Referee comments

October 14, 2024

1 Referee 2

The authors study two lightning cases (the first and fourth cloud of a thunderstorm event) using a dual frequency radar (with unfortunately only one usable frequency of 35 GHz). The authors combine polarimetry and Doppler spectra to present an interesting and novel study which looks at the presence of different hydrometeor types and their alignment in thunderstorm clouds around the times when lightning is occurring. Other processes such as turbulence are also considered.

Although the manuscript is interesting and novel, I think it will benefit from the edits described in this document. In particular, I believe some of the analysis is based on scattering simulations which are not representative of the problem. I would like to see improvements related to that, or at least some clarification on why the authors believe conclusions can be drawn from these scattering simulations. Because of this, my recommendation is a major revision.

The authors express their gratitude to Referee 2 for the thorough and meticulous review, which provided many valuable suggestions to enhance and improve the article. Referee 2 can find our responses in blue (italic) below.
Regarding the scattering simulation, for this initial study of thunderclouds based on radar observations at mm-wavelengths and spectral polarimetry, the authors aimed to use existing scattering codes or databases. The use of the T-matrix code was intended to aid in interpreting the spectral polarimetric measurements, and we are aware of its limitations. Specifically, we sought to gain a preliminary understanding of the variability and sensitivity of sZ_{DR} and $s\delta_{co}$ in relation to axis ratio, ice fraction, and canting angle.

1.1 General comments

1. I feel like the section/subsection organisation in section 5 could be better. The current organisation is:
   5 Case analysis
   - 5.1 First cloud
     - 5.1.1 Alignment of particles
     - 5.1.2 Supercooled liquid water
   - 5.2 Fourth cloud
     - 5.2.1 Evidence of conical graupel
     - 5.2.2 Alignment of particles
     - 5.2.3 Strong updraft and turbulence
     - 5.2.4 Possibility of chains

   In terms of the subsections (5.1 and 5.2) I find it slightly confusing to refer to the first and fourth cloud. Without reading the paper in depth, one might expect to find sections for the second and third clouds too. Perhaps it's worth changing to something like cloud A and cloud B rather than first cloud and fourth cloud, and then just pointing out which clouds they are.
   Considering the figures showing the four thunderstorm clouds (Figs 2-5), which relate to the weather radar images in Appendix A, the authors would like to keep the terminology first cloud and fourth cloud for clarity.
   Moreover, I think it might be better if the subsubsections were consistent in subsections 5.1 and 5.2. For example, something along the lines of:

5 Case analysis
5.1 Cloud A
5.1.1 Alignment of particles
5.1.2 Interesting microphysical properties
5.2 Cloud B
5.2.1 Alignment of particles
5.2.2 Interesting microphysical properties

The authors agree with the proposed restructure of the subsections, which are now:
5 Case analysis
5.1 First cloud
5.1.1 Alignment of particles
5.1.2 Interesting microphysical properties
5.1.2.1 Supercooled liquid water
5.2 Fourth cloud
5.2.1 Alignment of particles
5.2.2 Interesting microphysical properties
5.2.2.1 Evidence of conical graupel
5.2.2.2 Strong updraft and turbulence
5.2.2.3 Possibility of chains

2. In various places you refer to “Mie scattering” and the “Mie scattering regime”. I understand that you are talking about non-Rayleigh scattering, and to me describing this as the “Mie scattering regime” is ok (although you could consider “resonance regime”). Referring to “Mie scattering” on its own is slightly questionable to me, as Mie theory is applicable only to spheres. I recommend that in places where you say “Mie scattering” you could change to resonance or non-Rayleigh scattering (unless you are talking about spheres in any of these places...).
The authors kept "Mie scattering regime" and replaced "Mie scattering" by "non-Rayleigh scattering" or "resonance" in function of the context.

1.2 Specific comments

Line 11: these thunderstorm clouds, or all thunderstorm clouds?
The sentence was rewritten as: "From the results, there is a high chance that supercooled liquid water and conical graupel are present in the investigated thunderstorm clouds."

Consider adding Saunders and Wahab reference for lab measurements of chains forming due to electric fields at -12C and -8C: Saunders, C. P. R. and N. M. A. Wahab, 1975: The influence of electric fields on the aggregation of ice crystals. J. Meteorol. Soc. Jpn., 53, 121–126.

Also Stith et al 2002 for chains observed in clouds: Stith, J. L., J. E. Dye, A. Bansemer, A. J. Heymsfield, C. A. Grainger, W. A. Petersen, and R. Cifelli, 2002: Microphysical Observations of Tropical Clouds. J. Appl. Meteor. Climatol., 41, 97–117, https://doi.org/10.1175/1520-0450(2002)041<0097:MOOTC>2.0.CO;2.
The authors would like to thank Referee 2 for providing complementary references. Lines 65-70 are rewritten to include the results of these studies.

54/55: Riming doesn't necessarily form large, dense, near spherical particles. For example, if you have a single dendrite monomer which experiences light riming, it won't become much bigger or “near spherical”. Perhaps you could rephrase this in a less extreme way, such as “...generally resulting in increased particle size, density and sphericity”.
Rephrased. Lines 58-59.

60 and 63: You refer to aggregates as spherical. The appropriate shape approximation of aggregates is something that is still debated (e.g. see the introduction of this paper: https://doi.org/10.5194/amt-14-6851-2021), but usually a spheroidal or ellipsoidal shape would be assumed rather than a sphere. Anyway, in this instance it is probably sufficient to make very slight edits like:

- On line 60 you could maybe just make it more general, e.g. "...form larger particles that tend to be more spherical in shape". On line 63 you could just remove the word "spherical".
Thank you for the proposed edits.
Lines 64-68: "Aggregation occurs when ice crystals collide with each other and form larger particles that tend to be more spherical in shape. Various lab measurements have demonstrated that when an electric field of more than around 50 kV m^{-1} is present, aggregation of ice crystals may be enhanced due to attractive electrical forces induced between neighbouring conducting crystals, forming elongated chains rather than almost spherical clusters (Conolly et al. 2005)."

81: ", which also implies the existence of collisions of hydrometeors." I'm not sure what you mean here. Do you mean that collisions are more likely because there are mixtures of particles with different velocities?
We suppressed this part of the sentence.

118: Is the 94 GHz completely un-usable? The combination of 35 and 94 would be beneficial for determination of particle size. In fact, unless you are referring to something else, this is precisely thanks to "complications due to Mie scattering". Can you not just correct for attenuation; I think you can correct for liquid water attenuation because you know the LWP?
The authors agree with Referee 2 and may revisit the combination of 35 and 94 GHz using Dual-Wavelength Ratio. The main issue encountered was a significant decrease of sensitivity for the Doppler spectra measurements at 94 GHz at large heights.
Lines 135-137: "In this study of thunderstorm clouds, only the 35 GHz data is used since there are numerous issues associated with the 94 GHz data including significant attenuation, less sensitivity at large heights, Doppler aliasing and complications due to resonance."

112 (Section 2): In Figure 2 you have numbered clouds to identify which ones you are referring to. In the other figures (Figs. 3-5) it would be useful if you highlighted the regions of interest somehow, e.g. by drawing lines or a box around the specific times/heights you are looking at.
The authors think that based on Fig. 2, the clouds 1, 2, 3 and 4 can be clearly identified in Figs. 3-5.

150: does the high SLDR occur slightly later than the negative ZDR? Hard to tell on this axis.
This case was discarded and not studied in details. The authors focused on selecting appropriate times with no precipitation reaching the ground to avoid misinterpretation.

240-244: it would be helpful to include approximate values such as Doppler velocities close to 0m/s rather than just referring to the right and left part of the spectrum.
The authors did not change the formulation. The Doppler velocity measurement contains two contributions, one caused by the fall velocities and one due to the radial wind. Therefore, it can occur that Doppler velocities related to the smallest particles have significant positive values, while the Doppler velocities related to the largest particles have values near 0 m/s.

245/470: Your references Lu et al 2016 a and b are the same paper
Did you extract the conical graupel from the database, or does it have the information about negative ZDR and conical graupel in the reference you give?
Duplicated reference is fixed. The information about negative ZDR and conical graupel is not given in the paper Lu et al. 2016. Therefore, we obtained Zdr of conical graupel from the database. This is made clear in the following lines:
Lines 61-63: "Scattering simulations carried out by Oue et al. (2015) and data from the scattering database created by Lu et al. (2016) indicate that conical graupel can produce negative differential reflectivity (Z_{DR}) values at X-, Ka- and W-band."
Lines 270-271: "On the other hand, based on the database described by Lu et al. (2016), negative Z_{DR} for large particles only may indicate the presence of conical graupel."

Maybe the Aydin and Seliga (1984) paper could be useful for you: `https://journals.ametsoc.org/view/journals/atsc/41/11/1520-0469_1984_041_1887_rpbpoc_2_0_co_2.xml`
Thank you for the reference. The paper provides zdr of conical graupel at 10 cm wavelength.

255: could you add some references for "This part of the spectrum is often referred to as the Rayleigh plateau"?
A reference was added.

285: as you are saying m_eff can be determined, would it be better for the equation to be m_eff=sqrt(eps_eff)?
The equation was modified to better relate to the text.

291: "different types of particles" is a bit vague, please elaborate
The text was modified.
Lines 315-317: "In the first experiment, the axis ratio of spheroids with a zero mean canting angle was varied from 0.1 to 1.2. This range encompasses the axis ratios of plates, dendrites, aggregates, and graupel. The ice fraction was held constant at 0.6, representing the average ice fraction for the aforementioned ice particles."

295: Why did you choose these particular values of axis ratio and ice fraction? E.g. aggregates are often considered to have aspect ratio 0.6.
Citation added in the second sentence of the paragraph.
Lines 313-315: "The axis ratio and ice fraction of the particles in the simulation experiments were chosen according to the data given in Spek and al. (2008)."
Further, the authors replaced "aggregates" by "slightly oblate aggregates" in Line 321 and caption of Figure 10.

313: Can you provide an explanation of how a horizontally aligned prolate spheroidal model is different to an oblate spheroid?
Thank you for spotting this inconsistency. In section 4, "horizontally aligned spheroids" has been replaced by "spheroids with zero mean canting angle" in the text, the figures caption and Table 2.
We added the following sentence in the subsection 4.3 (canting angles):
Lines 358-360: "A zero mean canting angle corresponds to oblate spheroids being horizontally aligned and prolate spheroids being vertically aligned. To represent prolate particles as horizontally aligned, they are modeled with a mean canting angle of 90 degrees."

319 (and elsewhere): Figure caption – change "scatterers" to spheroids
Done.

320: Figure 9 and Figure 10 - You don't seem to refer to the reflectivity plots here, either include a reference to them in the discussion, or remove them. This could even be something simple like pointing out that the Mie minimums can be seen in the reflectivity plots.
There is now reference to Figures 9-10 first row (reflectivity) in Lines 347 and 357.

325: You are talking about ice fractions of 0.8 and 1, right? Thus, I think "For a radius of larger than 2.5 mm representing large aggregates such as graupel" is a bit misleading, as presumably such large ice fractions would only represent graupel / some heavily rimed particle and not any other unrimed aggregate type? If you agree, you could just rephrase e.g. "Particles of this size and ice fraction could represent graupel…".
Rephrased.
Lines 350-353: "When ice fraction is large (0.8 and 1), the sign of Z_{DR} flips soon after reaching the first extremum, and the trend is rather unpredictable. For particles of this ice fraction with radius larger than 2.5 mm, which could represent graupel, significant negative (positive) values could be obtained, which increases the interpretation challenge."

366: why small but not large? Do you just mean that large particles usually aren't oriented by the field? Please elaborate.
We rephrased the paragraph to improve its clarity.
Lines 396-402 : "From Fig. 11(a) and (b), intriguing polarimetric signatures can be observed within the cloud. Fig. 11(a) illustrates that Z_{DR} values are near zero with minimal variation. Conversely, Fig.

11(b) reveals a cluster of negative K_{DP} values between 7600 m and 9300 m, suggesting the alignment of non-spherical small ice particles. If these small ice particles are present in sufficient concentration, K_{DP} would become negative. The large ice particles, on the other hand, are expected to be slightly non-spherical, which leads to a small contribution to K_{DP}, and may not align with an electric field unless it is sufficiently strong. Because Z_{DR} is reflectivity-weighted, large ice particles significantly influence Z_{DR}, which likely explains why Z_{DR} does not exhibit significant negative values."

368: What is the temperature here, can you get any information on the particles from that? Perhaps you only have temperature measurements in the vertical.
The temperature from 7600 to 9300 m measured by the microwave radiometer is around -24 to -41 °C. However, it is challenging to get information on the particle types from the temperature since particles formed at certain temperature ranges are moved around by updrafts and downdrafts, and the temperature is measured vertically, so it is not the actual temperature in the measured cloud at 45 deg. elevation.

381: this is interesting, how did you obtain the "lightest 10%"?
We replaced "lightest" by "smallest" in the text and Fig. 13.
Lines 413-415: "Figure 13 shows the mean sZ_{DR} of the smallest 10% of the particles in each radar resolution volume at the three time instants. This is achieved by averaging sZ_{DR} over the rightmost 10% of the Doppler bins."

387: Be consistent with units, either m or km
Corrected.
Lines 420-422: "Negative K_{DP} appears at a distance of 7600 m to 9300 m away from the radar, but the lightning strikes occurred at least 13000 m away from the radar."

390: You mention Fig. 16 here but I think you have not yet discussed Figs 14 or 15, maybe the figures should be reordered.
Fig. 16 is dedicated to the section 5.1.2.1 Supercooled liquid water. Therefore, we must have it after Figs. 14-15.

406/408: make the vertical wind shear units the same.
Done.
Lines 436-439: "For a 10 m s^{-1} spectrum width and $V_t = 2$ m s^{-1} corresponding to the upper bound of the terminal velocity of plates (Spek et al. 2008), a shear of approximately 25000 m s^{-1} km^{-1} would be required to flip the spectrum, much larger than the 4 m s^{-1} km^{-1} observed from 7500 m to 10000 m in ECMWF data shown in Fig. 15(c)."

417: here and in the rest of the subsubsection, you refer to "a lightning" or "lightnings". I believe these should be "a lightning stroke" and "lightning strokes".
"stroke" was changed into " lightning strike".

450: What frequency? The caption of Fig 18 says 94 GHz but line 130 says LWP comes from 31.4GHz?
Thank you for noticing the discrepancy. That is now corrected in the caption of Fig. 18 and the text (Line 150). We used the embedded 89 GHz passive channel.

468: Can you explain what you mean by "Since small particles are more easily aligned by an electric field and they are not aligned in this case,"? Do you just mean that the part of the spectrum corresponding to small particles has sZDR close to zero, implying that the negative sZDR corresponding to the larger particles is not caused by vertical alignment?
We rephrased the sentence:
Lines 542-546: "When negative sZ_{DR} appears on the left part of the spectrum, the sZ_{DR} on the right part of the spectrum is close to zero. The observed negative sZ_{DR} values on the left part of the spectrum may suggest the presence of conical graupel (Lu et al. 2016), as smaller particles, which are typically more easily aligned by an electric field, do not appear to be aligned in this case, as indicated by the absence of slightly negative sZ_{DR} values."

There is also lower correlation coefficient in this region, implying mixture of particle shapes.
That is true. We have therefore mentioned this observation.

477: You hypothesize conical graupel, but you then model conical graupel with a spheroid. Please provide an argument for why you think you can get any information about conicality if you are using a spheroid. Perhaps you could just refer to results/simulations in the literature for conical graupel.
To strengthen the discussion related to the simulation, we analysed as well Lu et al. 2016 database results for conical graupels. We used 8 points corresponding to the radius, 0.2 mm, 0.3 mm, 0.4 mm, 0.5 mm, 1 mm, 1.5 mm, 2 mm and 2.5 mm and an approximate density corresponding to ice fraction 0.6. For the cone angles we selected 40 and 50 deg. In that case, simulations (T matrix prolate particles), (conical graupels Lu database) and observations provide comparable results in terms of trends for Z_{DR} *and* δ_{co}*. Fig. 22 includes now Lu results about conical graupels.*

486: supported by low correlation coefficient
added in the text.
Lines 574-576: "This suggests that the two peaks in spectral reflectivity represent two particle populations, the left peak corresponding to conical graupel and the right peak relating to nearly spherical smaller ice particles. This hypothesis is supported by a lower co-polar correlation coefficient."

Figs 22 and 28: It's quite hard to compare the measurements and simulations here due to different y-axis scales and different variables on x-axis. Consider at least making the scale of the y-axis the same for observations and simulations. Can you calculate the fall speeds of your model particles and plot that on x-axis? Also, are your labels and units accurate? E.g. are you plotting reflectivity [dBZ] or spectral reflectivity [dBsZ]?
Fig. 22: we reduced the y-scale of the modelled reflectivity and add different axis ratio for the T matrix simulation. The goal here is to obtain comparable trends between simulations and the three observations to identify the possibility of conical graupels. The analysis emphasizes spectral polarimetric observations, where polarimetric measurements provide greater insight compared to Doppler velocity data. The Doppler velocity does not express yet the fall velocity of the particles.
The linear spectral reflectivity (sZ) is expressed in $mm^6 m^{-3}$*. We consider 10*log10(sZ), which is then expressed in dBZ.*
Fig. 28: The simulations are removed.

578: I think you should rephrase this or expand it a bit. At the minute it might be misinterpreted as if chains can only be found if the temperature is below -40. I think what you are trying to say is that although aggregation is usually associated with slightly warmer temperatures (maybe above -25), the presence of electric fields allows chains to form in colder temperature regions, which has been observed at temperatures below -40 (Stith et al 2002; Connolly et al 2005; Gayet et al 2012)? Maybe this could be mentioned around line 65 when you are discussing chains in cold temperatures.
Rephrased.

581 onwards: Chains are modelled as prolate particles with axis ratio 7 and ice fraction 0.3. Can you put a reference here as to why you think 0.3 is suitable.
The simulation is removed.

At 17:22, From high ZDR and positive ZDR spectrum you hypothesize that there may be chain-like aggregates. The low correlation coefficient suggests a mixture of particles. If small particles and chains co-exist here, could you comment on why sZDR in Fig 28e would be positive. Do you think if there was a high E-field forming the chains, the small particles would be oriented vertically by the field giving negative sZDR?
Based on this comment and comment line 578, the text is rephrased:
Lines 629-634 : "The differential reflectivity of the Rayleigh plateau (Doppler velocity > 5 *m* s^{-1}*) is around 0.2 dB, and the entire* Z_{DR} *spectrum is positive. One hypothesis is that the large particles with positive* sZ_{DR} *are chain-like aggregates that formed earlier under a strong E-field. The lower copolar correlation coefficient in Fig. 26(g) suggests a mixture of particles (small ice crystals and chains), but currently, there is no high E-field to vertically align the small particles. At that moment, the temper-*

ature above 9600 m is lower than -40 °C, and it is indeed possible for chains to be present at such temperatures, according to Conolly et al. (2005)."

You say that you should use axis ratio much greater than 1, but that the maximum you can use is 7 otherwise the code cannot converge. Can you provide more specific details on sizes and axis ratios here please? For example, what are the maximum sizes that have been observed before? You have an example in Fig 1 which is 721 microns. You also say that the individual monomers could be 15-20 microns. Are you then calculating the axis ratio as, for example, 721/15=48? I don't think you can get much information about a chain with axis ratio 48 by modelling it as a prolate particle with axis ratio 7, which you also point out in the next paragraph. You show simulations in Fig. 28 for particles with a much larger maximum dimension of up to 3mm, and then point out that chains of this size have not been observed. Can the code converge if you use smaller sizes less than 1mm with a larger axis ratio?
The authors agree that simulation result of prolate particle with axis ratio 7 does not give much information about a chain with axis ratio 48. However, the simulation does not converge even if we only use sizes less than 1 mm. (For axis ratio 15, we can reach at most 670 microns, but still it is far from axis ratio 48) So, here, we encounter a clear limitation of the Tmatrix method using spheroids. It cannot approximately simulate chains. Therefore, the simulation is removed.

I personally think the section is not very useful because the scattering simulations kind of go nowhere, then you say an alternative would be to look at data which isn't possible. I think you should either repeat simulations using more representative particles, or just remove the section and add a line saying that the high ZDR could be caused by chains.
We focus on the observation. The simulation is removed and the section is shortened.

640: Is there any scope to track thunderstorm evolution using steerable radars, like they did with weather radars during the WOEST campaign in the UK?
Delft University of Technology has definitively interest in this topic. There is work in progress regarding tracking using steerable radars (PhD position) and development of a fast-scanning phased-array radar at Ku-band with polarization diversity (PHARA).

1.3 Technical corrections

Line 2: a cloud radar. *Corrected.*

Line 3: a thunderstorm case. *Corrected.*

Line 4/5: maybe "in the millimeter band", or something similar... kind of sounds like its exactly 1mm now. *Corrected.*

Line 5: studies of thunderstorm clouds. *Corrected.*

Line 18: phenomenon. *Corrected.*

Line 38: pellets. *Corrected.*

Line 70: when the ice particle number, High concentrations. *Both corrected.*

Line 73: Evidence. *Corrected.*

Line 101: need brackets around citations. *Brackets added.*

Around line 276: sometimes use 1 sometimes one. *Corrected. We chose "1"*

Line 151: associated with. *Corrected.*

Line 216: dealias. *Corrected.*

Line 232: change would align to can align? *Corrected.*

Line 240: spectra. *Corrected.*

329 Fig 9 caption: change (a-c) to Panels (a-c). Same for (d-f). *Modified.*

365: is are close to zero and do not show much variations. *Corrected.*

473: Scattering simulations are (or a scattering simulation is). *Corrected.*

578: In the case being studied, the temperature. *Corrected.*

580: Scattering simulations are. *Corrected.*

592: in Fig 28c or (Fig 28c). *Corrected.*