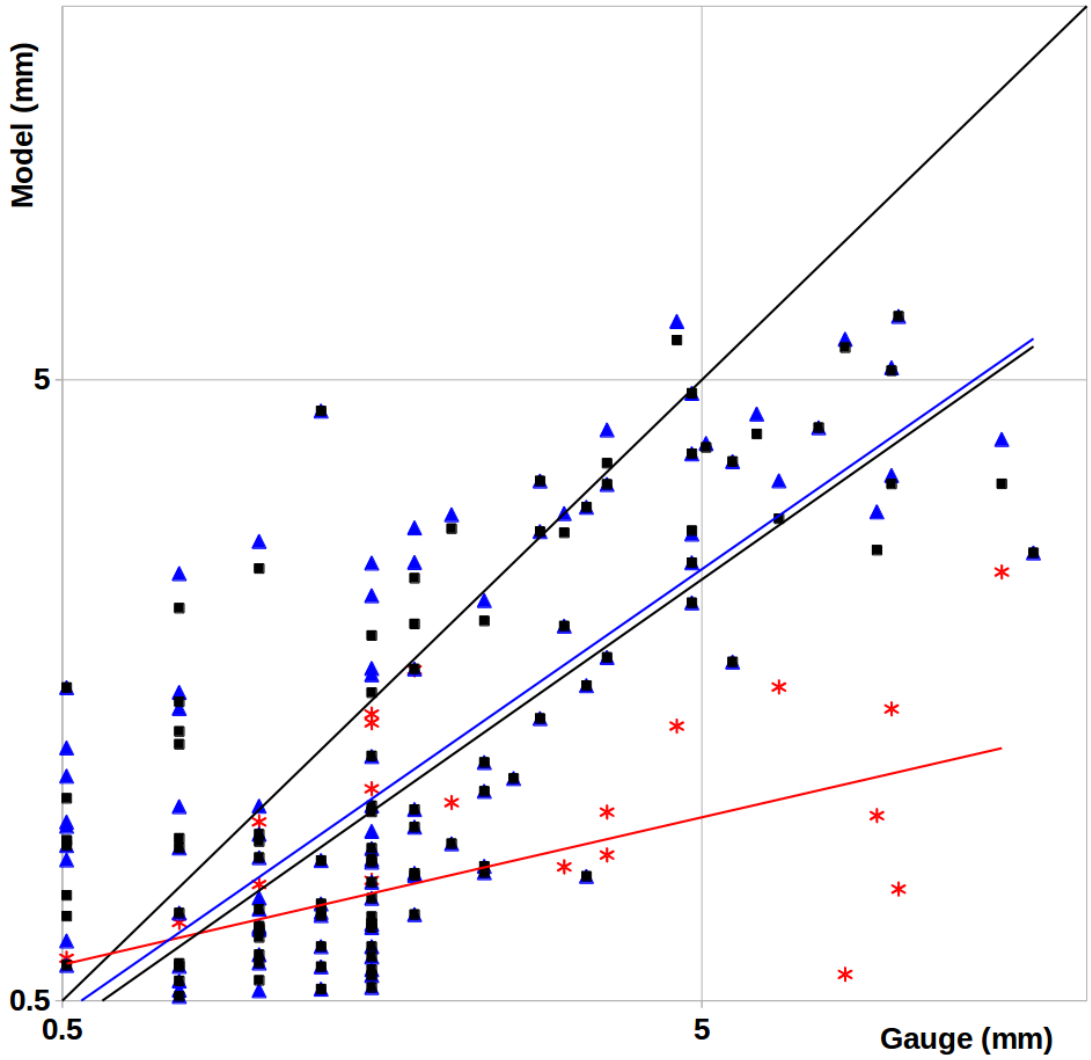

Figure 5. Verification of hourly accumulation values for LDA_Accum (red stars and line) and the merged Rad_LDA_Accum (blue triangles and line), compared to Rad_Accum (black boxes and line) for the 4-days period (July, 2014). The axes are log-scaled. Black solid line is the best fit line (1:1 fit).

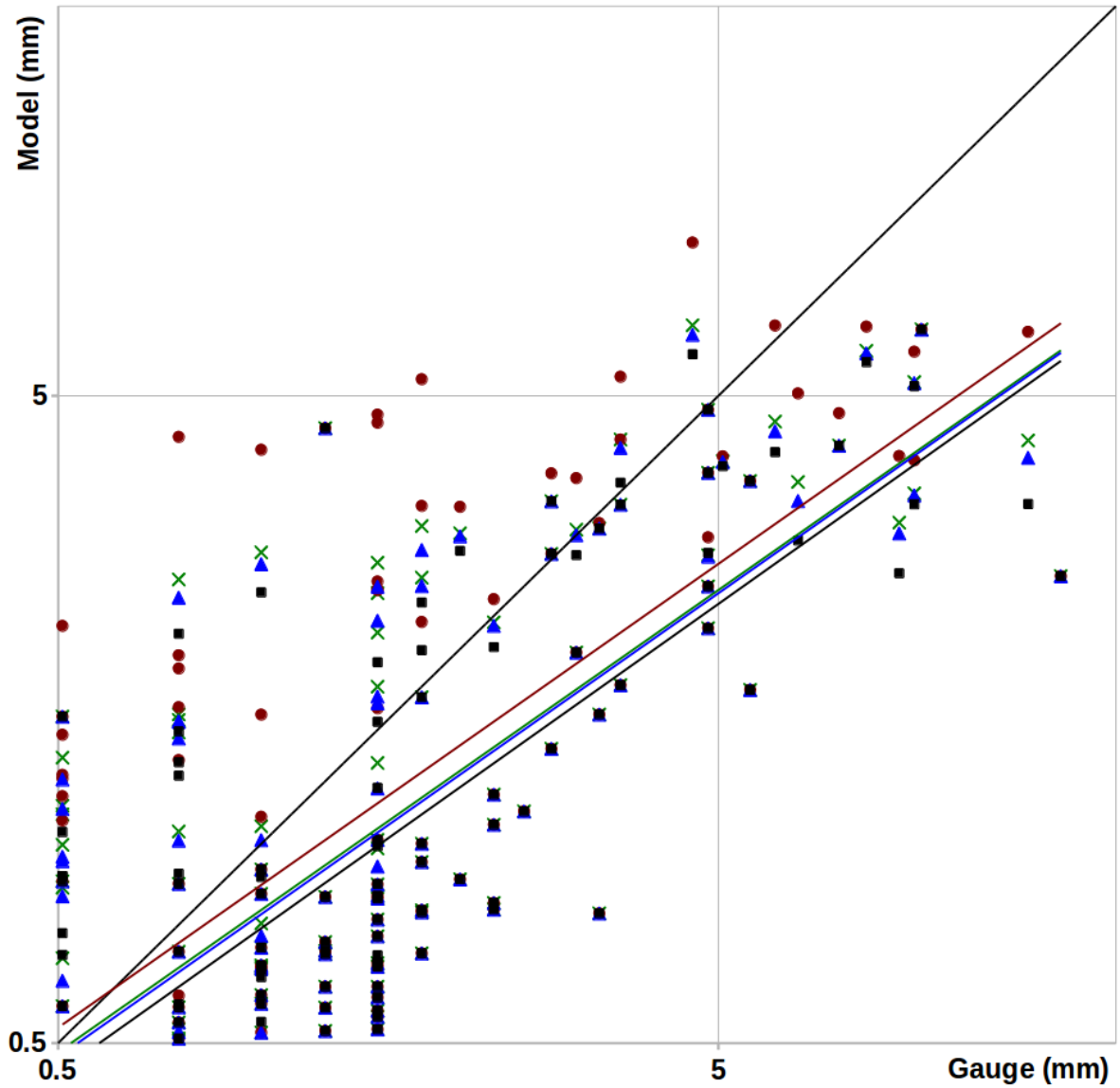

Figure 6. Comparison between Rad_Accum (black squares) and LDA_Accum (triangle-, cross- and circular markers), using 3 different methods to calculate the relationship profiles: Average- (blue triangles), 3'rd Quartile- (red circles) and the Variable Quartile (green crosses) accumulation estimates. The corresponding regression lines are represented with same color as the markers, for each method. Data are for the 4-days period in summer 2014 and as hourly accumulation values. The best fit curve (i.e. the 1:1 fit) is shown as black solid line.

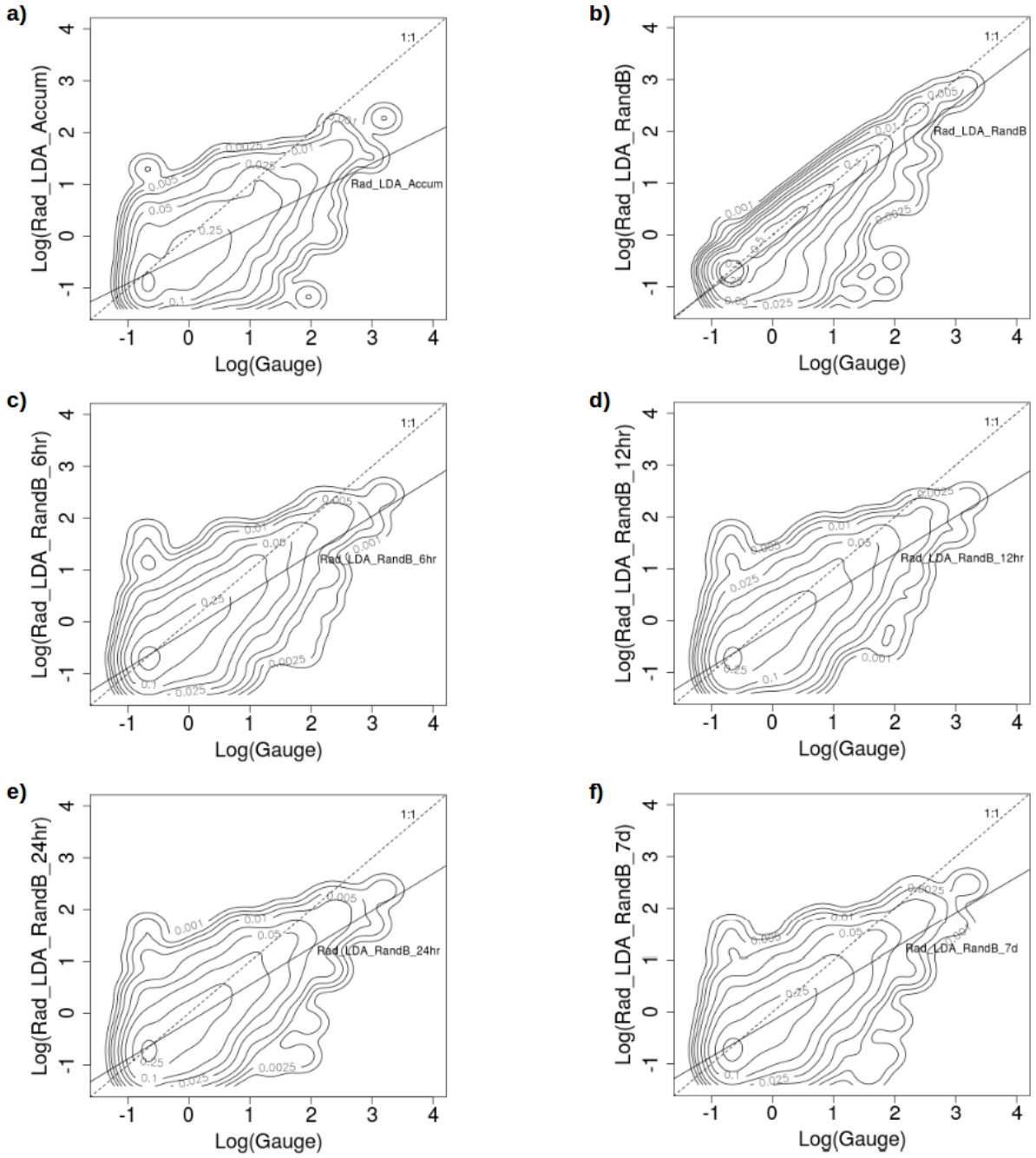

Figure 7. Impact of changing the integration time length (verification for the independent gauge datasets). Accumulation plots with density iso-lines of hourly values in mm and log-scale: a) Rad_LDA_Accum, b) Rad_LDA_RandB-, c) Rad_LDA_RandB_6hr-, d) Rad_LDA_RandB_12hr-, e) Rad_LDA_RandB_24hr- and f) Rad_LDA_RandB_7d.

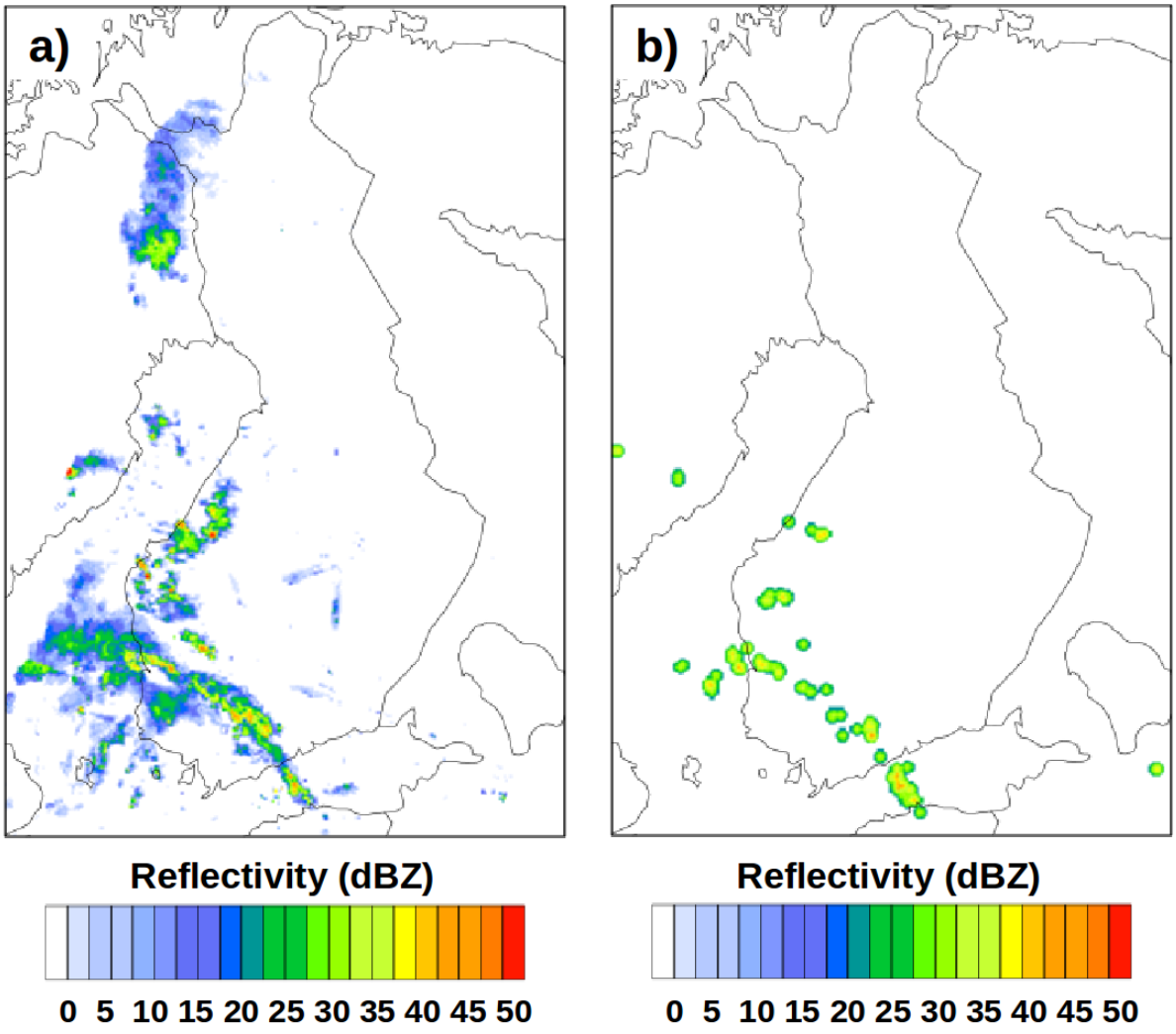

Figure 8. Example of lowest level reflectivity field from a) radar alone and b) converted lightning locator analysis alone (via LDA system) for 30 July 2014 at 16 UTC. Reflectivity color scale is shown below plots