Response to reviewer 2 of amt-2019-135

In this document we provide answers to the comments of reviewer 2 of the paper amt-2019-135. Our answers to the reviewer are given in *italic* font. Proposed changes to the manuscript are highlighted in blue color.

On 2017 during the Santis campaign, in Swiss, the unique chance for high resolution observations of convective cells and associated lightnings took place. For the first time in the Alps a LMA was set up allowing detection of intra-cloud (IC) and cloud-to-ground (CG) lightings in complex horography. The lightnings observations by LMA collected during the aforementioned campaign are analysed with EUCLID lightnings data and TRT severity rank. A general agreement between EUCLID and LMA observations is found but some relevant disagreements occurred.

TRT severity rank seems to be poorly correlated with lighting activity, while rimed particle columns is a better predictor of lighting activity. Related to their lightning activity, the detailed study of two convective cells confirmed different hydrometeor compositions between the two cells.

The paper is valuable, investigating one of the most relevant and still partially not well understood process in clouds: the lighting activity in convective atmosphere. Nevertheless, the paper is largely unclear and improvements are needed to increase the paper clearness.

First of all, the language is sloppy with a lot of mis-spellings and unclear sentences (e.g. page 7 line 5 "The hypothesis for that is that: : :", or same page line 17 "Moreover, when no RPC was retrieved, i.e. RPC height equals 0, The dominant type") : a deep language review is mandatory.

We thank the reviewer for positively valuing the paper. We have thoroughly reviewed its language

General comments and recommendations

As anticipated by the generic paper's title "Analysis of lighting production of convective cells", the main focus of the paper is unclear: is it to find good predictors of lighting activity? Or, is it to relate lighting activity and TRT severity rank? Or, is it to compare EUCLID and LMA observing systems? Or, is it to assess lighting efficiency? Or all these points?

We respectfully disagree with this comment according to which the main focus of the paper is unclear. The objectives of the paper are stated quite clearly in the introduction (lines 25-30 on page 2). In short there is a need for more targeted operational warnings regarding lightning activity (both cloud-to-ground and intra-cloud). Currently, the one product at MeteoSwiss that is used to issue warnings of convective situations (where most lightning is produced) is the TRT algorithm. It is just natural that we want to investigate whether there is a strong relationship between the TRT rank and the lightning activity. The paper demonstrates that there is a weak link between the two and hence a new predictor, the RPC column, is proposed. Its performance regarding both intra-cloud and cloud-to-ground activity is assessed, both statistically and through a case study, demonstrating positive results. LMA and EUCLID data are simply used because of their different observing capabilities to better differentiate intra-cloud from cloud to ground activity.

The introduction focuses on warnings based on lightning activity while it lacks of several references on lighting processes in clouds (Carey and Rutledge, 2000, Baker et al. 1995, Buiat et al. 2016, Adirosi et al. 2016 Mattos et al, 2016, Lund et al. 2008).

As mentioned in the response to reviewer 1, the link between microphysics and lightning activity was discussed in a previous paper by the authors. We now explicitly mention this paper in the introduction and have also added several of the suggested references in it. See the response to reviewer 1 for the introduced text.

The analysis is quite shallow (the physical explanations of results are often missing), resulting quite confusing and hard to follow. For example at page 5 line 7 "The cells that spent their entire lifetime within the LMA domain boundaries tended to be shorter-lived and weaker. The highest rank of a cell generated and dissipating within the domain was moderate (2.1)": why does LMA area show weaker storms?

We have re-formulated the mentioned lines to clarify what we meant:

Most cells were traveling from west/south-west to east/north-east. The cells that were most severe at the time when they crossed the reduced LMA domain originated from outside of it and were crossing it at an already fairly mature stage. Due to the relatively small area covered by the reduced LMA domain, the cells that spent their entire lifetime within its boundaries tended to be shorter-lived and weaker since they either dissipated early without growing in severity or they abandoned the reduced area. The highest rank of a cell generated and dissipating within the domain was moderate (2.1).

At page 7 line 4 "The hypothesis for that is that the strong updraft characteristic of severe cells would lift the charge centers higher up (thus making it less likely for flashes to reach the ground) and prevent particles to grow and acquire charge at a given level (thus reducing the IC flashes likelihood)". Here, the authors move from TRT severity rank to cell updraft. One difficulty is the relationship between TRT severity rank and updraft strength (not straightforward, indeed). Moreover, updraft–total lightning relationships of individual thunderstorms have been explored in several previous publications (Lang and Rutledge, 2002; Tessendorfet al., 2005; Wiens et al., 2005): authors hypothesis should be framed in this context that demonstrated the role of updraft area.

We agree that the relationship between TRT severity rank and cell updraft is not so clear cut. However, our observations are in line with multiple reports in literature. We have added the suggested publications to the already mentioned article from Montanyà et al. 2007.

The role of RPC columns is underlined by the authors. Several characteristic RPC heights derived by weather radar observations, are reported: heights error and uncertainties should be discussed and reported.

We decided to expand the discussion of the RPC column and devote a subsection to it. We added the following text:

2.1.4 Rimed particles column computation

Out of the hydrometeor-classification cell profile, constructed by taking the mode at each height level of 250 m resolution, we compute the rimed particles column. We consider the base of the column as the height of the bottom of the lowest height level where rimed particles or hail are predominant and the top of the column as the height of the top of the highest height level where those species are predominant. The RPC height is therefore the difference between those altitudes. The possibility that height levels within this column have other predominant hydrometeors is neglected since we assume that isolated rimed particle areas cannot exist so in any case a significant if not dominant proportion of hydrometeors would be rimed particles.

The RPC has several sources of uncertainty. In the first place, the nominal resolution of the column is equal to the resolution of the cell profile. Hence, in our particular case, columns less than 250 m high will not be detected. The effective resolution though depends on the length of the volume scanned by the radar, which is determined by the radar beamwidth. With a beamwidth of 1°, the effective resolution exceeds 250 m at approximately 14 km range. Secondly, it is dependent on the precision of the hydrometeor classification. Generally speaking, in areas with good visibility, rimed particle columns have a clear signature that allows a good differentiation between them and other solid species such as ice crystals and aggregates, provided that precipitation-induced attenuation has been sufficiently accounted for and the radar is reasonably well calibrated. Classification may be more prone to errors in transitioning areas, particularly close to the melting layer, where no hydrometeor can be considered dominant. Consequently, the uncertainty is higher in determining the base of the RPC. A third source of uncertainty is related to the time resolution of the radar scan. In our case, it takes 5 min to sample a full radar volume and 2.5 min to get a half volume. Cells moving fast with respect to the radar may have been displaced significantly, resulting in a tilted-shape cell and the cell core may already have partially or even totally left the area where the cell is estimated to reside. A final source of uncertainty is geometrical, which has two main issues. In the first place there is an issue with the minimum and maximum visible altitude by the radar. Assuming a typical melting layer top placed at 3000 mMSL and no beam blockage, the distance at which the radars in the Swiss radar network may observe the base of the RPC ranges from 200 km for the radar placed at the lowest elevation (Albis) to on the order of 40 km for the highest placed radar (Plaine Morte). Obviously, in areas of beam blockage (the Alps and the Jura mountains), such ranges are further reduced. The maximum visible altitude close to the radar is determined by the extend of the so-called cone of silence. For example, in the case of the Albis radar, the maximum visible altitude does not reach 10000 mMSL until up to 30 km from the radar. Furthermore, in order to reduce the data size, the highest radar beams maximum range is capped. Consequently, at ranges further than 160 km, the maximum visible altitude is reduced to below 10000 mMSL. Another source of error is related to how well the radar volume is sampled. Since the dominant hydrometeor is determined using all the data within the resolution volume formed by the cell area and the height resolution, the sampling is determined by how many radar gates cover such volume. If the cell area is small and/or there is a large gap between beams, it may happen that few or none radar range gates can be used in the sampling and therefore gaps may appear in the RPC.

Considering all the sources of error aforementioned, we estimate that for individual radars with good visibility, RPC can provide useful information in a range between roughly from 20 to 80 km. Outside of that range, they may still provide useful information but it should be considered qualitative in nature. In a dense radar network such as the Swiss one, the RPC coverage can be extended by making use of a radar composite, which benefits of the observation of the same column by multiple radars. For the purpose of this study though, we assume that, at least in the LMA coverage restricted domain discussed in the following subsection, the RPC coverage is sufficient.

In the cells analysis time are expressed in local time?

All times in the article are UTC. We have clarified that where it was ambiguous.

The authors find very weak correlation between TRT severity rank and lighting activity: it is not clear why a correlation was expected. Moreover, is it the sampling statistically meaningful (only eight severe cells)?

As stated in the previous answer to comments we wanted to assess whether there was correlation between the two parameters to see whether TRT rank can be used in an operational context. We already suspected that this was not the case and the results shown simply prove that. We think that even though the sampling size is relatively small we already proved the point that TRT rank cannot be used operationally to predict lightning activity.

At page 9 line 20 "Cells without lightning activity during their life cycle were mostly classified as weak but the rank of the convective cell is a poor indicator of its lightning activity, particularly considering CG flashes." The authors should try to explain the reason for this result.

We have reformulated the point and provide an attempt at explaining it:

Cells without lightning activity during their life cycle were indeed classified as weak. However, the rank of the convective cell is a poor indicator of its lightning activity, particularly considering CG flashes. In half of the cells studied, the maximum of lightning activity was reached after the maximum rank was reached and in a quarter it was reached before. Generally speaking, the maximum lightning activity was reached at the time period when cells were classified as weak to moderate. Our hypothesis is that this is linked to the VIL term in the ranking equation, effectively is an integral of reflectivity over height. As such, much more weight is given to the mixed-phase and liquid regions of the precipitating system which, due to the large dielectric constant of their hydrometeors, have a much larger reflectivity. However, it has repeatedly been shown in literature that increases in lightning rate tend to happen before and after the most severe (on the ground) phase of the convective precipitation.

The authors conclude that different ice distribution within clouds is responsible for different lighting efficiency: however, this conclusion is supported by the analysis of only two cells. It is a clue, but for a reliable assessment more cases need to be studied.

The conclusion is sustained both by the case studies and by the (limited) statistical analysis of the TRT cells. In this particular study we took the chance of having the LMA network to study in more detail intra-cloud lightning activity that is not observable by the operational EUCLID network. We agree that more case studies are needed but we think that nevertheless our observations are worth publishing.

Specific comments

Page 9 line 32 It is not evident why LMA network is usefulness in complex terrain: could the same result be obtained by satellite observation?

The LMA network provides details of the 3D structure of the intra-cloud lightning. Satellite observations cannot provide that.

Page 10 lines 1-4 Mosier et al 2010 and Seroka et al 2012 should be taken in account as pioneering works on this topic.

We added the suggested references to the introduction:

It should be mentioned that there have already been some attempts at lightning nowcasting based on single-polarization radar products (e.g., Mosier et al., 2011; Seroka et al., 2012).

Figure 1 Quite unclear: please change basemap, add distance reference, North arrow and more contrasting colors.

We have increased the base map resolution, increased the size of the text and add a north arrow and distance reference as requested. We hope that this satisfies the requests from the reviewer.

Figure 2 please y-axis range equal to x-axis. 500 LMA observations sound very strange.

Done as requested. We see nothing strange in the fact that 500 flashes were detected in a TRT cell by the LMA.

Figure 9 RPC base height equal zero m ASL is quite confusing.

We changed 0 to NA and mention its meaning in the figure caption.

Figure 10 please insert a base map with orography in track plots. Please, make y-axis with same range.

Done as requested

Figure 11 It is not clear the need to multiply by ten the cell rank. Please, make y-axis with same range

Done

Figure 12 The maximum values seem to be spikes (anomaly and isolated very high values)

The frequency of occurrence is computed over the total number of sources/flashes at each time step, hence if there is just one flash detected over the entire TRT cell volume it will get the value 100%. We have clarified that in the caption:

Note that the percentage is computed over the total number of flashes/sources at each timestep, i.e. if only one flash was detected over the time step, the corresponding height where the flash was detected will have a value of 100%.

Figure 13 which is the RPC base or top altitude estimations uncertainties? 50 meters?

The uncertainty is equal to the height resolution, i.e. 250 m