<u>Anonymous Referee #1 (Report #2)</u>
Submitted on 01 Jul 2016

The authors deeply reorganized the manuscript improving its presentation and making it easier to follow. Nevertheless, most of the comments by the reviewers have not been addressed. According to the authors, this is due to technical problems, in fact the presented analysis has been carried out on operational runs that cannot be repeated due to insufficient resources.

The problem concerns the most scientifically interesting part of the manuscript, i.e. the assessment of the inclusion of the lightning data into radar and radar-gauge merged rainfall accumulation products. The authors are unable to find any significant improvement in the rainfall accumulation estimates. Such an outcome, if supported by robust analyses, represents a standalone result deserving publication. Nevertheless I am still convinced that the presented outcome is caused by a significant flaw in the data analysis that depends on the scales used for the comparison - please check my first review - and is therefore not supported by scientific evidence.

For these reasons I have to suggest the rejection of the manuscript from this special issue.

Nevertheless, given the interest of the topic, the very good operational system used and the efforts already devoted to the issue, I strongly invite the authors to take some time to improve the analyses and to resubmit an updated version of the manuscript.

<u>Authors answer:</u>
We have reevaluated our datasets from summer 2015. Here we found one mistake (in the code retrieving and calculating the dependent and independent stations). After correcting for this, we calculated the data for 2015 all over again. The outcome was that there are enough independent data for the period of 25 of intensive lightning days, which is now included into the verification result. We also understood, that as gauges are not used in the Rad_Accum and Rad_LDA_Accum methods, all gauges are independent as their verification references. The text and tables have been changed accordingly.

We have now put an extensive effort to follow the reveiwer's advice and included new results from a “scaled” dataset. For this, a new dataset with 25 intensive lightning cases from 2016 have been manually selected. We have scaled down the dataset, both by the geography and the time-intervals, to only include observations affected by lightning during these 25 days. We have analysed the outcome and even studied the distance dependancy to radar stations, in order to take into account other reveiwers suggestions. The new results from 2016 are included into this revised version of article and we can show an improvment using the LDA-method within LAPS accumulation process. See the new reorganized table 1 and related text in the result and discussion sections.

We want to point out that LDA is originally intended for complementing radars in the USA (where shadowing mountains create remarkable areas of missing data, and Ocean areas are included in analysis, without radar or gauge coverage). In this study we include LDA into an already existing operational analysis system, in order to complement the radar information and thereby improving the precipitation accumulation analysis but also other processes within the LAPS processes (like 3D clouds and moisture, which is of interest for LAPS-users but not a target in this specific publication). These are new developments in LAPS, using new methodologies, which might not be perfect from start but would need several years of further developments. We think there is value of publishing/sharing this work and by that, reach other workers in the same field, doing similar developments and possible help others to start from an advanced development point, using radar-lightning information.

One of the main result is that lightning is useful in areas of no radar data! If there is no radar, LAPS accumulation process has no way to continue, it need the reflectivity field. Therefore the lightning information can be crucial, it is there to complement the radar. There are areas (and even countries) which does not have radars, in souther latitudes the lightning is more frequent and here the LAPS-LDA model could be of even more importance, than in for example Finland.

Even though we here in Finland have a very good radar network, the results are improved.

Referee #2: Dr. Hidde Leijnse, hidde.leijnse@knmi.nl (Report #3)
Submitted on 08 Jul 2016

The readability of the paper has greatly improved by restructuring the paper. The main aim of the paper is now also much clearer. The authors have taken most reviewer comments seriously, and have implemented changes in the paper accordingly. However, the main issue that I still have with the paper is that the amount of data that is used for the analyses of the impact of using lightning data on the quality of the final precipitation estimates is not sufficient to draw any conclusions. Although I understand that it takes a large effort to produce a longer dataset, I still think that this is necessary in order for these analyses to have scientific value. If I understand it correctly, these analyses only require radar, gauge, and lightning data (and not NWP model data or satellite data), for which I know there are archives at FMI. Using such a dataset, this would also allow the selection of more independent rain gauges, and it would allow investigating whether there is an optimal integration time between 1 and 6 hours for the RandB method.

As two of the reviewers remarked that using linear scales for the scatter diagrams (and the ones with the contours), I would really like to urge the authors to use these linear scales. Especially because I found the graphs using linear axes that were provided with the response to the reviewers more instructive than the ones with logarithmic axes currently used in the paper.

So I am still of the opinion that the paper needs additional analyses of radar merged with lightning data before it is ready for publication.

Authors answer:
We have reevaluated our datasets from summer 2015. Here we found one mistake (in code retrieving and calculating the dependent and independent stations). After correcting for this, we calculated all the data for 2015 over again. The outcome was that there are enough independent data for the period of 25 of intensive lightning days, which is now included into the verification result. We also understood, that as gauges are not used in the Rad_Accum and Rad_LDA_Accum methods, all gauges are independent as their verification references. The text and tables have been changed accordingly.

We must again state that building up a new "experimental" LAPS-LDA system, to rerun periods with extensive datasets not being directly available (unless fetching form archive) would require a very extensive amount of work. In fact, also the NWP model data is required in order to run the LAPS accumulation process. The accumulation process module in LAPS is also producing other parameters, which relay on input data such as surface parameters and 3D-temperature (see http://laps.noaa.gov/software/README.html#ACCUM). Retreiving, unpacking, formatting and converting all involved datasets would require tools and systems to be combined and setup in an environment that does not yet exists, i.e. a routine that is outside LAPS operational routines. Please also remember that we are talking about massive data here (5 minutes of volume radar data, 3D NWP model data etc) and requirement of run-time demands on supercomputer facilites. This is simply not doable within in the limited amount of worktime and funding available.

Though, in order to follow the reviewer's suggestion to increase the dataset used for verification, we have spent much time to prepare and validate the new data output from summer 2016. Here we have followed the other reviewers suggestions on verifying "scaled" dataset and the distance dependeny from radar stations. With these new results, we are now confident that there are sufficient amount of data to draw the conclusion that lightning data and the LDA-mehtod does improve the accumulation estimates in LAPS. This is now included in the updated version of article, please see table 1 and the related text in results and discussion sections. Note that we reorganized and merged the tables to make the readability and comparison easier.

Also, as suggested, we have now changed to use linear scales within the figures with contour plots (Figs. 4 and 7) and the scatter diagrams (Figs. 5 and 6).

Anonymous Referee #3 (Report #1)
Submitted on 28 Jun 2016

I was reviewer # 3 for the initial submission of the paper.

I appreciate the improvement of the readability of this paper on a relevant topic. However I still think that the analysis in its current state does not enable to conclude on the interest or not of the use of LDA. The authors basically chose not to address all the serious concerns raised by me (and the other reviewers) with regards to the fact that the methodology suggested does not enable to reach a conclusion (either positive or negative that is not the point) with regards to the use of LDA. I understand that not everything is possible with operational data, but still think that more should be done before publication. See comments below with some suggestions of potential analysis with available (from my understanding) data. The innovative aspects of the paper should also be stressed more clearly.

Authors answer:
We appreciate the comments and suggestions by the reviewer.

We have reevaluated our datasets from summer 2015. Here we found one mistake (in code retrieving and calculating the dependent and independent stations). After correcting for this, we calculated all the data for 2015 over again. The outcome was that there are enough independent data for the period of 25 of intensive lightning days, which is now included into the verification result. We also understood, that as gauges are not used in the Rad_Accum and Rad_LDA_Accum methods, all gauges are independent as their verification references. The text and tables have been changed accordingly.

In order to reach a clear conclusion, whether LDA is useful or not, we have spent much time to prepare and validate the new data output from summer 2016. Here we have followed the reviewer's suggestion on verifying the distance dependeny from radar stations. With these new results, we are now confident that there are sufficient amount of data to draw the conclusion that lightning data and the LDA-mehtod does improve the accumulation estimates in LAPS. This is now included in the updated version of article, please see table 1 and the related text in results and discussion sections. Note that we reorganized and merged the tables to make the readability and comparison easier.

Detailed comments:

1) Introduction

- Some improvement, but not really a state of the art on assimilation of LDA for QPE. This would also help in understanding the novelties brought by the paper.
Authors answer:
We have reviewed all recent literature we could find. The problem with novel assimilation methods, as well as with other operational activities, seems to be that much of development happens in operational departments, where colleagues do not publish in journals that often. One of the motivations for this paper is actually to lower the wall between operational and scientific communities.

- l. 108-111 : this is a bit disappointing for a scientific paper... although the argument is partly valid, I still believe that more analysis can be done with the data available (see suggestions below).
Authors answer:
Setting up an LAPS-LDA system for rerunning experiments would require a very extensive amount of work. In fact, archived data from radars, NWP models, surface stations and lightning are required in

order to run the LAPS accumulation process. To retreive, unpack, format and convert all involved datasets would require tools and systems (to be combined and setup) in an environment that does not yet exists (i.e. a routine that is outside LAPS operational system and therefore not using operational input, on the contrary archived input). Please also remember that we here talk about massive data amounts (5 minutes of volume radar data, 3D NWP model data etc) and the requirement of run-time on supercomputer. This is simply not doable within in the limited amount of work-time and funding available.
Though, with much effort we have been able to follow the suggestion by the reviewer on distance dependancies, for which we used the most recent data as of summer 2016 (see below). Additionally we analysed the "scaled" datasets for this period (see below).

2) Observation and instrumentation

Please add a subsection on the event / period (summer / 25 days / 4 days) selection to clearly present them (moving the paragraph from the method section).
Authors answer:
We have now moved (and rewritten) the explanation of periods/events from section 3.5 to a new: Sect. 2.4.

3) Methods

- l.181 : "uses statistical methods", as already pointed out in the previous review, this formulation is not appropriate for a scientific paper, please be more specific.
Authors answer:
This has now been changed/removed.

- l. 227-228 : please clarify, how the quantiles are computed with regards to altitude (computed for each altitude). How is done the variable Quartile rad-Lig profiles. Since it is mentioned as a new method introduced by the authors, it should be more discussed, also in the results section.
Authors answer:
Information about calculation at altitudes is now included to the sentence: "For each of these 6 categories, the average reflectivity is calculated at each grid-point, for each level, and gives the Average Rad-Lig profiles (Fig. 3a) which is the baseline method."
More explanations on how the Variable Quartile profiles are calculated are now included to the text: "The specific percentiles used for the 6 categories are the 50-, 50-, 60-, 75-, 90- and 95% percentiles, respectively. The reason is to take into account the larger uncertainties in low categories (due larger spread and bias in the collected datasets) and on the other hand, rely on the higher percentiles for the higher categories (since these have less spread)."
We have now included some more text about Variable Quartile in the result section.

- l. 232-234 and figure 3.b : there seems to be somehow two regimes (at least one point -the one with the smallest number of strokes) seems isolated.
Authors answer:
Using a logarithmic scale and bins for lightning rate make the first category (the first point) contain mainly the weakest storms with one lightning stroke. Changing the bins might make the goodness of fit even better, however, we believe that R-square value of 0.95 is still relatively good.

- l. 238-241 : I still find it weird to chose simply maximum and was not convince by the answers of the authors. It seems that this rule also applies when you are close from the radar where radar data is much more reliable. Why not testing other merging schemes that would for example take into account the distance to the radar or the attenuation. I guess that you have access to both radar mosaic and lightning maps separately (given that it is what is plotted in Fig. 8) ? This could add some novelties to the paper.

Authors answer:

We have now mentioned the uncertainty aspect in the article. We still believe that this is a valid scheme, to be used as a baseline, in our relatively dense radar network.

We are agree, there are many techniques/developments that could be tested, especially the radar-station dependancy has been discussed. Though, it would require a new study to find out the distance dependancy of radar and attenuation, which could be considered in upcoming versions of LAPS-LDA system.

In this paper we present the first results, using the first version of LAPS-LDA system, which we think bring novelties to the research, since these methods have not been used before. In a couple of years we hopefully have refined the techniques/models to perform even better. But again, we had to start from a baseline method and evolve from that. Therefore these are the results we have so far and which we think are important to share with others in same field of work.

- l. 244 : please remind the unit of Z (mm6 m-3)

Authors answer:

Yes, this is the correct unit and it is now put into the text.

- 3.3.1 : as already pointed out, it is weird to have a 3.3.1 and no 3.3.2...

Authors answer:

We have now change section 3.3.1 to be section 3.4.

- 3.4 : what is the interest of presenting results for periods without lightning ? l.312 : remind here why only 7 independent stations are used (as explained in the answer to reviewers)

Authors answer:

It is a standard procedure when introducing new components in the assimilation schema to make sure that these do not have a harmful impact in cases of missing data. Hence, we have investigated the impact by LDA-method over several periods, to prove robustness and impact of the new developments in an operational environement. It is important to verify that the system works for all different weather situations. We have reorganzed the tables into only one table (thereby including new results and improving the comparabiltiy of data) and in order to follow the reveiwer's suggestion, we have now removed the information on the long summer period of 2015 from the table content. Instead this is only mentioned in the result section's text, but there is still the plot in figure 4.

Since the verification was performed during operational runs, the independent stations had to be set beforehand (i.e. excluded from the assimilation). Because of this we could not set more stations aside, without risking the quality of the end product. The seven independent stations were selected subjectively from different physiographical areas such as coastline, inland, lake district, and proximity to each other. On average, within a radius of 50 km from the independent station point, there are 11 dependant stations and the average distance to the nearest dependant station is 9.8 km. Please also see the notification at top of this document, which relate to the independent stations.

4) Results

- l. 335-345 : it is frustrating that no lightning occurred over the 7 independent stations during the 25 selected events... Given that it seems some lightning was recorded for some events (since an improvement is noticed), why not selecting a sub-set of event for which lightning was observed over the independent stations and discuss the results for them.

Authors answer:

Please see the notification at top of this document, which relate to the independent stations.

We went over the data from 2015 and discovered one mistake in the programs that we used. Now we are able to include independent data for the 25 lightning intensive days from 2015 into the result (see Table 1). Also, the Rad_Accum and Rad_LDA_Accum are data that are independent dataset, since gauges are not involved when estimating the accumulation with these methods.

In the data from 2016, 25 lightning days, we have made a "scaled" subset of data. We have manually scaled down the dataset, both by the geography and the time-intervals, to only include observations affected by lightning during these 25 days. See the new reorganized table 1 and related text in the result and discussion sections.

- l. 359-360 : comments on Fig 6 : "The 3'rd Quartile gives the largest overestimate, over the whole accumulation scale", it seems rather obvious no ? An explanation on the variable Quartile profile is missing.

Authors answer:

Yes, it might be obvious (for most of us) but should still be mentioned in the results.

We have added the following text related to Variable Quartile: "*The Variable Quartile gives the overall best result, with improved estimates for high accumulation values and only slight overestimation at low values.*"

- Section 4.2 : please give more explanations and also comments on the curves of Fig. 7.

Authors answer:

The curves in Fig. 7 can be seen as isolines of density of points in a scatter plot. We have found this approach more useful than scatter plots when the points would overlap each other, and the approach was also recommended by reviewers of our earlier paper.

We have added more text into section 4.2 and figure caption.

5) Discussion and conclusion (by the way add a number for this title section)

Authors answer:

We have added the Section number (5).

- l.374 : "at least leave them as unaffected as possible", somehow weird formulation as a goal...

Authors answer:

This sentence has been changed.

- l. 375-378 : this is indeed an interesting point but not demonstrated.... it could be done with the available data (i.e. not re-running past events) by considering scores for stations located only far (testing different distances) from the radars (ex. : stations with distance to the radar equal to 0-50 km, 50-100km, 100-150km...).

Authors answer:

We have now made a big effort to follow the reveiwer's suggestion on analyzing the distance dependancy of radar station location and gauge stations, to see the effect on accumulation scores. For this we used the newest dataset from summer 2016, which uses the Variable Quartile profiles. The results can be seen in Table 1 and related text is included into result and discussion sections. These new results shows improved scores (because of the use of Variable Quartile method) and we can conclude the usefullness of assimilating lightning data in the LAPS accumulaiton process.

- l. 404-406 : “3rd quartile gives higher impact....”, I may be confused, but it is somehow surprising the median does not work better on average (was the estimation correct). Please discuss this point more.
Authors answer:
We are not sure if the reviewer here means “mean” instead of “median”? In the article we have used Average- and Quartile profiles. We have also made some unpublished testing with Median, which then lead us to test different Quartile approaches, showing that the Variable Quartile method outperformed both Average- and Median methods.
When collecting the corresponding radar profiles from the different bins (as in Fig. 3a), the spread/bias are relatively larger for the lowest bins (i.e. with few lightning strikes) than for the higher bins. The spread comes from different factors, such as the mismatch between instruments, lightning might not occur right above the precipitation and there is of course a fluctuation of amount of lightning for each storm event. There are many uncertainties involved and by building the statistics for a long time-period, some of the uncertainties are minimized.
The lowest bins (less lightning) are related to a very widespread range of precipitaion amounts (here we have the biggest uncertainties and with longer statistics this spread becomes even larger). Therefore, it is “safer” to use the average (e.g. 50% percentile) value to calculate the profiles for the lowest 2 bins. The higher bins (intense lightning) mainly occurs during intense rainfall and here is less spread in the data, so using a 90-95% percentile for these cases are realistic and our testruns have proven that.
By using the Variable Quartile approach we try to include these uncertainties, i.e. a sliding scale of changing percentiles is used (ranging from 50-95%), where average is used for lowest 2 bins and 95% percentile for the highest bin.

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

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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~~do improve the analysis when no ~~radar is~~radars are available, and even with radar~~, lightnings~~ data, lightning data 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~~results.

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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~~electricity 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)

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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~~are 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 (NWP) models~~ to improve~~, using nudging techniques, or improving 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~~Mediterranean area, and showed improvement in forecasts up to 12 hours lead time. Pessi and Businger (2009) derived a lightning-convective rainfall relationship over the North Pacific Ocean and used it for latent heat nudging method in an NWP model. They were able to improve the pressure forecast of a North Pacific winter storm significantly.

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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. We also anticipate the usefulness of lightning data as backup plan in the occasions when radar data is either missing or of detoriated quality. Even though these occasions are rare, they often occur on days when detailed precipitation estimates are of great interest. Thunderstorms producing heavy localized rainfall are also often producing heavy winds, causing unavailability of radar data due to breaks on electricity and data communications. 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~~weather 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.

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2 Observations and instrumentation

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

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~~2016, FMI operated ~~eight~~ten C-band Doppler radars (~~two more were added to the network~~newest one operational since 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.

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2.4 Verification periods

The verification periods are limited to summer season (the active convective season in Finland) with one period ranging from 1 April to 1 September, 2015 and a second period from 1 May to 26 July from 2016. These datasets includes many precipitating cases without lightning and therefore, the effective impact by lightning is diluted (e.g. no influence by the LDA-method). Therefore, subsets of 25 days with frequent lightning (e.g. > 100 CG strokes/day) were selected from both summers 2015 and 2016. The 25 days period from 2015 include observations of full days (i.e. 24 hours) and from whole Finland area, while the 2016 dataset were manually filtered to explicitly include the stations and time-intervals affected by lightning (hereafter called scaled dataset).

In order to perform several autonomous experiments with the FMI-LAPS LDA system, an additional 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 CG strokes/day) in Finland, during year 2014.

3 Methods

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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. 3.3-3.4 and, finally, the verification methods in Sect. 3.~~4~~5.

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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~~LAPS performs 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~~results 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 at each grid-point, for each level, and gives the Average Rad-Lig profiles (Fig. 3a), which is the baseline method. 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). We extend this method to also calculate the ~~-~~3'rd Quartile (i.e. 75%-percentile) and ~~a~~the Variable Quartile Rad-Lig profiles, for each category. 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 specific percentiles used for the 6 categories are 50-, 50-, 60-, 75-, 90- and 95% percentiles, respectively. The reason is to take into account the uncertainties in the low categories (due to larger spread and bias in the collected datasets) and on the other hand, rely on the high percentiles for the high categories (since these have less spread). 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. This is an approximation, aiming to compensate for the most serious radar error sources, which could be subject for further improvement in future developments (especially if independent quality

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estimates of the radar data become available). 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; mm^6/m^3) 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 hydro-meteors. 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~~lightning 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~~4 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.

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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~~5 Verification methods

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~~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). Note that in the Rad_Accum and Rad_LDA_Accum products the gauge data has not been used, therefore all gauge stations are independent references for their verification. In a separate verification exercise for the 2016 data, only stations located more than 100 km and more than 150 km from nearest radar station were used, to demonstrate the potentially detoriating quality of radar data with distance to the radar due to e.g. attenuation and beam blocking.

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):

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

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

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

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~~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~~scores for the entire summer of 2015~~ (~~, i.e. including days with no thunderstorms, give no significant impact by using lightning to estimate the precipitation accumulation (shown in Fig. 4, where the data are from dependent stations). Same result is seen in the scores of RMSE, STDEV and CORR values (not included here). Since the data have been much influenced by weather situations not relating to lightning, the focus will be on the subsets, i.e. the 25 days periods of intense lightning days, of both 2015 and 2016.

The 25 days period with frequent thunderstorms during summer 2015, for which we used the Average mehtod to calculate the Rad_Lig profiles, shows a biased result using lightning data (see Table 1; left column). For the independent dataset the Rad_LDA_Accum has a slightly improved result (lower RMSE value), when comparing with Rad_Accum. On the other hand, Rad_LDA_RandB get worse results, as can be seen from the RMSE and CORR. The Dependent data show almost neutral impact (RMSE is slightly better for Rad_LDA_RandB), by the use of LDA-method and Average calculated Rad-Lig profiles.

Figure 5 show the results using different Rad-Lig profiles, e.g. 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 add to the overestimate in low accumulation values (< 5 mm). The 3'rd Quartile profiles gives the largest overestimate, over the whole accumulation scale. ~~) the~~The Variable Quartile gives the overall best result, with improved estimates for high accumulation values and only slight overestimation at low values.

Using the Variable Quartile profiles in the accumulation analysis for the 25 days dataset of summer 2016 give a positive impact to the accumulation estimates (see Table 1, right column), where most of the scores are improved. The independent ~~stations show some improvement (Table 2). The correlation (i.e.~~verification give decreased RMSE and increased CORR~~) is higher~~ values 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~~ . Also, Rad_LDA_RandB get smaller errors than Rad_RandB (see STDEV and RMSE in Table 1; most upper right panel). 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.~~all scores are improved using LDA-method, especially the RMSE (as seen in Table 1; right column, second panel). The verification of distance dependancies, i.e. for observations further away than 100- and 150 km from nearest radar stations, show improved accumuation estimates when using the LDA-method (see Table 1, right column, two last panels). The RMSE and CORR scores for Rad_LDA_Accum and Rad_LDA_RandB are better than Rad_Accum and Rad_RandB, respectively. Here, only dependent gauges are availabe for verification. The results, from the scaled dataset and the dependancy of distance to radar location, relieve the positive impact by using the lightning data as input for the LAPS-LDA model.

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Comparing ~~the~~ accumulation results from the 4-days period for radar alone (i.e. Rad_Accum; black markers in Fig. ~~5~~6) and lightning alone (i.e. LDA_Accum; red markers in Fig. ~~5~~6), it is clear that the use of LDA_Accum is less accurate than Radar_Accum results. Figure ~~5~~6 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~~6; 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~~7, where the density of points are drawn as isolines in the scatter plot, 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~~2 also imply the same result. ~~Note that~~The Rad_LDA_Accum (e.g. a method not using RandB~~,~~) is included as ~~an~~a reference~~) is included~~, when comparing the results of different integration periods.

5 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~~as much as

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Formatted: WW-Default Paragraph Font11111, German (Germany) possible, also for 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.

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The ~~long verification~~ whole summer period ~~(i.e. summer~~of 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~~results, using the LDA-method (scores are not included here but Fig. 4 show the graphs). In order to narrow down our analysis to areas and times where lightning did occur (i.e. exclude stratiform precipitation), we focused our results on the subset of 25 lighting instense days for both 2015 and 2016. The subset of 2015, using the Average method, show biased results and no significant conclusions could be drawn from them (Table 1, left column).

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New methods to calculate the Rad-Lig profiles were tested and 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. 5). 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. 5). 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. ~~2 and Fig. 4).~~

The newest results from 2016 and the 25 days subset shows that there is a benefit using the LDA- (Variable Quartile) method. Mainly all scores are becoming better, few are unchanged, when lightning information is used to estimate the precipitation accmulation (see Table 1; right column). Verifying the dataset with distance to radar stations (i.e. gauges situated further away than 100- and 150 km) also show the same results, the accumulation product is improved with LDA-method. The impact on scores are mainly in the second decimal, but they are consistent, and cleary show the tendency of improvement by using LDA-method with the Variable Quartile profiles. 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~~utilization rate and therefore less impacted by the LDA-method. In upcoming version of FMI-LAPS the verification will be focusing on including areas with poor (or none) radar coverage where gauges are available.

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~~.~~ (not shown here). 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 shown in figure 6, where accumulation would be generated from the LDA-method (as seen in Fig. 6; red markers) and also 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.~~. This case study also demonstrates, how the LDA method can reconstruct the highest reflectivities, but areas with weak precipitation are missing.

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

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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.

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~~New methods to calculate the Rad-Lig profiles~~In the present analysis area we mainly anticipate the usefulness of lightning data as a backup plan of rare but significant cases. For the rare nature of such events it is not possible to collect a statistically representative dataset in a few years: even though attenuation of radar signals or completely missing data is observed several times a summer, it is not so often when such events happen just over a rain gauge station. However, our overall analysis shows that when we include the lightning data every day at every point, it makes in average a small improvement, and it is there as a safety network waiting for the cases where radars fail.

~~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~~2 and Fig. 7). We see correlation ~~peeking~~peaking 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~~ from summer of 2015 (left column) and 2016 (right column), for periods of the 25 intensive lightning days (e.g. > 100 CG strokes/day) during both years. For summer 2016, only those gauge measurements which were near a lightning (in time and space, manually selected) were used. Precipitation results are shown for radar (Rad_Accum) and radar merged with lightning ~~dat~~data (Rad_LDA_Accum), together with and without gauge measurements included with RandB-method (Rad_RandB and Rad_LDA_RandB, respectively). In the lowest panels, only data from more than 100 or 150 km from the nearest radar are used. Verification is performed against both ~~for the dependent and~~ independent and dependent stations ~~dataset, for a period of 25 intensive lightning days (e.g. > 100 CG strokes/day) during summer 2015.~~ ie. those used or left out from the gauge analysis.

Summer 2015 (Average scheme)					**Summer 2016 (Variable Quartile scheme)**				
Independent ~~**Dependent**~~	Rad_Accum	Rad_LDA_Accum	Rad_RandB	Rad_LDA_RandB	**Independent**	Rad_Accum	Rad_LDA_Accum	Rad_RandB	Rad_LDA_RandB
Nr ~~of observations~~Obs	3206	3332	~~3822~~256	~~3823~~256	Nr Obs	1320	1333	74	74
STDEV ~~(log(R/G))~~	0.27	0.27	0.11	0.11	STDEV	0.32	0.~~12~~32	0.12	0.11
RMSE	1.66	1.64	0.58	0.70	RMSE	2.62	2.60	0.~~76~~92	0.~~76~~89
CORR	0.67	0.67	0.97	0.96	CORR	0.~~93~~64	0.~~93~~65	0.96	0.96
Dependent~~**Independent**~~					**Dependent**				
Nr Obs			3566	3567	Nr Obs			1364	1376
~~Nr of observatio~~	~~0~~	~~0~~	0.12	0.12	STDEV			0.14	0.13

~~ns~~STDEV							
RMSE	0.77	0.76	RMSE			1.27	1.19
CORR	0.93	0.93	CORR			0.93	0.94
>100 km			**>100 km**				
Nr Obs			Nr Obs	656	656	694	698
STDEV			STDEV	0.34	0.34	0.15	0.15
RMSE			RMSE	2.44	2.39	1.03	1.01
CORR			CORR	0.66	0.67	0.95	0.95
>150 km			**>150 km**				
Nr Obs			Nr Obs	153	153	168	171
STDEV			STDEV	0.39	0.39	0.20	0.20
RMSE			RMSE	2.46	2.42	1.47	1.43
CORR			CORR	0.33	0.35	0.80	0.81

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~~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.~~Table 2. Impact of the integration time length on RandB-method, for the dependent and independent stations datasets, during summer 2015. ~~Note that~~The Rad_LDA_Accum (e.g. a method not using RandB~~,~~) is included 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

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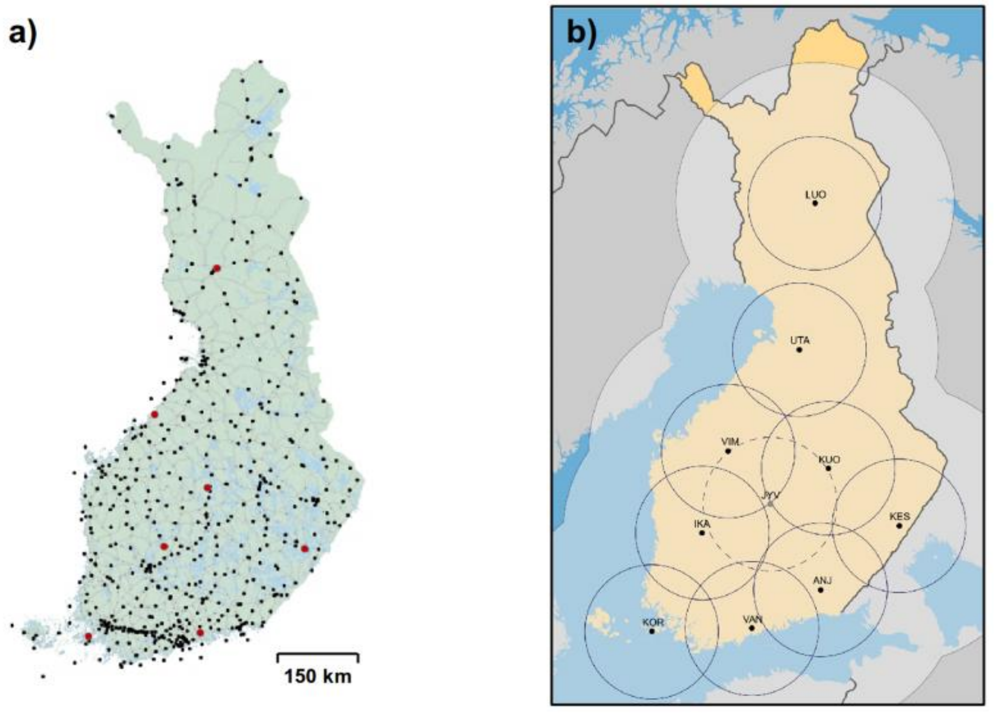
a)
150 km
b)
LUO
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ANJ
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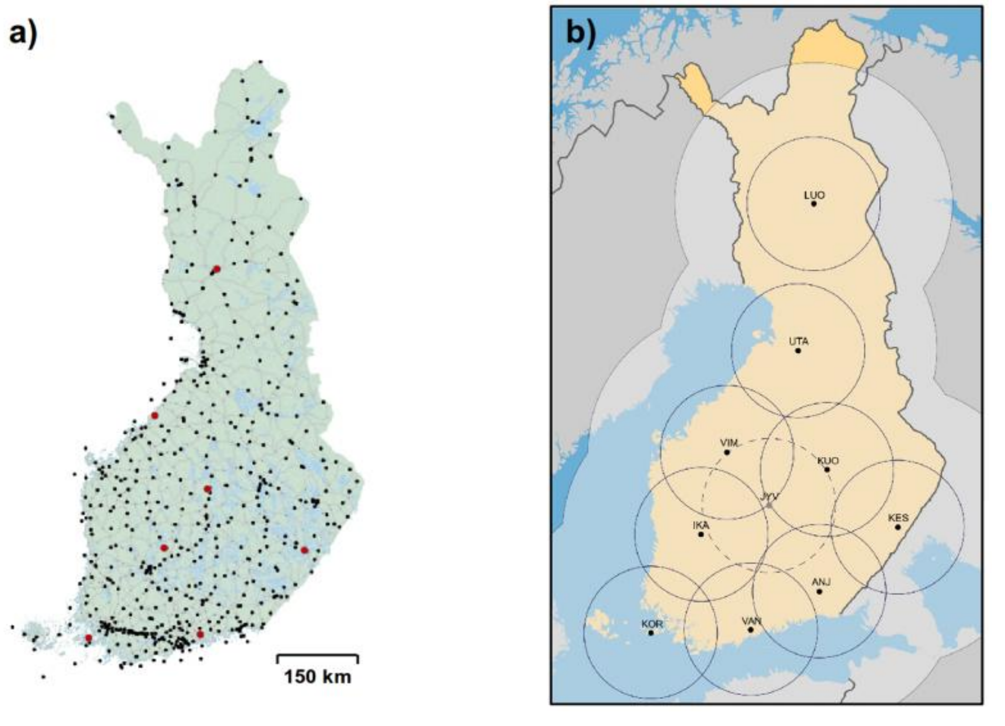


Figure 1. In (a) the Finnish surface gauge stations are shown (as dots on the map), these are used to measure the hourly precipitation accumulation. The red dots indicate the position of the 7 independent stations used for the verification. In (b) the outer rectangular frame of the map depicts the LAPS 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. Dashed circle indicates Petäjävesi radar near Jyväskylä (see JYV in map), which was not included in summer 2015.

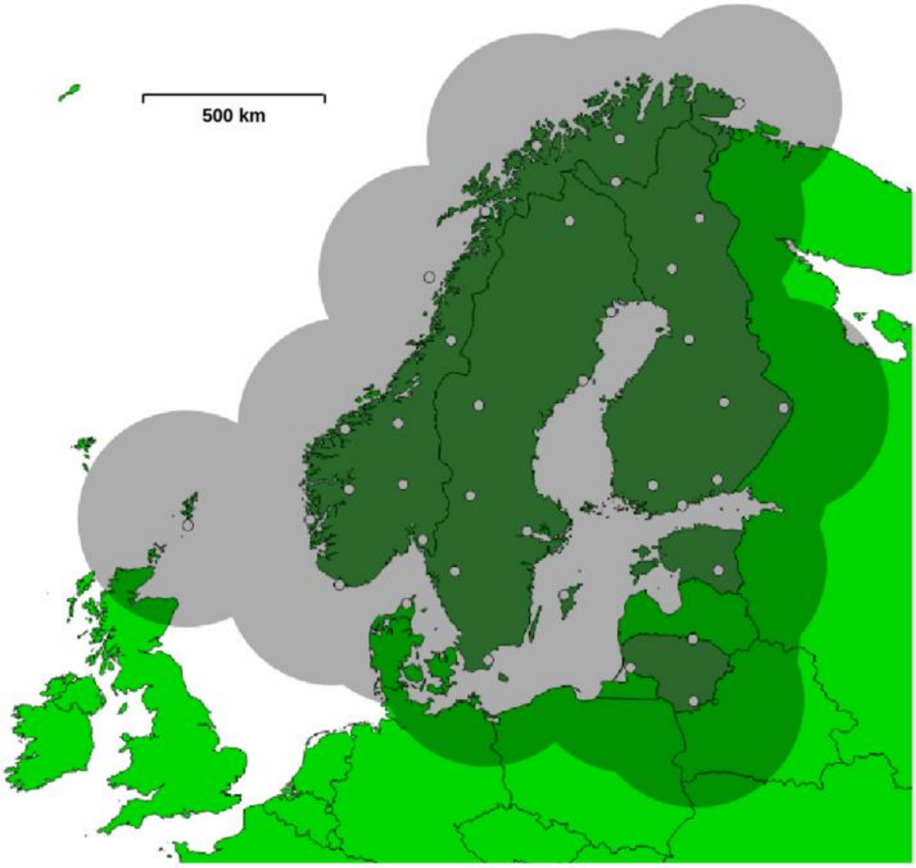
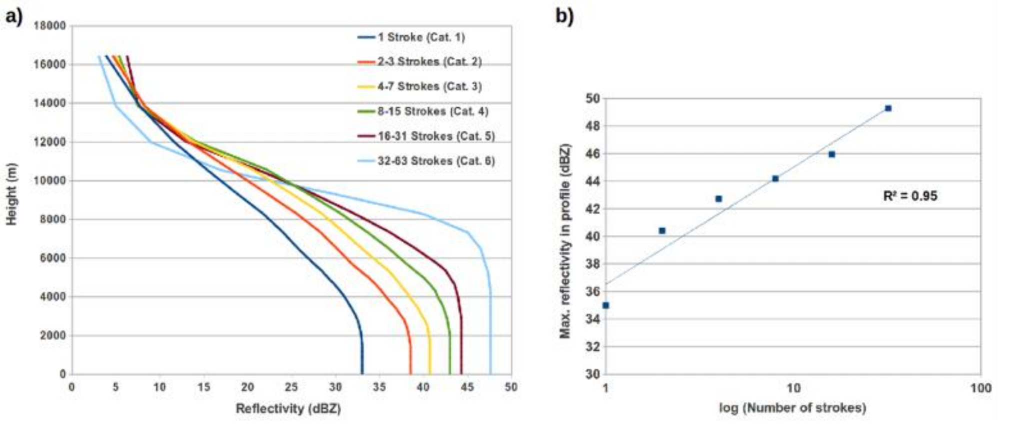


Figure 2. The LLS sensor locations (white dots) and coverage (grey circular areas), as of year 2015.


a)
b)
1 Stroke (Cat. 1)
2-3 Strokes (Cat. 2)
4-7 Strokes (Cat. 3)
8-15 Strokes (Cat. 4)
16-31 Strokes (Cat. 5)
32-63 Strokes (Cat. 6)
Height (m)
Reflectivity (dBZ)
Max. reflectivity in profile (dBZ)
log (Number of strokes)
R² = 0.95

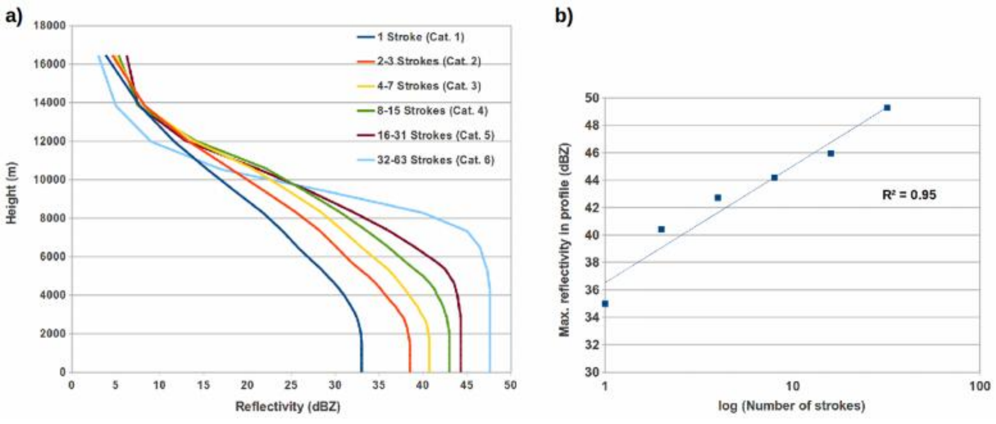
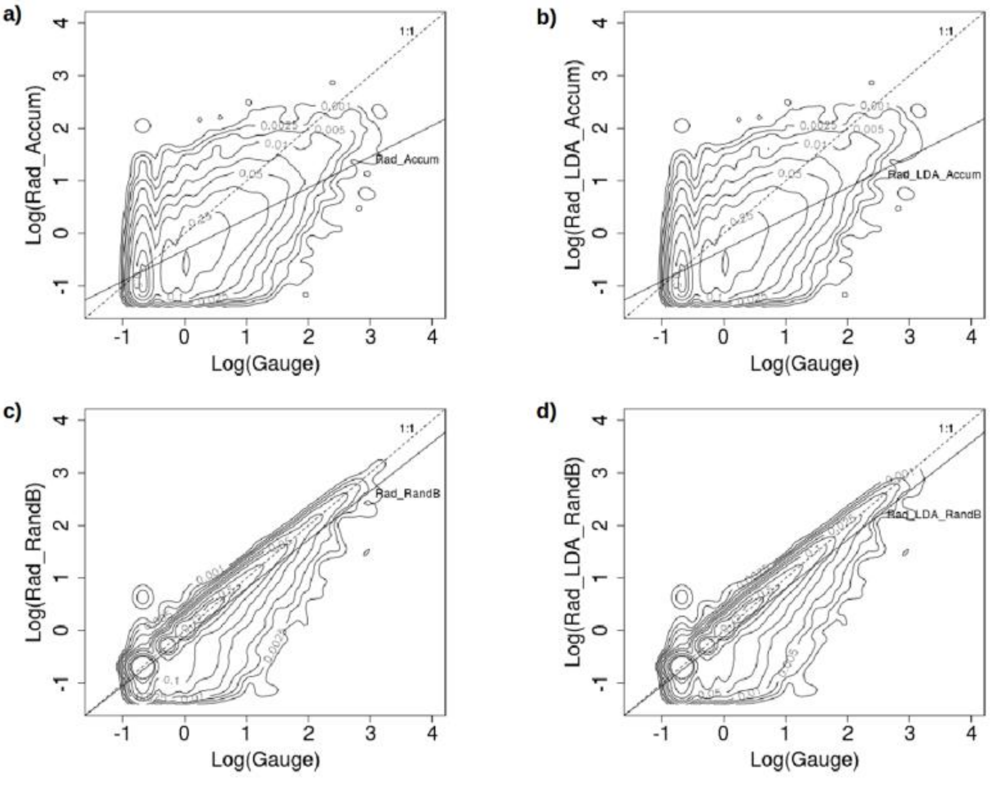


Figure 3. In a) Rad-Lig relationship profiles (smoothed) from Finland NORDLIS-LLS, calculated using dataset from summer 2014. Profiles are divided into binned categories of strokes, with temporal resolution of 5 minutes and spatial resolution of 3 km. In b) profile's max reflectivity values versus lightning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


a)
b)
c)
d)
Log(Rad_Accum)
Log(Rad_LDA_Accum)
Log(Rad_RandB)
Log(Rad_LDA_RandB)
Log(Gauge)
1:1
Rad_Accum
Rad_LDA_Accum
Rad_RandB
Rad_LDA_RandB

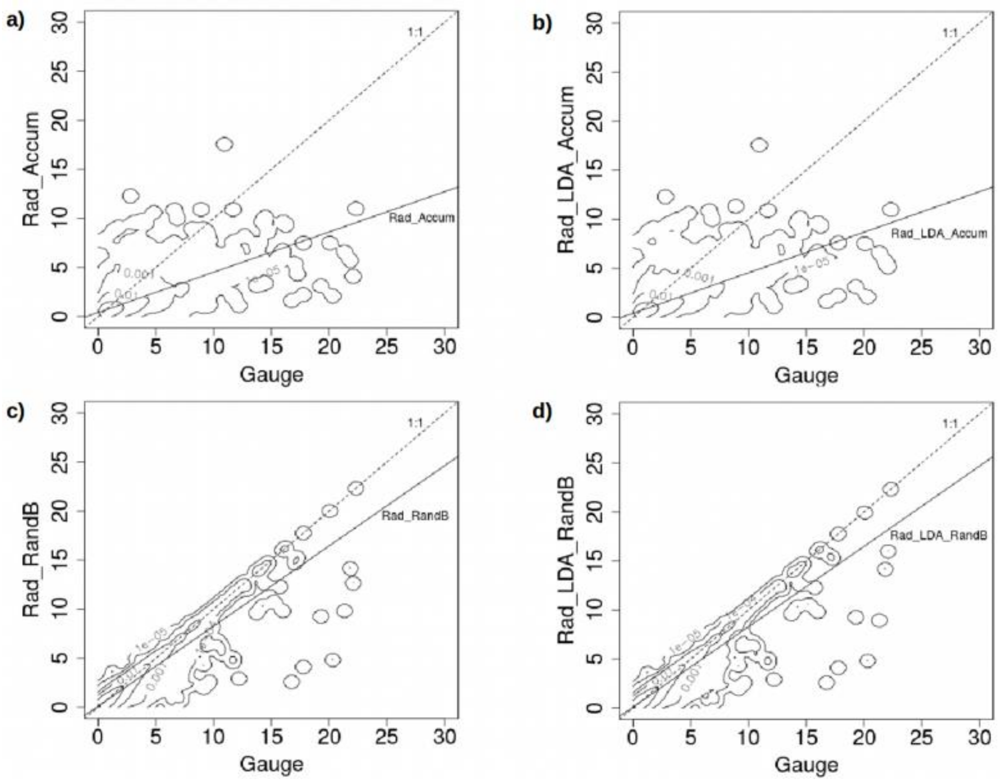


Figure 4. The FMI-LAPS precipitation accumulation (described in plots with density iso-lines of hourly accumulation values~~,~~ in mm ~~and log scale~~) calculated using 4 different methods: a) Rad_Accum, b) Rad_LDA_Accum, c) Rad_RandB and in d) Rad_LDA_RandB. Results are from the dependent gauge dataset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

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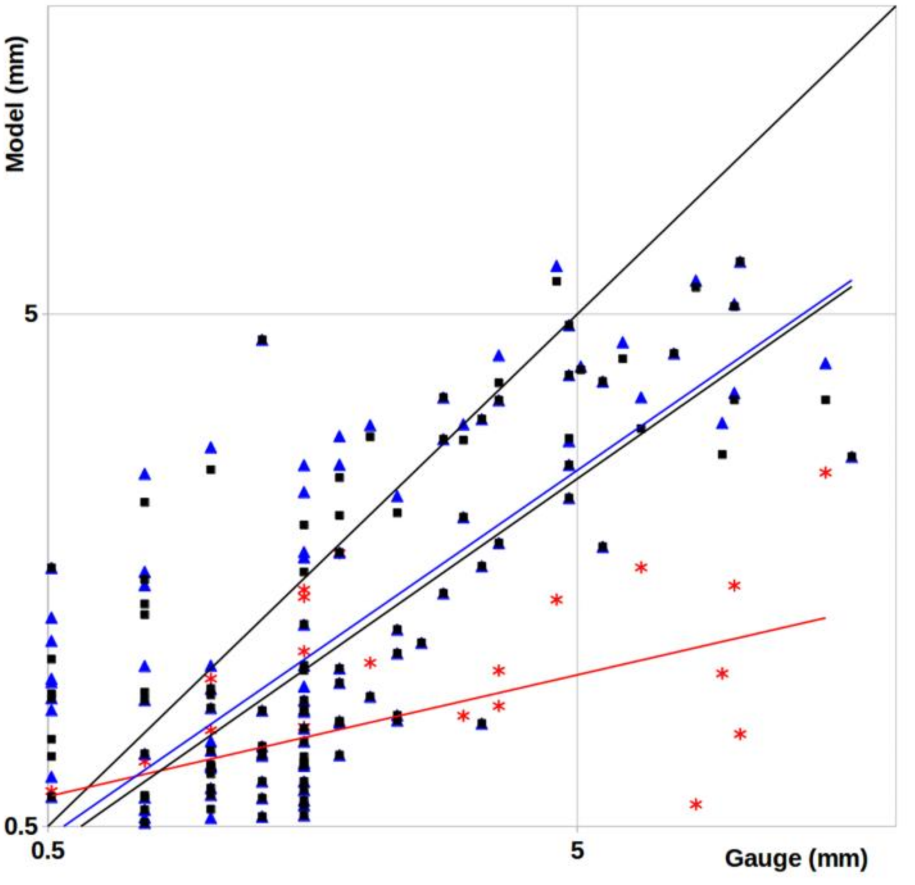
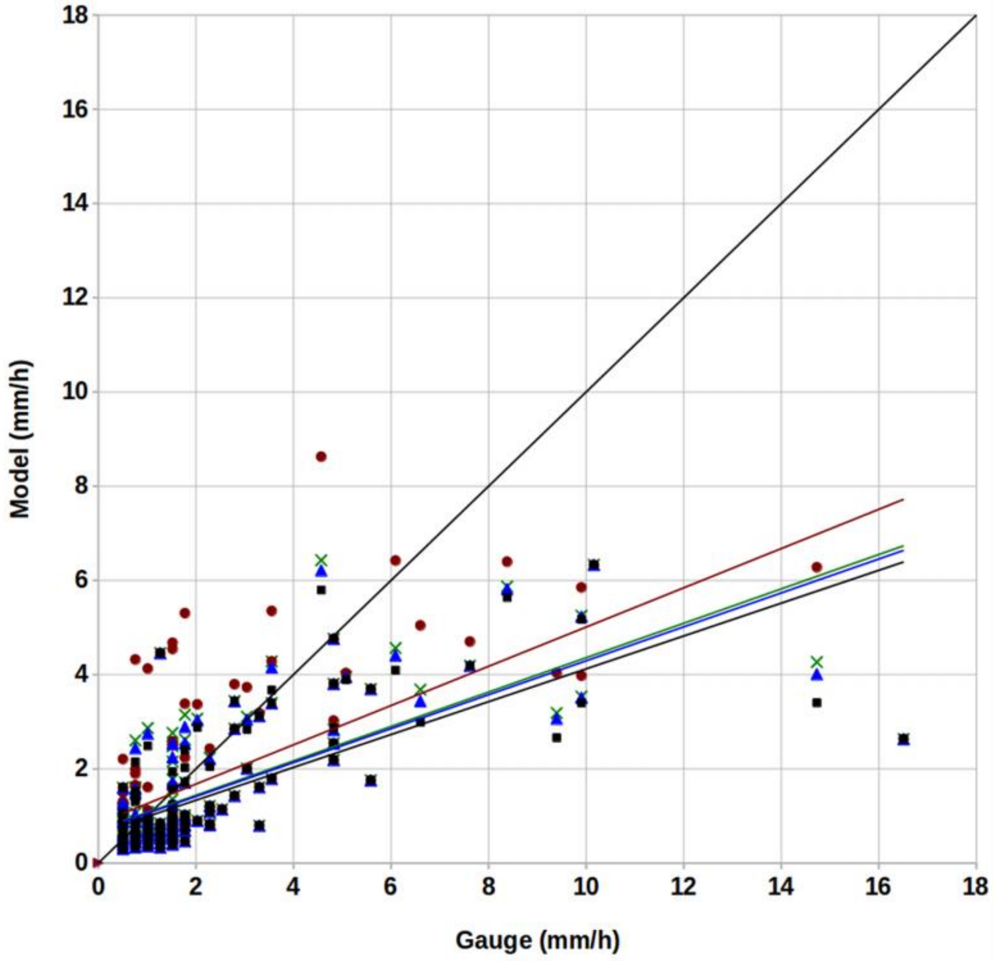

Model (mm)
5
0.5
0.5
5
Gauge (mm)



~~Figure 5.~~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).~~

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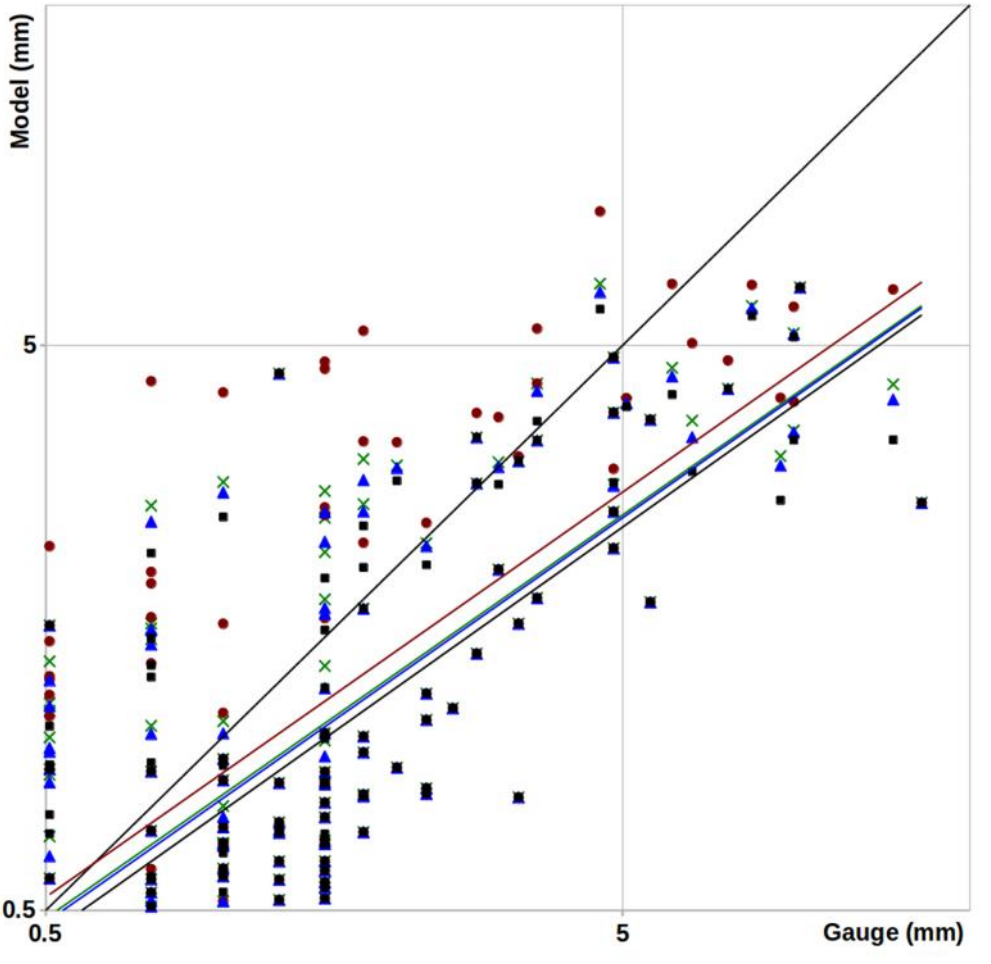
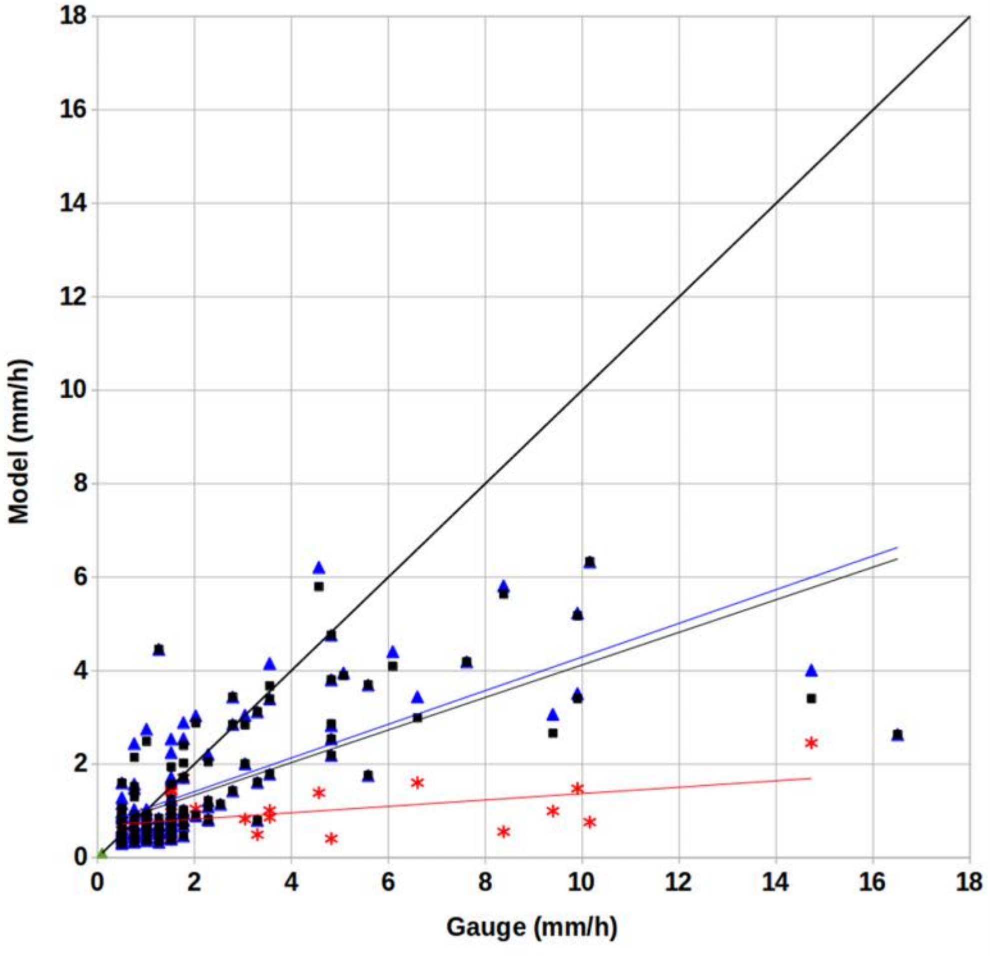

Model (mm)
5
0.5
0.5
5
Gauge (mm)

~~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.


Model (mm/h)
Gauge (mm/h)
0
2
4
6
8
10
12
14
16
18

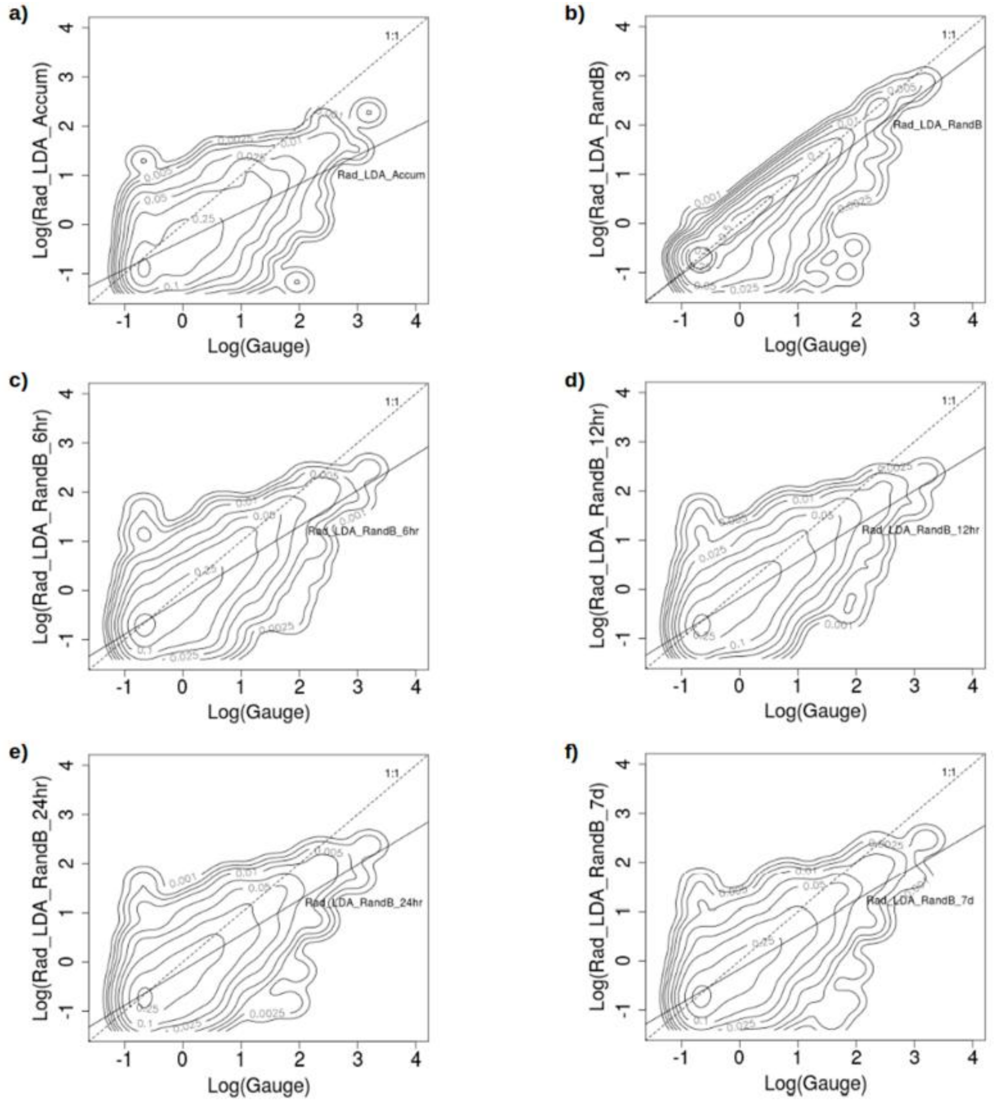


Figure 6.

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). Black solid line is the best fit line (1:1 fit).

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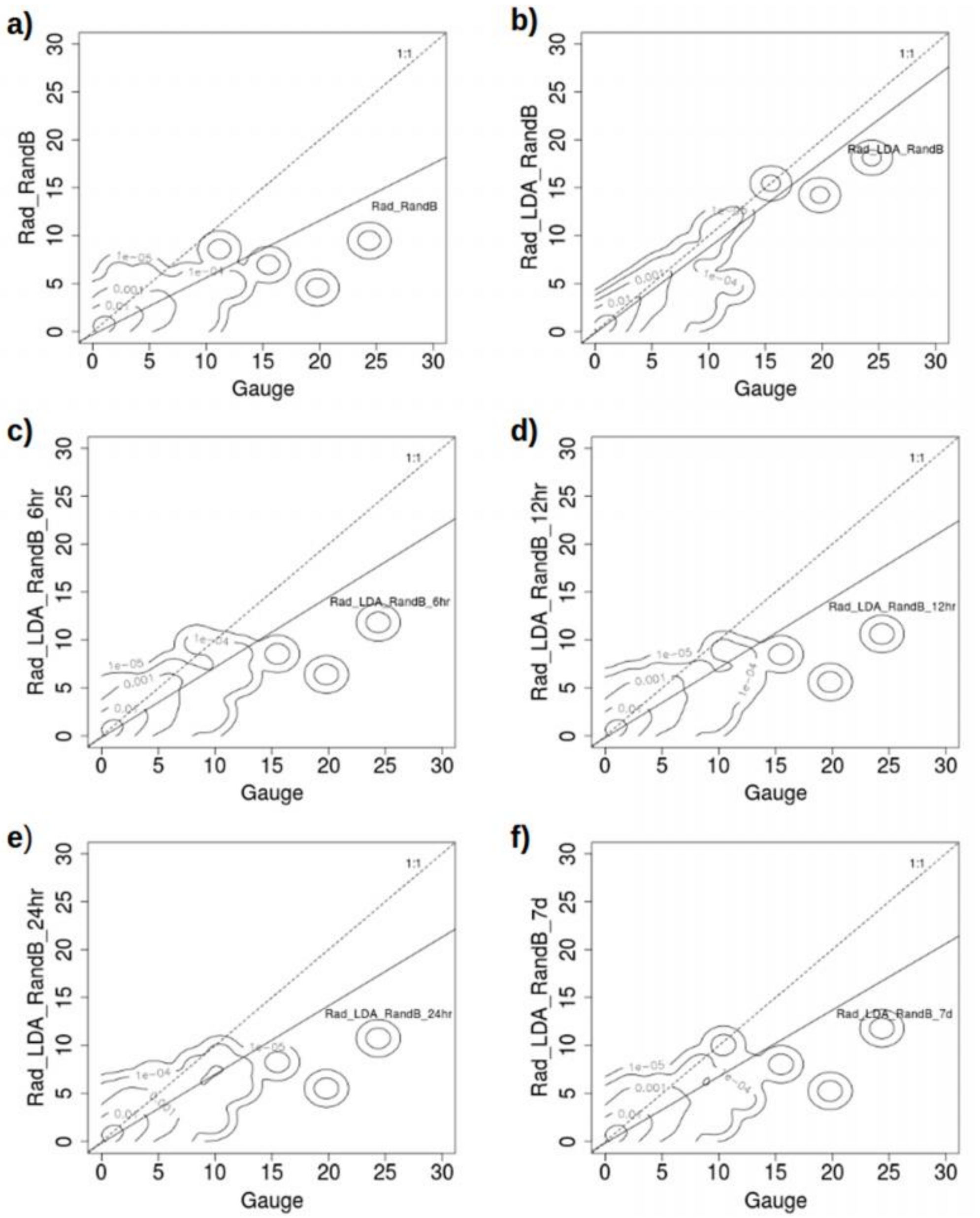

Figure 7. Impact of changing the integration time length (verification for the independent gauge datasets). Accumulation plots with density iso-lines of hourly values in mm~~ and log scale~~: a) Rad_LDA_Accum, b) Rad_LDA_RandB-, c) Rad_LDA_RandB_6hr-, d) Rad_LDA_RandB_12hr-, e) Rad_LDA_RandB_24hr- and f) Rad_LDA_RandB_7d. Dashed line represents a perfect match, solid line is a fit-curve to the dataset.

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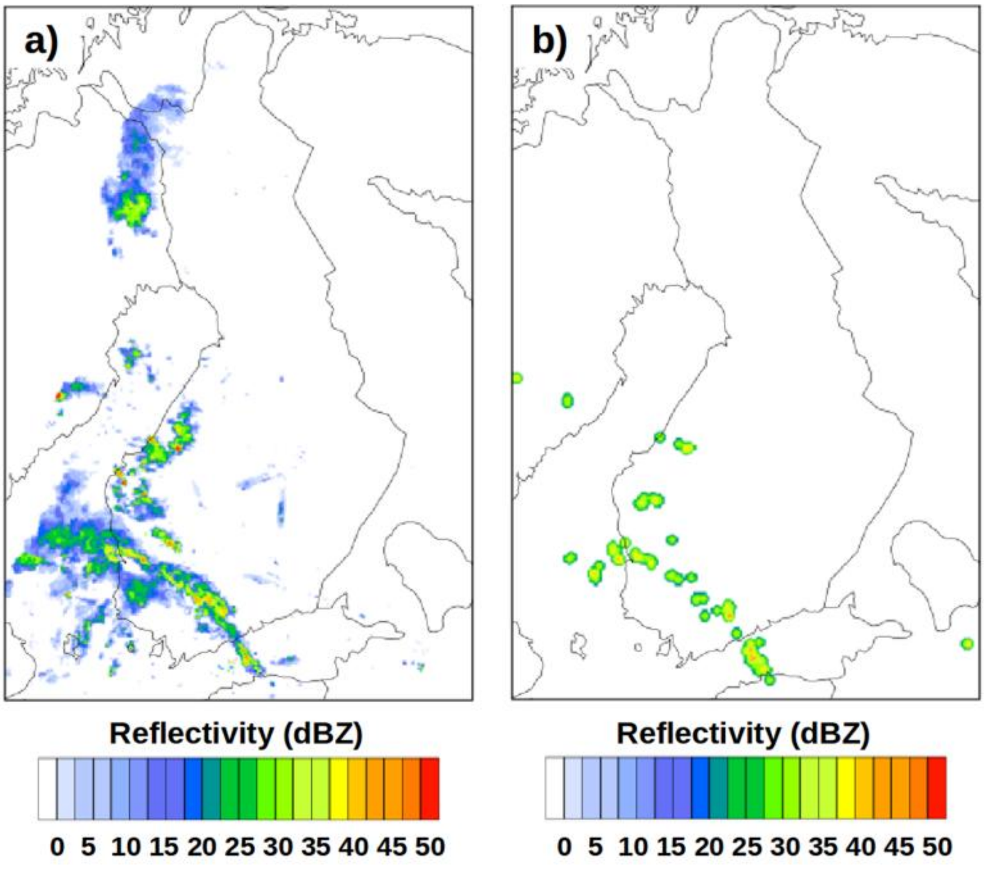
a)
Reflectivity (dBZ)
0 5 10 15 20 25 30 35 40 45 50
b)
Reflectivity (dBZ)
0 5 10 15 20 25 30 35 40 45 50

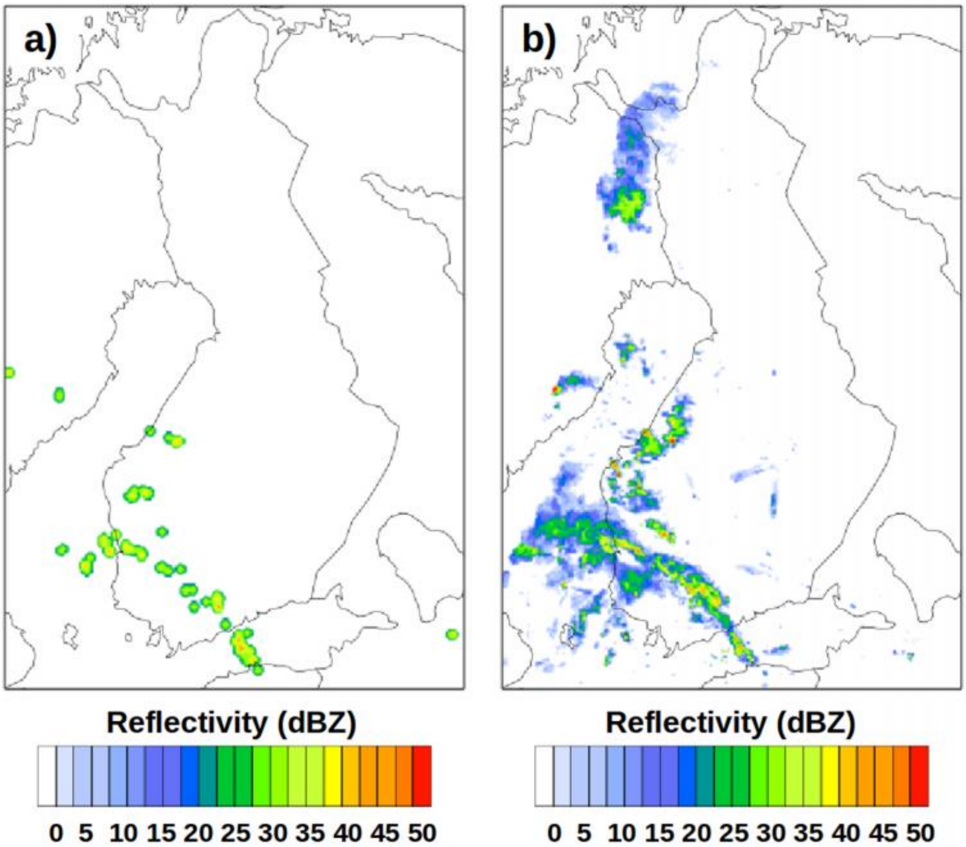

Figure 8. ~~Example of lowest level reflectivity~~ Reflectivity field simulated from ~~a) radar alone and b) converted~~ lightning ~~locator analysis~~data alone (left) and, for verification, from radar data alone (~~via LDA system) for~~ right) 30 July 2014 at 16 UTC. Reflectivity color scale is shown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

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