The paper presents a method for identifying riming and aggregation processes from gradients of multi-frequency polarimetric Doppler radar measurements. I have several major concerns related to the manuscript and the proposed methodology.

The underlying assumption of using gradients of radar variables to identify riming and aggregation is that these gradients can only be attributed to these processes. While radar observations of precipitation often appear as a single continuous cloud, in many cases the true structure is multilayered (see, for example, Verlinde et al., 2013). In such systems, sublimation and growth by vapour deposition can also produce gradients in radar variables. The manuscript does not discuss this important limitation of the method. Additionally, the potential impact of fall streaks on the proposed gradient-based approach is not addressed.

Verlinde, J., M. P. Rambukkange, E. E. Clothiaux, G. M. McFarquhar, and E. W. Eloranta (2013), Arctic multilayered, mixed-phase cloud processes revealed in millimeter-wave cloud radar Doppler spectra, J. Geophys. Res. Atmos., 118, 13199–13213, doi:10.1002/2013JD020183.

Response: Thank you for your insightful comment. We agree that more and complex microphysical processes can also be included in radar observables. In the original manuscript, we did not sufficiently describe these limitations,

such as "attributing the post-03:00 UTC low-level echo weakening solely to aggregation" whichwas incomplete. In reality, once the snowfall entered a drier layer, the smaller ice crystals likely sublimated first, leaving only the larger snowflakes; this resulted in reduced reflectivity and an increased DWR. This behavior is opposite to what one would expect from pure aggregation: if aggregation alone were producing larger snowflakes, the reflectivity should increase or at least not decrease.

Therefore, we introduced the sublimation process to account for the weak low-level echoes, which more accurately reflects the physical processes occurring at that time. We have now analyzed Ze in conjunction with MDV and SW to illustrate the role of sublimation during this stage. The revised text is as follows: "*After about 03:00 UTC on 4 January, the overall Ze weakened substantially, with only very faint echoes remaining at low altitudes. At the same time, the MDV increased toward about –1 m/s, the SW broadened further (exceeding 0.3 m/s). These combined signatures suggest that by this time, riming and pure aggregation were no longer the dominant processes in the cloud. Instead, the presence of large, low-density snowflakes (along with the sharp drop in reflectivity) indicates that many of the smaller ice particles were likely undergoing* *sublimation (partial or complete evaporation) as they fell through a drier layer of air."* In *180-182* line 3 Results and Analysis Page 8.

Upon further consideration, we believe that the apparent increase in D_0 during the early-morning observations on 4 January was not caused by additional aggregation, but rather by strong sublimation that preferentially removed smaller particles, thereby shifting the particle size distribution toward larger diameters. This interpretation is supported by the radar observations: during that period Ze decreased, MDV increased, and DWR remained high, which are characteristic signatures of sublimation rather than continued growth. Accordingly, we have revised the text as follows: "By the early morning of 4 January, D_0 was observed to increase rapidly from around 4 km altitude downward, with values exceeding 4 mm. however, the joint evolution of Ze, D_0 and DWR no longer indicated further growth by aggregation: relatively large D_0 values occurred together with large DWR and a pronounced decrease in Ze, implying that The sublimation preferentially removed the smaller ice particles, effectively skewing the particle size distribution toward larger diameters and thus elevating the observed D_0. The loss of the small crystals also kept the DWR high during this period, reflecting a particle population dominated by larger snowflakes. This sublimation-driven interpretation is supported by the concurrent radar signatures—namely, a marked drop in Ze, a rise in MDV, and a persistently high DWR—each of which is characteristic of sublimation rather than continued growth..*"* In *219* line 3 Results and Analysis on Page 9.

Between 20:00 and 22:00 UTC on 3 January, there was a sublimation process that we had previously overlooked. "*Between 20:30–22:00 UTC on 3 January, around the 1 km altitude level, the radar observations reveal signatures distinct from those at higher altitudes. In this near-surface layer, the Ze decreases noticeably with decreasing height, indicating substantial particle loss. Meanwhile, the MDV becomes less negative (rising to values above –1 m/s). However, the DWR_(K_a-W) remains significantly positive. This combination – a marked reduction in Ze, a pronounced increase in MDV, and a sustained high DWR – is a distinctive radar signature of snow-particle sublimation."* In 206 line 3 Results and Analysis on Page 9.

in Section 4 (Discussion) we now state that vertical increases in reflectivity or particle size with descent are not unique to riming/aggregation; they could also arise from slow depositional growth of ice crystals (vapor deposition) or other microphysical growth mechanisms, even in the absence of riming. Moreover, multiple cloud layers can produce overlapping signatures: precipitation falling from an upper cloud layer may modify the microphysics of a lower layer, yielding complex vertical gradient patterns Verlinde et al. (2013) documented a clear example of such complexity showing that snowfall from higher embedded cloud layers changed the growth pathways of particles in lower layers. In light of these considerations, we have added text in the Discussion to clarify a limitation of our gradient-based method. Since our method was developed with riming and aggregation in mind, it may inadvertently attribute some vertical gradient features to those processes even when other phenomena (such as vapor depositional growth, sublimation, or multi-layer cloud interactions) are contributing. This caveat is now explicitly mentioned as a limitation of the method in Section 4 of the revised manuscript. "*It is important to note that vertical gradients in radar observables are not exclusively caused by riming and aggregation. Gradual increases in reflectivity or particle size with decreasing height can also result from other microphysical processes. For example, slow growth of ice crystals by vapor deposition in ice-supersaturated layers can produce a downward increase in reflectivity even in the absence of riming. In addition, complex cloud structures involving multiple layers can lead to overlapping signatures: precipitation falling from an upper cloud layer may alter the microphysics in a lower layer, yielding vertical gradient patterns that are not unique to riming or aggregation (Verlinde et al. 2013).*"

While reading the introduction, I found several instances where the authors' interpretation of the literature is incorrect or misleading.

1. Reflectivity ranges for riming vs. aggregation

The manuscript states:"In riming-dominated areas with abundant liquid water, Ze can reach up to 25 dBZ due to the presence of graupels or dense snow particles (Bringi et al., 2017), whereas in aggregation-dominated regions, owing to ice's lower dielectric constant and the porous nature of aggregates, Ze typically remains between 0 and 15 dBZ (Kneifel et al., 2015; Matrosov et al., 2019)."

The values reported in Bringi et al. (2017) are for S-band radar, whereas Kneifel et al. (2015) and Matrosov et al. (2019) use millimetre-wavelength cloud radars. Comparing reflectivity values across such different frequencies without acknowledging the wavelength dependence is inappropriat. This is essentially comparing apples and oranges. Radar wavelength has a major influence on the reflectivity range.

Furthermore, drawing classification criteria from a report of a case study is not advisable. For centimetre-wavelength systems, a more appropriate basis would be the overview papers such as

Straka et al. (2000), in addition to Bringi et al. (2017).

Straka, J. M., D. S. Zrnić, and A. V. Ryzhkov (2000): *Bulk Hydrometeor Classification and Quantification Using Polarimetric Radar Data: Synthesis of Relations*, J. Appl. Meteor. Climatol., 39, 1341–1372.

Reply: We sincerely thank the reviewer for this insightful suggestion. After careful consideration, we agree that the reflectivity factor (Ze) is strongly dependent on radar wavelength. In our original manuscript, we inadvertently compared reflectivity values from different radar frequencies (S-band vs. Ka/W-band) without proper clarification, which was indeed misleading. To address this issue, we have revised the manuscript to avoid mixing data from different radar bands. Specifically, we now focus our discussion on X-band radar when describing reflectivity ranges for riming vs. aggregation, as X-band provides a clearer distinction between these processes than Ka- or W-band observations. "Line 47 on Page 3: *In riming-dominated areas with abundant liquid water, Ze typically ranges from 14 to 55 dBZ, consistent with the prevalence of graupel and other dense rimed snow particles. By contrast, in aggregation-dominated regions, owing to ice's lower dielectric constant and the porous nature of aggregates, Ze typically ranges from 15 to 33 dBZ (Dolan and Rutledge, 2009; Lim et al., 2019.; Oue et al., 2016; Thompson et al., 2014a).*"

Dolan, B. and Rutledge, S. A.: A theory-based hydrometeor identification algorithm for X-band polarimetric radars, https://doi.org/10.1175/2009JTECHA1208.1, 2009.
Lim, S.: X-band dual polarization radar observations of snow growth processes of a severe winter storm: case of 12 december 2013 in South Korea, J. Atmospheric Ocean. Technol., https://doi.org/10.1175/JTECH-D-18-0076.1, n.d.
Oue, M., Galletti, M., Verlinde, J., Ryzhkov, A., and Lu, Y.: Use of X-band differential reflectivity measurements to study shallow arctic mixed-phase clouds, https://doi.org/10.1175/JAMC-D-15-0168.1, 2016.
Thompson, E. J., Rutledge, S. A., Dolan, B., Chandrasekar, V., and Cheong, B. L.: A dual-polarization radar hydrometeor classification algorithm for winter precipitation, J. Atmospheric Ocean. Technol., 31, 1457–1481, https://doi.org/10.1175/JTECH-D-13-00119.1, 2014a.

2. SW and MDV ranges for aggregation

The manuscript states: "Aggregation processes primarily occur in relatively stable regions with more uniform particle types, thus displaying lower SW (<0.3 m/s) and MDV (0.5–1.2 m/s)."

There is no reference supporting this claim. Aggregation broadens the particle size distribution (see Westbrook et al., 2004); therefore, I do not understand what "uniform particle types" refers to. It also remains unclear how the authors justify the assumption that SW < 0.3 m/s is characteristic of aggregation.

Westbrook, C. D., R. C. Ball, P. R. Field, and A. J. Heymsfield (2004), Universality in snowflake aggregation, Geophys. Res. Lett., 31, L15104.

Reply: Thank you for pointing out this confusion. We acknowledge that the original description was not sufficiently precise, and the citations were not positioned to clearly support the relevant claims. We have revised the statement to clarify that: while aggregation does broaden the size distribution, once large snowflakes dominate, they tend to fall at similar speeds, resulting in a reduced spread of fall velocities This means that in stable regions dominated by aggregates, the Doppler spectrum width (SW) can remain quite low (on the order of 0.2–0.3 m/s). We have added references to support these points. "Line 51 on Page 3: *MDV, representing the mean fall velocity, and SW, indicating the spread of particle velocities, are closely related to particle size, density, and shape, making them widely useful for particle identification. Rimed particles, being denser and more compact (often nearly spherical), leading to significantly faster fall speeds and broader velocity distributions than aggregates. Observations show that heavily rimed particles can have MDV exceeding 1.5 m/s (Blanke et al., 2025; Vogl et al., 2022). In contrast, aggregate snowflakes are low-density clumps of ice crystals with large, irregular shapes. As aggregates grow larger, their increasing mass is largely offset by greater drag from their extended form, so their terminal velocities remain modest. Typically, aggregate-dominated snowfall exhibits moderate MDV on the order of 0.5–1.0 m/s and a narrow velocity spread (SW often <0.3 m/s)(Mosimann, 1995; Zawadzki et al., 2001).*"

Blanke, A., Gergely, M., and Trömel, S.: A new aggregation and riming discrimination algorithm based on polarimetric weather radars, Atmospheric Chem. Phys., 25, 4167 – 4184, https://doi.org/10.5194/acp-25-4167-2025, 2025.

Vogl, T., Maahn, M., Kneifel, S., Schimmel, W., Moisseev, D., and Kalesse-Los, H.: Using artificial neural networks to predict riming from doppler cloud radar observations, Atmospheric Meas. Tech., 15, 365–381, https://doi.org/10.5194/amt-15-365-2022, 2022.

Mosimann, L.: An improved method for determining the degree of snow crystal riming by vertical doppler radar, Atmospheric Res., 37, 305–323, https://doi.org/10.1016/0169-8095(94)00050-N, 1995.

Zawadzki, I., Fabry, F., and Szyrmer, W.: Observations of supercooled water and secondary ice generation by a vertically pointing X-band doppler radar, Atmospheric Res., 59–60, 343–359, https://doi.org/10.1016/S0169-8095(01)00124-7, 2001.

3. Inconsistent use of LDR thresholds

The manuscript states: “LDR, which measures particle non-sphericity and orientation consistency, is approximately –15 dB for aggregated snowflakes and can increase to around –10 dB near melting (Teisseire et al., 2025; Vogl et al., 2022).”

It is unclear whether these values are actually reported in the cited work. Moreover, this statement contradicts Table 1, where LDR < –28 dB is used for aggregates.

Similarly: “Rimed particles, being nearly spherical yield virtually no cross-polarized return, resulting in LDR values between –36 and –28 dB (Bringi et al., 2017; Tyynelä and Chandrasekar, 2014).”

But Table 1 lists LDR > –20 dB for rimed particles.

These inconsistencies suggest confusion in interpreting the literature and completely undermines the justification for the proposed classification thresholds.

Response: In our original Table 1, the LDR thresholds for rimed vs. aggregated snow were mistakenly reversed. Literature shows that heavily rimed snow (graupel-like, nearly spherical) produce extremely low LDR values, whereas aggregated snowflakes (large, irregular clumps of ice crystals) yield higher LDR values. We acknowledge this error and here provide corrected typical LDR ranges from the literature, which will be used to adjust our classification thresholds. “Line 55 on Page 3: *Aggregated snowflakes are typically large and irregularly shaped, which leads to stronger depolarization returns. Consequently, the LDR values of aggregated snow are significantly less negative than those of rimed particles. Specifically, aggregated snowflakes exhibit LDR values around –15 to –18 dB, which can increase to about –10 dB as they near melting (Dias Neto et al., 2019; Illingworth and Lees, 1991; Tyynelä and von Lerber, 2019). In contrast, rimed particles, being nearly spherical due to a smooth ice coating and high symmetry, produce virtually no cross-polarized return; as a result, their LDR values are extremely low, typically between –36 and –26 dB (Bringi and Chandrasekar, 2001; Bringi et al., 2017; Tyynelä and Chandrasekar, 2014; Tyynelä and von Lerber, 2019).*”

	Rimed particles	**Aggregated particles**
LDR(dB)	＜-26	＞-18

Dias Neto, J., Kneifel, S., Ori, D., Trömel, S., Handwerker, J., Bohn, B., Hermes, N., Mühlbauer, K., Lenefer, M., and Simmer, C.: The TRIple-frequency and polarimetric radar experiment for

improving process observations of winter precipitation, Earth Syst. Sci. Data, 11, 845 – 863, https://doi.org/10.5194/essd-11-845-2019, 2019.
llingworth, A. J. and Lees, M. I.: Comparison of lightning location data and polarisation radar observations of clouds, NTRS Author Affiliations: Manchester Coll. of Science and Technology (England)., Electricity Council Research CentreNTRS Document ID: 19910023396NTRS Research Center: Legacy CDMS (CDMS), 1991.
Bringi, P. V. N. and Chandrasekar, V.: Polarimetric doppler weather radar: principles and applications, 2001.
Bringi, V. N., Kennedy, P. C., Huang, G.-J., Kleinkort, C., Thurai, M., and Notaroš, B. M.: Dual-polarized radar and surface observations of a winter graupel shower with negative zdr column, J. Appl. Meteorol. Climatol., 56, 455–470, https://doi.org/10.1175/JAMC-D-16-0197.1, 2017.
Comment on Table 2
Tyynelä, J. and Chandrasekar, V.: Characterizing falling snow using multifrequency dual-polarization measurements, J. Geophys. Res. Atmospheres, 119, 8268–8283, https://doi.org/10.1002/2013JD021369, 2014.
Tyynelä, J. and von Lerber, A.: Validation of microphysical snow models using In situ, multifrequency, and dual-polarization radar measurements in Finland, J. Geophys. Res. Atmospheres, 124, 13273–13290, https://doi.org/10.1029/2019JD030721, 2019.

In Table 2, the authors propose “criteria for identifying riming and aggregation in the Gradient-Based Multi-Parameter Identification Method.” I do not understand these criteria.

Why would aggregation lead to a negative gradient? Aggregates forming from pristine crystals generally increase fall velocity. Likewise, why should spectrum width decrease? Can you site any study that would support these assumptions?

These conditions appear to be ad hoc assumptions. Proposing them is acceptable, but then the method must be validated, for example with in situ data. Without such validation, the approach remains speculative. This is highly problematic because, if published, the method may be adopted by others without realising that it is based on unvalidated and poorly supported assumptions.

Reply: We sincerely thank the reviewer for pointing out the need for clarification and validation of the criteria in Table 2. In the revised manuscript, we have added the appropriate references to Table 2：

	∇_{DWR}(dB/m)	**∇_{MDV}(s^{-1})**	**∇_{SW}(s^{-1})**	**∇_{LDR}(dB/m)**
Riming	$\nabla_{DWR_{X-Ka}} > 0$	> 0	> 0	> 0
Aggregation	$\nabla_{DWR_{Ka-W}} > 0$	< 0	< 0	< 0
References	*(Dias Neto et al., 2019; Kneifel et al., 2015; Tridon et al., 2022)*	*(Gayatri et al., 2017; Kalesse et al., 2016; Locatelli and Hobbs, 1974)*		*(Illingworth and Lees, 1991; Oue et al., 2021)*

Dias Neto, J., Kneifel, S., Ori, D., Trömel, S., Handwerker, J., Bohn, B., Hermes, N., Mühlbauer, K., Lenefer, M., and Simmer, C.: The TRIple-frequency and polarimetric radar experiment for improving process observations of winter precipitation, Earth Syst. Sci. Data, 11, 845–863, https://doi.org/10.5194/essd-11-845-2019, 2019.

Kneifel, S., von Lerber, A., Tiira, J., Moisseev, D., Kollias, P., and Leinonen, J.: Observed relations between snowfall microphysics and triple-frequency radar measurements, J. Geophys. Res. Atmospheres, 120, 6034–6055, https://doi.org/10.1002/2015JD023156, 2015.

Tridon, F., Silber, I., Battaglia, A., Kneifel, S., Fridlind, A., Kalogeras, P., and Dhillon, R.: Highly supercooled riming and unusual triple-frequency radar signatures over McMurdo Station, Antarctica, Atmospheric Chem. Phys., 22, 12467–12491, https://doi.org/10.5194/acp-22-12467-2022, 2022.

Gayatri, K., Patade, S., and Prabha, T. V.: Aerosol–cloud interaction in deep convective clouds over the indian peninsula using spectral (bin) microphysics, https://doi.org/10.1175/JAS-D-17-0034.1, 2017.

Kalesse, H., Szyrmer, W., Kneifel, S., Kollias, P., and Luke, E.: Fingerprints of a riming event on cloud radar doppler spectra: observations and modeling, Atmospheric Chem. Phys., 16, 2997–3012, https://doi.org/10.5194/acp-16-2997-2016, 2016.

Locatelli, J. D. and Hobbs, P. V.: Fall speeds and masses of solid precipitation particles, J. Geophys. Res. 1896-1977, 79, 2185–2197, https://doi.org/10.1029/JC079i015p02185, 1974.

Illingworth, A. J. and Lees, M. I.: Comparison of lightning location data and polarisation radar observations of clouds, NTRS Author Affiliations: Manchester Coll. of Science and Technology (England)., Electricity Council Research CentreNTRS Document ID: 19910023396NTRS Research Center: Legacy CDMS (CDMS), 1991.

Oue, M., Kollias, P., Matrosov, S. Y., Battaglia, A., and Ryzhkov, A. V.: Analysis of the microphysical properties of snowfall using scanning polarimetric and vertically pointing multi-frequency doppler radars, Atmospheric Meas. Tech., 14, 4893–4913, https://doi.org/10.5194/amt-14-4893-2021, 2021.

We sincerely thank the reviewer for highlighting the importance of thorough method validation in our study. We acknowledge that our current work has inherent limitations and should be viewed as an initial exploratory effort. We fully agree that independent validation is crucial for verifying the accuracy of our method. While we could not perform such validation in the present study due to the lack of concurrent external or in-situ observations, we are committed to addressing this gap moving forward. We plan to carry out dedicated experimental campaigns with a ground-based triple-frequency radar and co-located in-situ instruments, which will allow us to independently validate and refine our classification approach.

"Line 349 on Page 14: *An independent validation of the riming- and aggregation-dominant regions identified by our method is not feasible due to the absence of concurrent external or in-situ observations. Consequently, the present classification results should be viewed as a proof-of-concept demonstration. As a physical consistency check, we examined the triple-frequency radar scattering space to ensure that the identified riming and aggregation signatures fall within physically plausible regimes. This approach* *provides a measure of physical validation by confirming that each classified process's radar signatures align with theoretical expectations. However, because the DWR are integral to our classification algorithm, this check does not constitute an independent validation and has inherent limitations. To establish independent verification, we have already deployed a ground-based triple-frequency (X/Ka/W) radar at a mid-latitude site and will(Chang et al., 2023), in forthcoming campaigns, co-locate in-situ instruments such as multi-angle snowflake cameras and optical disdrometers (e.g., 2D-video systems). These collocated measurements will capture detailed snowflake characteristics (size, shape, degree of riming) and provide ground-truth data for direct comparison with the radar-based classifications. Implementing such coordinated observations will enable rigorous independent testing of the identification method, further refinement of the identification criteria.*"