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Discussions

Improving the precipitation accumulation analysis using radar-, gauge- and lightning measurements

Erik Gregow[1], Antti Pessi[2], Antti Mäkelä[1] and Elena 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 aim of this article is to introduce and compare new methods on how to perform precipitation accumulation analysis, with special focus on the high intensity cases. This includes assimilation of lightning observations, in combination with radar and gauge measurements, and the impact of different integration time intervals on the radar-gauge correction method. The article is a continuation of previous work in the same research field, by Gregow et al. (2011).

A new Lightning Data Assimilation (LDA) method has been implemented and validated within the Finnish Meteorological Institute- (FMI) Local Analysis and Prediction System (LAPS). The performed precipitation accumulation analyses show the usefulness of lightning assimilation, together with radar information.

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 eceonomically 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). It is projected that annual precipitation will increase in Northern Europe and in Finland by 10-30% due to climate change (Ruosteenoja, 2013).

Gregow et al. (2013) has proven that there is a benefit of assimilating various sources of data to better estimate the precipitation accumulation (e.g. combining radar and gauge data via the RandB-method). It was also shown, that the largest uncertainties took place during heavy rainfall (i.e. convective weather situations). These are weather situations when lightning is likely to take place and the use of this unconventional data source could impact the final precipitation analysis. 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).

The research of combining radar and surface observations, in order 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). In Norway, Abdella and Alfredsen (2010) have shown that the use of average monthly adjustment factors leads to leass than optimal results.

To improve the precipitation analysis as much as currently possible, new methods are adopted to enable estimation of accumulated precipitation in a spatially precise and timely accurate manner. 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 and the accumulated precipitation for the benefit of hydropower management and other related application areas.

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

Rain gauges provide point observations of the accumulation, usually with a higher quality than radar and are frequently used to correct the radar field. Weather radar data, with its high resolution reflectivity, resolves the fine-scale patterns of precipitation field. Together with these two sources, the lightning data is assimilated within the LAPS to calculate the precipitation analyses, using the standard Z-R equation formula (Marshall and Palmer, 1948).

2.1 Surface observations

For this study, a total of about 472 rain gauges, both weighting gauges and optical sensors, provide detailed point information, used both to correct the radar field and for the verification. There are 7 stations taken out from the LAPS assimilation, to be used as independent dataset. The verification periods consists of a longer period ranging from 1 April to 1 September, 2015 (i.e. to avoid the winter season and snow precipitation) and additionally a shorter period with intense thunderstorms; 03, 23, 24 and 30 July, 2014.

The surface precipitation observations are from 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, those stations are blacklisted within LAPS 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. 1b.

2.2 The radar network

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. 1a) are dual-polarization radars. 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 figure 1a. 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 up to 68 N latitude. The Finnish radar network does have a very high system utalization rate (e.g. no interruption), years 2014 and 2015 it 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 data are further used in LAPS routines both for the rain-rate calculations but also, as as proxy data to the LDA method (see Sect. 3.2).

The raw Finnish radar volume data are remapped to LAPS internal Cartesian grid and the mosaic process combines data of the different radar stations. In LAPS, 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. Details of FMI-LAPS radar processing and factors causing differences between radar and gauge measurements and differences in sampling sizes of instruments are explained in Gregow et al. (2013).

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 figure 2. The sensor types and the working principles of the LLS 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 system used to assimilate radar, gauge and lightning measurements is described in Sect. 3.1-3.3. The impact of different integration time intervals on the RandB-method is shown 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 a dense observational input, from several sources, are fitted to a coarser background model first-guess field. Additionally, high resolution topographical data are used when creating the final analysis fields.

The FMI-LAPS produces output mainly 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 is calculating the output at a 3×3 km grid. Other information on observational usage, first-guess fields, the coordinate system etc, is well 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 Lightning Data Assimilation (LDA)

A Lightning Data Assimilation (hereafter LDA) method has been developed by Vaisala and distributed as open and free softwares (Pessi and Albers, 2014). The LDA method converts lightning rates over each grid cell into vertical radar reflectivity profiles. In addition, horizontal smoothing and quality control are performed. If there is radar coverage over the area, the lightning-derived reflectivity and real radar reflectivity data are merged. 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 LDA software is also constructed to build up statistical relationships between radar and lightning measurements. The radar reflectivity-lightning (hereafter Rad-Lig) relationships may differ depending on the local geographical regime and climate. Therefore, the end-users can collect data and derive their own Rad-Lig relationships using the LDA-method, given that the area has radar coverage. The LDA software counts the amount of CG lightning strokes within each LAPS grid-cell and, simultaneously, saves the corresponding radar reflectivity profiles. From those data, new Rad-Lig profiles are derived.

Thereafter, the new Rad-Lig reflectivity profiles are used to complement (i.e. merge or replace, depending on settings) the radar measurements within the area of LAPS analysis.

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). Those profiles can be used, for example, in case there is no radar coverage over the user's domain and new profiles cannot be derived.

For this study, new Rad-Lig reflectivity relationship profiles were constructed using NORDLIS-LLS lightning information and operational radar data from Finland area, during summer 2014. 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. $2^n ... 2^{n+1}$), according to methods used in Pessi (2013), resulting in 6 different lightning categories for the NORDLIS-LLS dataset. For each of these 6 categories, the average radar reflectivity profile is calculated (Fig. 3a). The profiles have been manually smoothed (i.e. removing peaks in the generated profiles), especially from 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).

3.3 LAPS radar and lightning based accumulation

Radar reflectivity can in some cases suffer from poor quality, resulting from; electronic mis-calibration, beam blocking, attenuation and overhanging precipitation (Saltikoff et al., 2010). In some cases the radar can even be missing, due to upgrading or technical problems. In order to potentially improve the precipitation accumulation, we investigate the inclusion of lightning data, via the LDA-method, in the LAPS precipitation accumulation calculations.

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

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

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. Although such situations 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 then calculated at every 5 minutes and the 1 hour accumulation is thereafter obtained by summing up over the 5 minutes intervals.

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In the FMI-LAPS LDA settings (i.e. when the reflectivity profiles are used for accumulation calculations), one can choose to either merge the radar and lightning data or use them separately. When merging the two sources, the highest dBZ value at each 3D grid-point will be used, derived either from radar or lightning data.

As a result, 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.

3.4 The FMI-LAPS RandB analysis method

The original FMI-LAPS RandB-method, which corrects the precipitation accumulation estimates using radar and gauges, is described in Gregow et al. (2013). The first step in this method is to make the radar-gauge correction at large scale, with the use of the Regression method. The resulting accumulation field is thereafter used as input for the second step; the Barnes analysis. Here, the final correction is done at smaller areas, gauge station surroundings, using the radar-gauge quotients.

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 following three FMI-LAPS accmulation products; Rad_RandB, LDA_RandB and Rad_LDA_RandB, respectively.

3.4.1 RandB-method and the integration time length

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 can therefore, naturally, 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 are thereafter used to make the correction within the RandB-method.

One could also consider a long historical dataset (i.e. monthly or climatology dataset). But, the idea here is 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. Note; for comparison, we use the Rad_LDA_Accum as the reference accumulation.

4 Results and verification

The focus of this article is to improve the precipitation accumulation estimates, especially the range with high accumulation values (i.e. > 5 mm/h). The performance of the LDA-method has been verified against surface gauge observations of precipitation accumulation data, 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. The 7 independent stations are excluded from the LAPS analysis. In this study we apply a filter to the datasets, accumulation data with less than 0.3 mm/h are discarded in order to avoid artificial effects, due to different detection sensitivities of the different instruments.

To test the LDA-method together with the current operational RandB-method, new FMI-LAPS runs were performed for the summer period (i.e. 1 April to 1 September) in 2015. In this setup we used the averaged (i.e. 50%-percentile) Rad-Lig reflectivity profiles from the LDA-method. In order to perform several autonomous experiments with the FMI-LAPS LDA system, a test-dataset was selected. The dataset consist of four days with heavy rain and strong convection; 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 validation of the different analysis methods are based on the standard deviation (STDEV; Eq. 4), root-mean-square deviation (RMSE; Eq. 5), coefficient of determination (R^2; Eq. 6) and Pearson's correlation coefficient (CORR; Eq. 7):

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

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

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

$$CORR=\frac{\sum_i\left(\left(Gauge_i-\overline{Gauge}\right)\left(Analysis_i-\overline{Analysis}\right)\right)}{\sqrt{\sum_i\left(Gauge_i-\overline{Gauge}\right)^2\sum_i\left(Analysis_i-\overline{Analysis}\right)^2}} \quad . \qquad (7)$$

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. R^2 describes the goodness of fit of a model and is the square of CORR which, gives a measure of dependence between two quantities.

4.1 FMI-LAPS LDA results

The overall result, using lightning data from summer 2015, shows neutral to slightly positive impact (Table 1 and Fig. 4). The verification with dependent dataset indicate neutral impact, while the independent data is slightly improved by using lightning information (Table 1). The correlation (i.e. CORR and R2) is marginally higher for Rad_LDA_Accum independent data (compared to Rad_Accum), and even though the RMSE is higher, the STDEV has been improved. The impact of using LDA-method is not transferred into the results of Rad_LDA_RandB. This is mainly because the RandB correction is more strongly influenced by the gauge correction, which therefore overrides the influence from LDA-method.

Naturally, the full dataset of summer 2015 includes many precipitating cases without lightning. The effective impact from lightning is diluted, due to the large amount of data that is not affected by LDA-method. Therefore, a subset of 25 days with more frequent lightning (e.g. > 100 CG strokes/day) were selected. The results for the dependent dataset show a neutral to slightly positive impact with improved RMSE. Whereas, for the independent data, there were no observations available (i.e. lightning did not occur at the independent stations, and therefore no results; Table 2).

In order to further narrow down the effects of the LDA-method we use the 4-days period to rerun the FMI-LAPS LDA analysis. Looking at the accumulation results from radar (i.e. Rad_Accum; black markers in Fig. 5) and lightning (i.e. LDA_Accum; red markers in Fig. 5) separately, it is shown that the use of LDA_Accum is less accurate than Radar_Accum results. The result is expected, since the lightning usually only takes place in specific areas of the precipitation field. This is visualized through the example in figure 6, where the radar- and Rad-Lig lowest reflectivity fields are plotted for one analysis time; 16 UTC, 30 July 2014. Though, this also proves that in case there would be no radar data, for example if the radar is malfunctioning, at least some information of the precipitation amount were available. The strength of the LDA-method is that the radar and lightning information can be merged and complement each other. Rerunning the 4-days period to generate the merged product, show that many of the accumulation estimates are amplified over the whole range of precipitation values (Fig. 5; compare the blue with the black markers). For the higher accumulation values (> 5 mm/h) this is a positive effect, while in lower range (< 5 mm/h) there is a small over estimation of the results. Note that the plot uses log-scale at each axis.

We investigate the LDA-method further, focusing on the impact of using different relationship profiles within the LDA-method. From the previous results we can see that the Rad_LDA_Accum has a larger bias (e.g. RMSE) in the result, compared to Rad_Accum. Here we attempt to correct this bias by formulating a new calculation of the Rad-Lig relationship profiles, in order to achieve better results for the higher accumulation values (i.e. > 5 mm/h). This experiment compares the effect of using the Average- (i.e. 50%-percentile), 3'rd Quartile- (i.e. 75%-percentile) and Variable Quartile values to generate the new Rad-Lig reflectivity profiles. The Variable Quartile approach uses a range between 50%-percentile (for the lower dBZ values) up to the 95%-percentile (for the highest dBZ values). These percentiles are chosen aiming to improve the high accumulation range (> 5 mm/h). The new Rad-Lig profiles are then used to rerun the 4-days period and to produce new precipitation accumulation output. The results are validated against Rad_Accum and can be seen in figure 7. They all improve the precipitation accumulation estimates at high accumulation values, the Averaged has weakest effect and 3'rd Quartile the strongest of the three. They all do overestimate the accumulation values in lower ranges to some extent. The Variable Quartile calculation method seems favourable, since it improves the high range accumulation values, while it still does not overestimate the low ranges too much. Note the use of log-scale, which enlarges the differences in the range of low values and reduces it in high ranges.

4.2 RandB-method and impact from the integration time length

Sect. 3.4.1 described how to extend the time sampling interval of the collected radar-gauge datasets, to be further used in the RandB-method. The plotted results are seen in Fig. 8, where verification has been done 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 (e.g. reference dataset), 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.

Discussions and conclusions

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

The longer verification period (i.e. summer 2015) and the subset of this (25 lighting instense days), show neutral to slightly improved results using the LDA-method. One reason we don't see larger impact by LDA-method is due to the use of averaged Rad-Lig profiles, which was proven to give rather low impact to the accumulation results. Another reason 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 summer of 2015 had fewer days of lighting compared to other years (on average), therefore the verification dataset was limited.

New methods to calculate the Rad-Lig profiles reveal that the Average-method smoothens out the small-scale variances, which is observed in heavy convection. Therefore, the collected radar reflectivity profiles are less representative and, hence, the calculated Rad-Lig profiles will have too low values in these cases. As a result, the Average-method will give lower impact to the final precipitation accumulation estimates, compared to the use of 3'rd Quartile- and Variable Quartile method (Fig. 7). The 3'rd Quartile approach gives the highest impact to the whole accumulation field, unfortunately this also results in largest overestimates for the low accumulation values (i.e. between 0-5 mm/h). The Variable Quartile method gives a more reasonable result, not too much overestimation in low accumulation, while there still are improvements for the large accumulation, i.e. > 5 mm/h.

One should also mention that there is an overall uncertainty due to instrumental errors. This could potentially result in dislocation and bad quality of the received radar- and lightning measurements, which would affect the LDA-method. For example in case of radar attenuation, where strong rainfall weakens some part of the reflectivity field. Here the collected radar profiles (from which we build the LDA relationship profiles) will be too low, 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 longer period. Also, for verification purposes, inclusion of areas with poor (or none) radar coverage where gauges are available, will be studied.

The usage of longer integration time for RandB-method, up till 7 days in this case, does not improve the precipitation accumulation analysis, according to this study. Instead, for the near real-time accumulation product the data used from the recent hour of analysis time does give the best result. One could speculate that there is an intermediate choice of temporal resolution. For example, there could be better results using intervals of 2-5 hours. This has not been investigated in this article but will be, 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 was performed against both the dependent and independent stations datasets, during 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
R^2	0.42	0.42	0.87	0.87
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
R^2	0.51	0.52	0.84	0.84
CORR	0.71	0.72	0.92	0.92

Table 2. Same as in Table 1 but for a period of 25 intensive lightning days (e.g. > 100 CG strokes/day), during summer 2015. Verification both for the dependent and independent stations dataset.

	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
R^2	0.45	0.45	0.87	0.87
CORR	0.67	0.67	0.93	0.93
Independent				
Nr of observations	0	0	0	0

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Table 3. Impact of the integration time length on RandB-method, for the dependent and independent stations datasets, during summer 2015.

	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
R^2	0.41	0.86	0.83	0.81	0.80	0.80
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
R^2	0.48	0.84	0.62	0.59	0.59	0.59
CORR	0.39	0.92	0.79	0.77	0.77	0.77

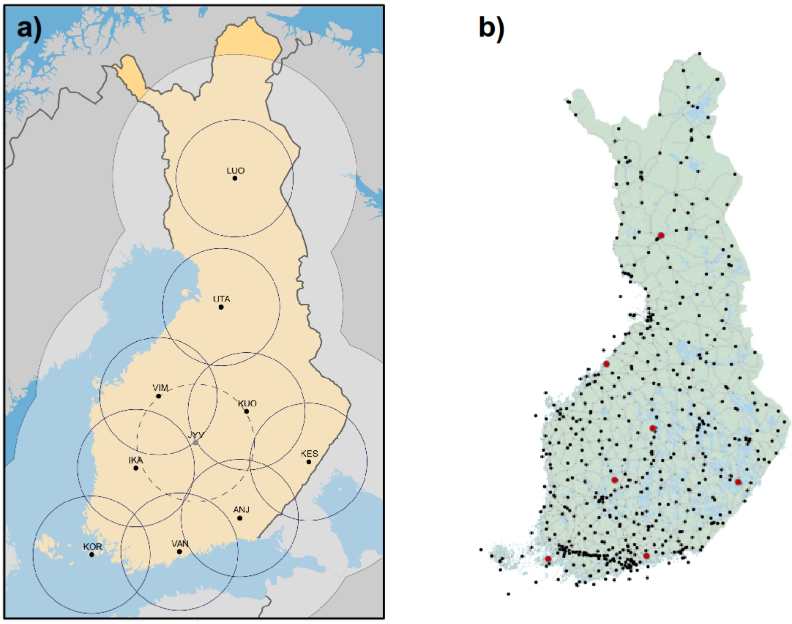

Figure 1. (a) The outer rectangular frame of the map depicts the LAPS analysis domain. The red dots represent the 10 Finnish radar stations and the thick, black curved lines display their outer coverage. The thin circles surrounding each radar represent the areas where measurements are performed below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

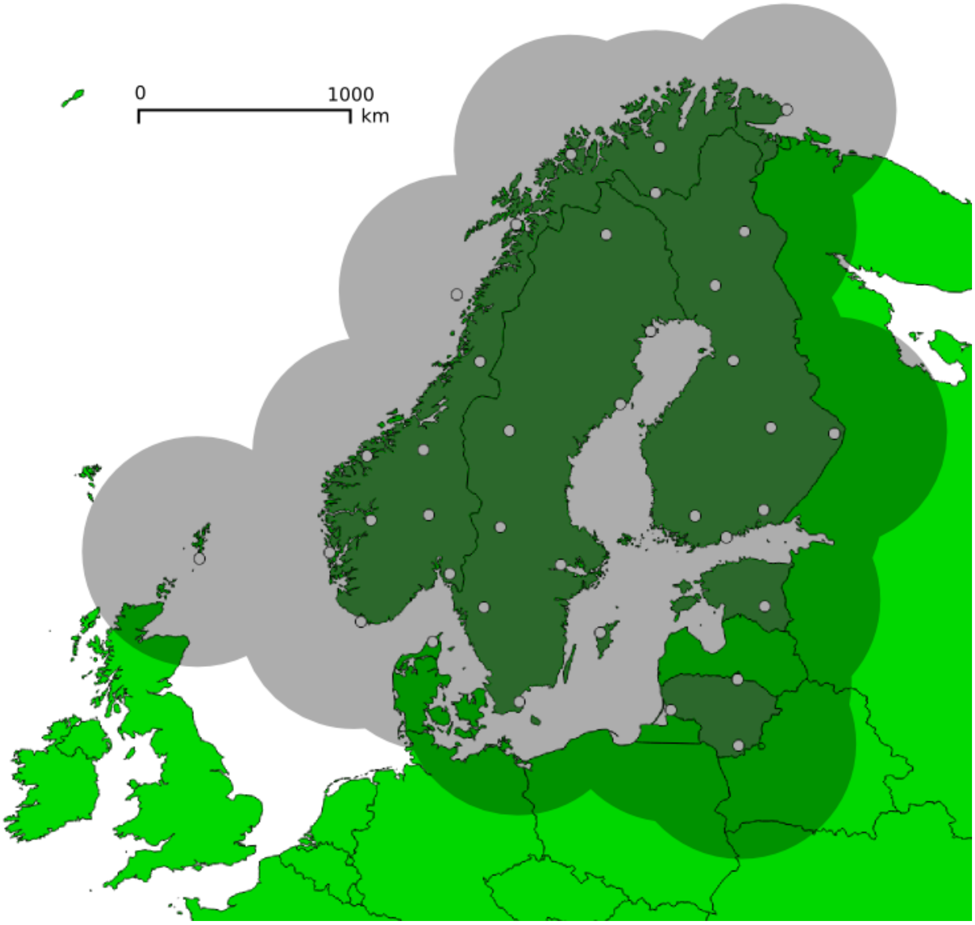

Figure 2. The LLS sensor locations (white dots) and coverage (grey circular areas), as of year 2015.

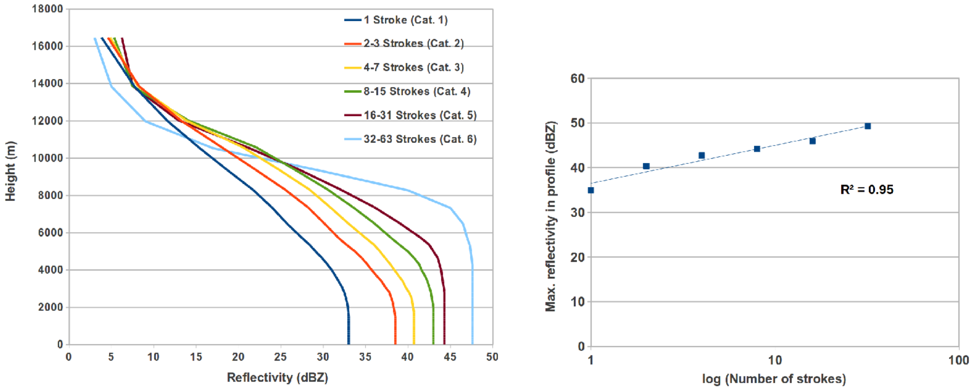

Figure 3. In a) Rad-Lig relationship profiles (smoothed) from Finland NORDLIS-LLS, calculated from summer 2014 dataset. In b) profile's max reflectivity values versus lightning rate (logarithmic-scale of bins).

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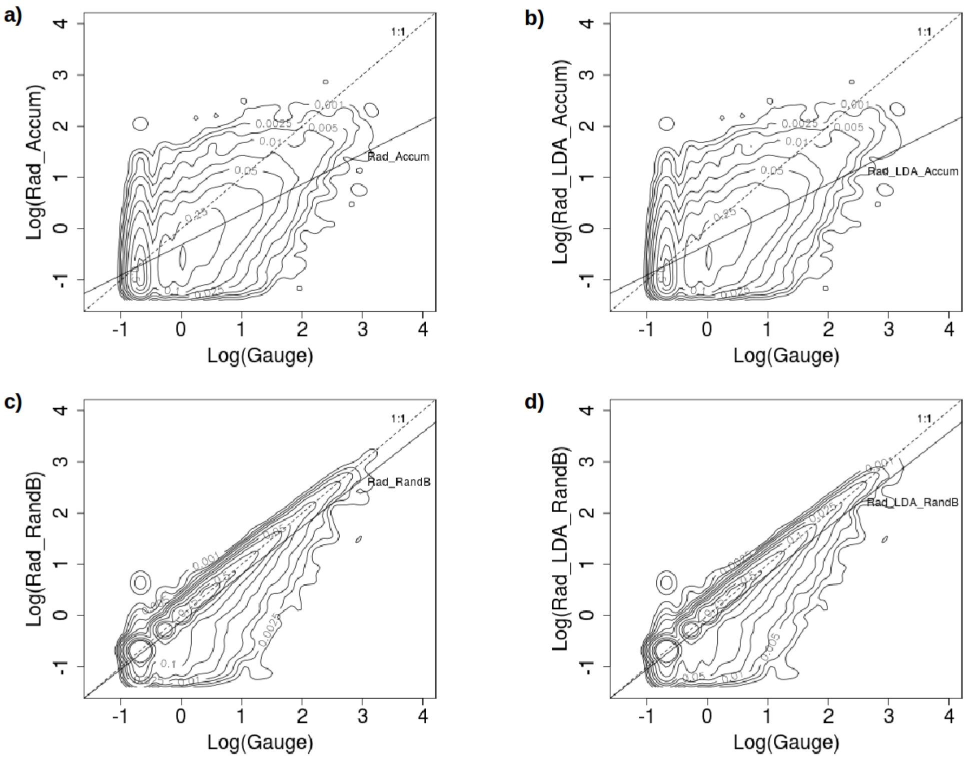

Figure 4. The FMI-LAPS precipitation accumulation (mm/h in log-scale) calculated using different methods. Results in; a) Rad_Accum, b) Rad_LDA_Accum, c) Rad_RandB and in d) Rad_LDA_RandB, for the independent dataset of summer 2015. Shown is also the best fit line (1:1).

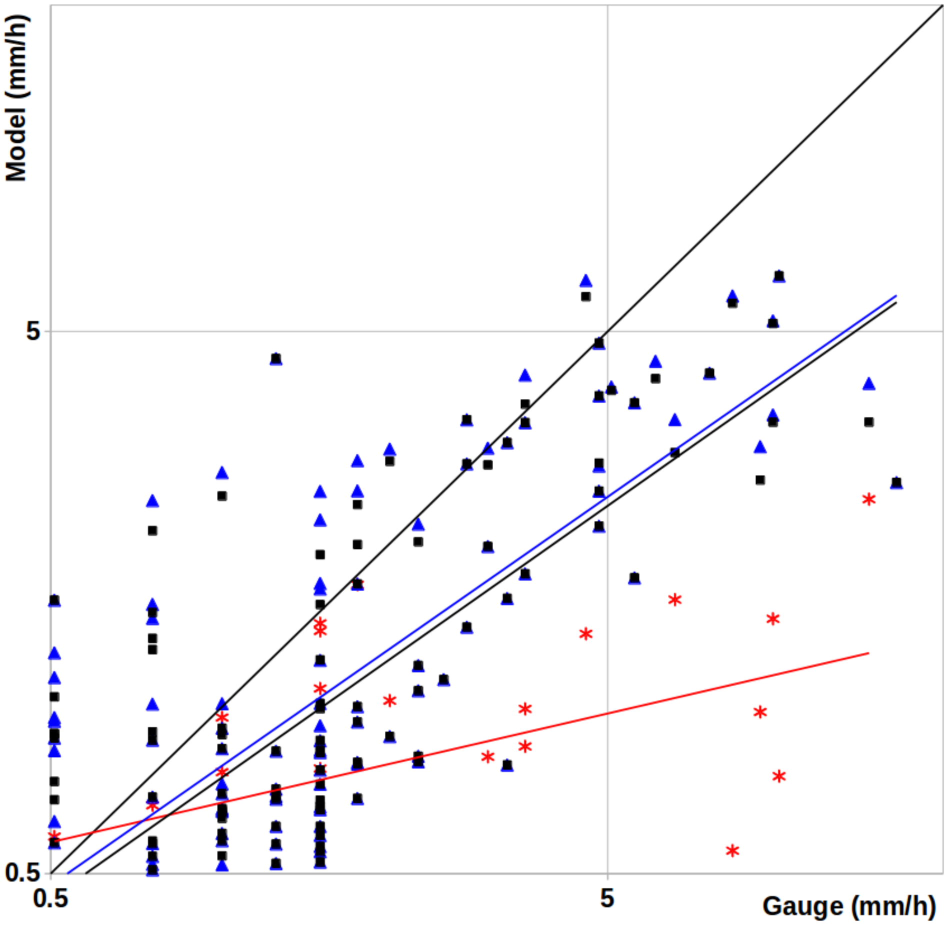

Figure 5. Verification results for LDA_Accum (red stars and line) and the merged Rad_LDA_Accum (blue triangles and line), compared to Rad_Accum (black boxes and line) for the 4-days period (July, 2014). The axes are log-scaled. Black solid line is the best fit line (1:1 fit).

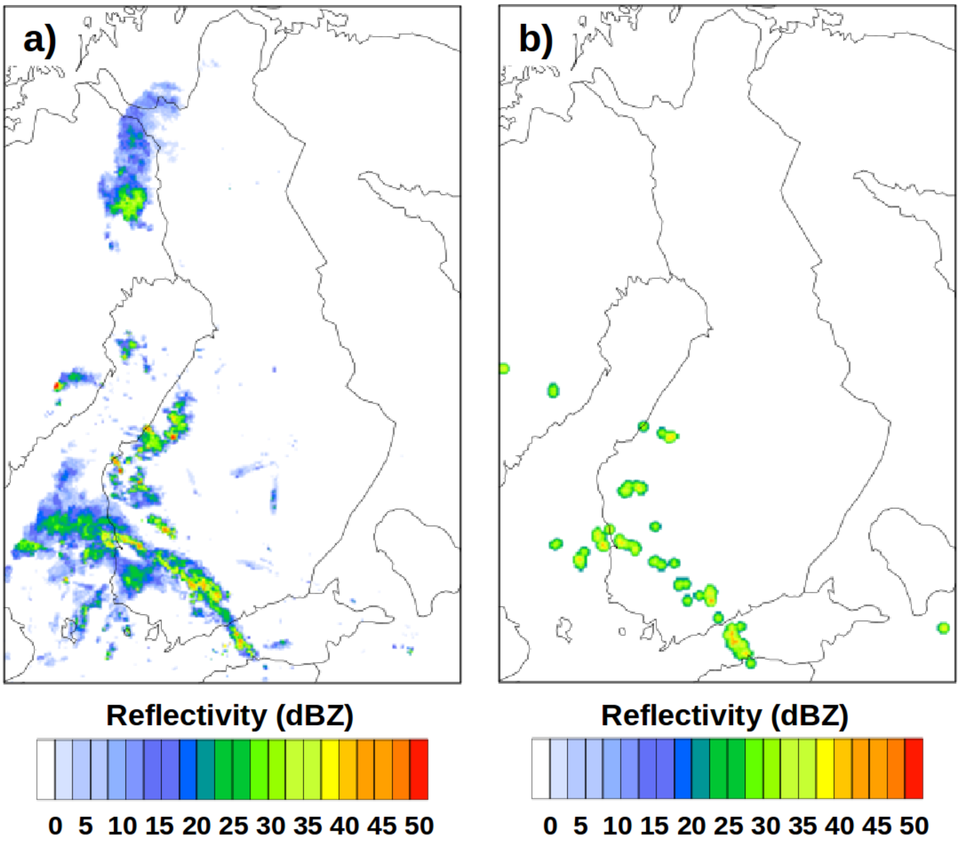

Figure 6. Example of a) radar reflectivity and b) LDA (only lightning) generated reflectivity, for 30 July 2014 at 16 UTC. Reflectivity color scale is shown below plots.

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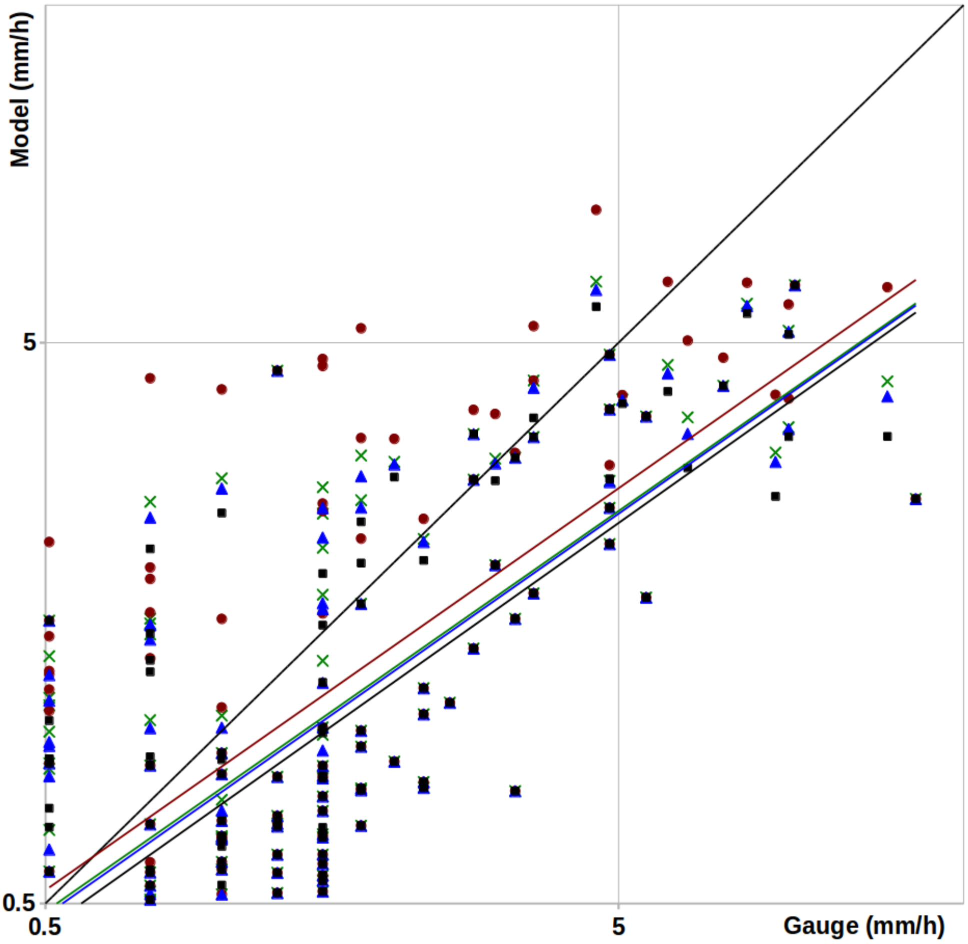

Figure 7. Comparison between Rad_Accum (black squares) and LDA_Accum (triangle-, cross- and circular markers), using 3 different methods to calculate the relationship profiles; Average- (blue triangles), 3'rd Quartile- (red circles) and the Variable Quartile (green crosses) accumulation estimates. Data are for the 4-days period in summer 2014. The best fit curve (i.e. the 1:1 fit) is shown as black solid line.

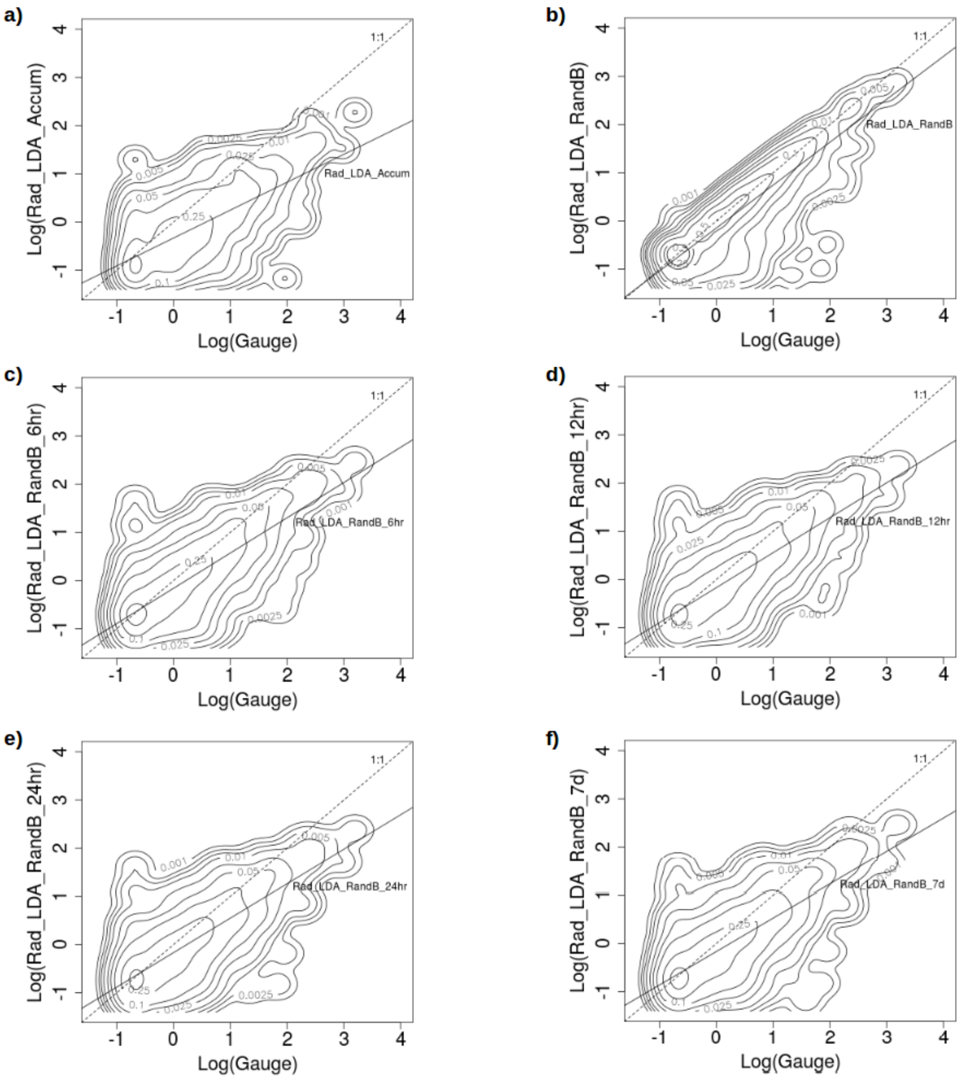

Figure 8. Impact of changing the integration time length (verification for the independent gauge datasets); a) Rad_LDA_Accum, b) Rad_LDA_RandB-, c) Rad_LDA_RandB_6hr-, d) Rad_LDA_RandB_12hr-, e) Rad_LDA_RandB_24hr- and f) Rad_LDA_RandB_7d accumulation estimates.