

Response to referee

RC1: 'Comment on egusphere-2025-3596', Anonymous Referee #1

General Comments: To demonstrate the utility of the newly available EarthCARE data, the authors in this study investigate the EarthCARE CPR radar measured Doppler velocity in convective and stratiform precipitating clouds and interpret it in relation to precipitation growth processes. The uniqueness of this study is the combined use of both EarthCARE CPR and GPM DPR data, which allows the authors to explore the difference of particle growth processes in stratiform and convective clouds. The paper seems to serve 2 purposes: First, it demonstrates the quality and usefulness of the first-ever space-borne cloud radar Doppler velocity measurements, and second, using the Doppler velocity measurements, it confirms some of the understandings on microphysical processes in convective and stratiform clouds. The paper is well structured, and the messages are well presented. It will be a good contribution to this special collection of papers on EarthCARE. I suggest accepting after addressing some minor concerns.

The authors sincerely thank the reviewer for carefully reading the manuscript and for providing constructive feedback. We also appreciate the reviewer's recognition of the value of our study. We have carefully reviewed the manuscript in response to the reviewer's comments. My point-by-point responses are provided below in red. Please note that the line numbers indicated in our responses refer to the revised manuscript.

Specific Comments:

1. Doppler velocity V_d in the EarthCARE product. In the manuscript, the authors stated that the Doppler velocity in the EarthCARE product is derived from "the phase shift of the radar signal and is therefore less affected by attenuation". I understand that the retrieval of V_d is not the focus of this paper, but I do like to see a brief explanation on this topic in the Data and Methods section. Because many of the cases involved in this study are related to moderate to heavy rainfall, CPR should suffer significant attenuation particularly for the rain portion in the vertical profiles. Are there any studies on the impact on V_d retrieval accuracy by attenuation when using phase shift method?

Thank you for this important suggestion. We have added an explanation about the principle and previous studies showing that Doppler velocity is less affected by attenuation than radar reflectivity. It is also known that the reliability of Doppler velocity decreases under conditions of strong attenuation; such cases were excluded from the statistical analysis in this study. The original description could be misinterpreted as implying that Doppler velocity is completely unaffected by attenuation, so we have revised the text to clarify these points as follows.

Line 222–229

In contrast, V_d is retrieved from the pulse-to-pulse phase difference rather than from signal amplitude (Eisinger et al. 2024), and is therefore intrinsically less affected by attenuation of returned power (Doviak and Zrnic, 1993). In practice, pulse-to-pulse phase correlation is maintained under moderate attenuation, allowing the velocity retrievals to remain stable (Tian et al., 2007; Kollias et al., 2014). The main limitation arises when severe attenuation and multiple scattering

associated with heavy rain or ice precipitation substantially degrades the pulse-to-pulse phase correlation, leading to large errors (Matrosov, 2008; Battaglia et al., 2011). In this study, cases containing rain, wet snow, and graupel were retained, while severe attenuation were excluded by applying screening following Battaglia et al. (2011), leading to preserve physically meaningful velocity information in these hydrometeor regimes.

2. 10 km horizontal integration. Please explain the reason for 10 km integration for EarthCARE data. The DPR footprint size is about 5 km, then you have to average 2 DPR pixels to match 13 (=10./0.75) EarthCARE pixels? Is there a reason not using ~7 EarthCARE pixels to match 1 DPR pixel? Will the results be different if do so? In short, the decision to use 10 km seems to be somewhat arbitrary, may need couple sentence to justify.

In this study, a 10 km along-track integration was originally applied for each CPR grid point to mitigate the effects of footprint differences between CPR and DPR and to reduce errors contaminating the Doppler velocity. There is a trade-off in selecting the integration length: a longer integration reduces random errors and small-scale natural fluctuations in V_d , but if it is too long, the smoothing can become excessive and the observed features may no longer correspond spatially. To assess this, we reanalyzed all data using a 5 km integration. Although the variance slightly increased, the overall results remained essentially unchanged. Considering consistency with the DPR footprint as well, we decided to adopt the 5 km integration and replaced all original Figures 2–10 with the updated ones.

Based on the above, we have added the following explanation regarding the integration length to the manuscript. We also clarified that, although the native footprint diameter is about 750 m, the product provides data at 500 m intervals along the track.

Line 128–134

In this study, EarthCARE L1B CPR one-sensor products (JAXA, 2024a) from 1 August 2024 to 30 June 2025 was utilized, providing radar reflectivity factor and Doppler velocity products. Although the native footprint diameter is about 750 m, the product provides data at 500 m intervals along the track. The vertical resolution is 500 m with 100 m vertical grid spacing. In this study, 5 km along-track integration is applied for each CPR grid point using neighboring 10 grid points to mitigate the effects of footprint differences between CPR and DPR. This horizontal integration also helps reduce the errors that contaminate the Doppler velocity, as described in Section 2.2. The integrated data retains the original 500 m spacing, rather than being resampled at 5 km intervals.

3. The use of temperature as vertical coordinate. The use of temperature as vertical coordinate is an interesting way to investigate microphysical processes. However, there is a shortcoming when global data are mixed into one figure such as Figure 4. I suspect that most of data near 20°C are from tropics or warm season mid-latitudes. In the meantime, data near 0°C are from almost all the places. When we put all data into one figure, explaining the features in a way that particles are falling from aloft to lower part is somewhat misleading. I'd like the authors mention this shortcoming, and remind readers that future studies should separate data into groups with similar temperature range in the vertical.

Thank you for your careful comments and suggestions for future research. As you pointed out, the transition in the CFED diagram from 0°C to 20°C may not necessarily reflect vertical microphysical growth processes, but

could instead result from combining data from different geographical locations. To avoid potential misinterpretation, we have added the following text to clarify the aspects that this study does not address:

Line 356–360

It should be noted that although Z_{Ku} and Z_{Ka} increase with increasing temperature between 10 °C and 25 °C (Figs. 4c and 4d), this does not necessarily imply stronger precipitation lower in the column. Near the melting layer, the data include contributions from all latitudes, whereas the observations around 20 °C are dominated by low-latitude regions. Although the limited number of samples makes detailed discussion difficult at present, future work should involve analysis separated by weather systems and freezing level height to better investigate the vertical growth processes of hydrometeors.

4. Just a comment. It is great to see in Figure 5 that V_d in the cold range (-10C) is around -1 m/s and the derived V_t is matching well with measured V_d . This gives us great confidence that the V_d quality is high.

We thank the reviewer for providing this valuable comment from a new perspective. As you pointed out, the observed V_d of ice clouds in cold range is useful for comparison with the theoretically derived reflectivity-weighted terminal fall velocity (V_t). Indeed, as seen in Fig. 5e of the previous version of the manuscript, the measured V_d appears to agree reasonably well with the theoretical V_t . However, in this temperature range, it is more appropriate to discuss the relationship using histograms of Z at W-band from CPR observations. Therefore, we have added theoretical Z_W – V_t relationship curves to Figs. 5a–d.

Because the V_t of ice particles has been reported for various densities and shapes, there is ongoing discussion regarding which theoretical values should be adopted. The line shown in the original Fig. 5 was calculated under a specific condition and was therefore somewhat arbitrary. Therefore, to avoid misinterpretation, we have plotted theoretical curves for different densities (0.05, 0.1, 0.2, and 0.3 g cm⁻³). We have also revised the corresponding text related to this point in the manuscript accordingly:

Line 361–370

To examine the relationship between Z and V_d in more detail across different frequencies, histograms were constructed for various temperature ranges, as shown in Fig. 5. The dashed and dotted black lines in Fig. 5 represent the theoretical Z – V_t relationship for rain and snow, respectively, calculated under the assumptions described in Section 2.2. Figures 5a–5d use Z_W as the horizontal axis, while Figs. 5e–5h use Z_{Ku} . For snow, lines corresponding to ρ_s of 0.05, 0.1, 0.2, and 0.3 g cm⁻³ are plotted. Such Z – V_d relationships have long been investigated using ground-based radar observations and serves as a useful metric for inclusion in weather and climate models. In the upper troposphere ($T < -10^\circ\text{C}$; Fig. 5a), V_d tends to increase with increasing Z_W , indicating that larger reflectivity is associated with faster-falling particles. Assuming that the vertical air motion averages to zero over many samples, the mean V_d can be interpreted as representative of the V_t . The Z_W – V_d distribution in Fig. 5a follows the theoretical V_t curve for $\rho_s = 0.05 \text{ g cm}^{-3}$, showing that the downward fall speed increases with increasing Z_W , which provides insight into the growth of ice particles.

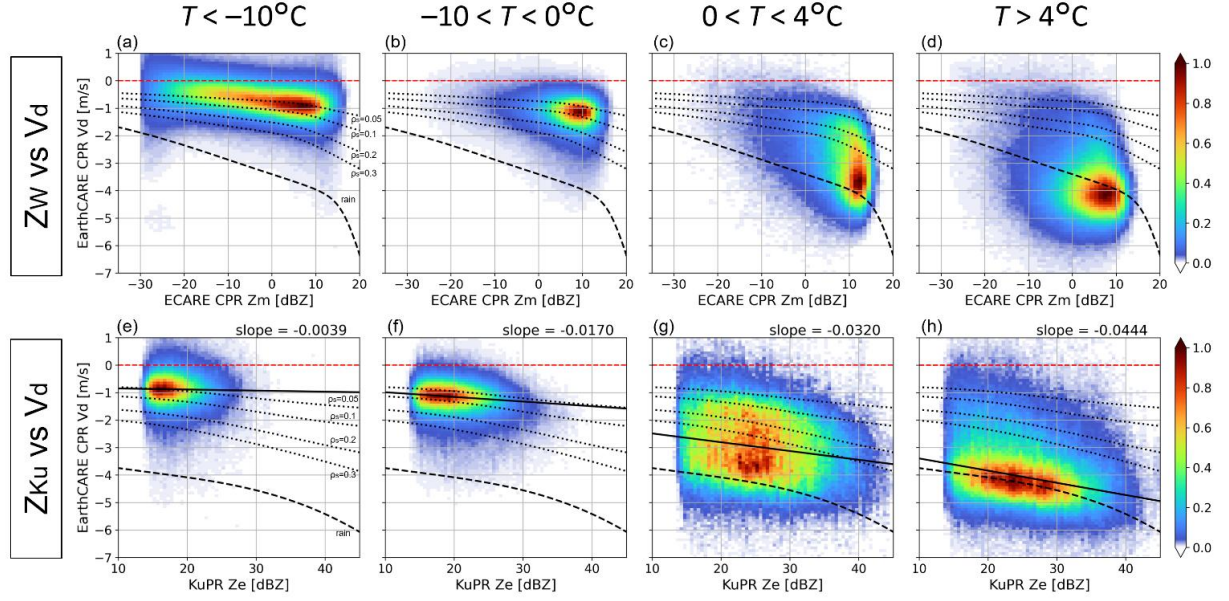


Figure 1: Joint histograms of radar reflectivity and Doppler velocity for four temperature ranges: (a, e) $< -10^\circ\text{C}$, (b, f) -10 to 0°C , (c, g) 0 to 4°C , and (d, h) $> 4^\circ\text{C}$. Panels (a–d) use CPR radar reflectivity on the x-axis, while (e–h) use KuPR attenuation-corrected radar reflectivity. The red dashed line indicates 0 m/s Doppler velocity. The solid black lines in (e–h) represent regression lines fitted using the least squares method, with their corresponding slopes indicated in the upper right corner outside each panel. The dashed and dotted black lines represent the theoretical $Z_{Ku} - V_t$ relationship for rain drops at 850 hPa and 10°C , and for snowflakes with a densities of 0.05 , 0.1 , 0.2 and 0.3 g cm $^{-3}$ at 600 hPa and -10°C calculated from eq. (4), where radar reflectivity in W-band and Ku-band is calculated assuming $N_w = 10^3$ mm $^{-1}$ m $^{-3}$.

In addition, because the original manuscript did not explicitly describe how V_t for snow was calculated and did not discuss the limitations of the assumed particle properties, we have revised and added the following text to Section 2.2:

Line 237–257

For rain layers, v_t was computed using the empirical relationship proposed in Atlas and Ulbrich (1977), with a correction factor for air density, as given:

$$v_t(D) = -3.78D^{0.67} \cdot c(\rho_a), \quad (5)$$

$$c(\rho_a) = \sqrt{\frac{\rho_{a0}}{\rho_a}} = \sqrt{\frac{\rho_{a0}RT}{p}}. \quad (6)$$

Here, the unit of D is millimeters, ρ_a denotes the ambient air density, ρ_{a0} is the standard air density (set to 1.225 kg m $^{-3}$), R is the specific gas constant for dry air (287 J kg $^{-1}$ K $^{-1}$), and p and T represent pressure and temperature obtained from auxiliary data. The backscattering cross-section σ_b was derived from Mie scattering calculations for spherical raindrops at W-band frequency.

For snow, σ_b and v_t was calculated in the same manner as in the 2A.DPR algorithm, assuming homogeneous spherical particles with a density of 0.10 – 0.13 g cm $^{-3}$ and a melted-equivalent diameter following the particle size distribution given by Eq. (3). The terminal fall velocity of snow was calculated following Magono and Nakamura (1965) as follows:

$$v_t(D_s) = -8.8(0.1D_s\rho_s)^{0.5} \cdot c(\rho_a), \quad (7)$$

where D_s is the unmelted snow particle diameter in mm, and ρ_s is the density of snow particles in g cm $^{-3}$. On the

other hand, ice particles can take various shapes, sizes, and densities, such as those of snow, graupel, and hail. Because σ_b and v_t vary depending on these parameters, the assumptions made for snow in this study are often not valid. Although it would be ideal to account for more realistic and complex scattering and fall characteristics of ice particles (Kuo et al. 2016; Ori et al. 2021), considering such diversity is challenging because the CPR observes only in the nadir direction and therefore cannot provide information on particle asymmetry. This contrasts with ground-based dual-polarization radars, which observe the hydrometeor from the side, where particle asymmetry is more evident and can provide additional information. In addition, such information on particle diversity cannot be inferred from the current version of the 2A.DPR algorithm and is therefore left for future work.

5. Misc.

Line 55. “The Tropical ... (TRMM) was launched in 1997, and the TRMM carried ...”. I think it is better to say: “The Tropical ... (TRMM) *satellite* was launched in 1997, and it carried ...”

We have revised the manuscript accordingly (Line 55).

Line 105. I don’t see “CSATGPM” appearing in any place before this point. Please define it.

We added the following definition to Line 102:

CloudSat–GPM coincidence dataset (CSATGPM; Turk et al., 2021)

Line 137. The exclusion of 5 and 10 range bins are somewhat arbitrary. Are they about 0.5 and 1.0 km, respectively? Please add a couple of sentences to explain why excluding these many bins is enough.

We have added the answer to the reviewer’s question to the manuscript as follows:

Line 142–146

Pre-launch studies suggested that the EarthCARE CPR would be less affected by surface clutter than the CloudSat CPR and that, over flat surfaces, clutter would not extend above 600 m (Roh et al., 2023). Observations are consistent with this expectation, although the altitude affected by clutter is higher over mountainous terrain. Taking these factors into account, we excluded data within five range bins (~500 m) above the ocean surface and ten range bins (~1000 m) above land to avoid potential contamination from ground clutter.

Line 164-165. Earlier in the text, it is mentioned that EarthCARE data is integrated to a 10 km “pixel”. Here it sounds like the matching is between 1 EarthCARE original pixel (750 m size) with 1 DPR pixel (5 km size). Please clarify.

In this study, 5 km along-track integration is applied for each CPR grid point (with 500m interval) using neighboring 10 grid points. Consequently, the resulting data retains the original 500 m spacing, rather than being resampled at 10 km intervals. I have revised the manuscript to make this point clear.

Line 127–134

In this study, EarthCARE L1B CPR one-sensor products (JAXA, 2024) from 1 August 2024 to 30 June 2025 was utilized, providing radar reflectivity factor and Doppler velocity products. Although the native footprint diameter is about 750 m, the product provides data at 500 m intervals along the track. The vertical resolution is 500 m with 100 m vertical grid spacing. In this study, 5 km along-track integration is applied for each CPR grid point using neighboring 10 grid

points to mitigate the effects of footprint differences between CPR and DPR. This horizontal integration also helps reduce the errors that contaminate the Doppler velocity, as described in Section 2.2. The integrated data retains the original 500 m spacing, rather than being resampled at 5 km intervals.

Line 170–171

For each coincidence event, the nearest DPR footprint was matched to every CPR horizontal grid points with 500 m spacing.

Line 276-277. Do you have a rough number of profiles (in percent) that is detected by CPR but not DPR?

The following information has been added regarding the number of profiles:

Line 313–314

Only profiles where echoes are detected by both DPR and CPR are included. These profiles correspond to 5.1% of all profiles and 10.1% of the profiles in which echoes are detected by the CPR.

Figure 6. An interesting feature is that most stratiform precipitation tops (by DPR) are around -15C although their cloud tops (by CPR) are all over the place. Any explanations?

Thank you very much for your helpful comments. Indeed, the PTH of stratiform precipitation is concentrated within the temperature range of -10°C to -20°C , which is noteworthy. We have revised and added the following explanation and discussion to the manuscript:

Line 411–419

When the PTH is located above the 0°C level, it is indicative of a cold-type precipitation process, in which ice particles grow into relatively large snow aggregates or graupel through aggregation and riming. In stratiform precipitation, the PTH is mostly at temperatures lower than 0°C , indicating that most cases are associated with cold-type precipitation (Fig. 6a). In particular, a high frequency of occurrence is confined within the PTH range of -20°C to -10°C regardless of CTH. This temperature range corresponds to the layer where ice habits transition with temperature, as shown in the classical Nakaya diagram (Libbrecht 2005). It is also referred to as the dendritic growth layer, where cloud ice particles are thought to grow into snow through depositional growth, aggregation, and potentially secondary ice processes (von Terzi et al. 2022). Such temperature-dependent microphysical processes may explain why ice particles in typical stratiform clouds become large enough to be detected by the KuPR only when they reach below the -20°C level.

Furthermore, unlike in stratiform cases, the PTH in convective precipitation can vary widely from about 20°C to -40°C . We have revised the following discussions to the manuscript to reflect this point:

Line 420–429

In contrast, convective precipitation shown in Fig. 6b exhibits a much wider range of PTH values, extending from 20°C down to below -40°C , with a sparse distribution in the CTH–PTH histogram. Focusing on deep clouds with CTH above the -20°C level, the PTH tends to lie close to the one-to-one line between PTH and CTH, indicating that the precipitation top height is nearly as high as the cloud top. This situation can be interpreted as the result of strong updrafts within the system that lifted large hydrometeors toward the cloud top, as discussed in Takahashi and Luo (2014). In addition, in convective cases, a pronounced peak in occurrence is found where the PTH is below the 0°C level. When the PTH is below the 0°C level, it suggests a warm-type precipitation process, where raindrops grow through collision and coalescence of liquid water droplets. Such warm-type shallow precipitation is likely associated mainly with shallow cumulus or congestus clouds, because the DPR has limited sensitivity to detect light precipitation ($\sim 1 \text{ mm h}^{-1}$ or less; Hayden and Liu, 2018), and thus does not effectively capture shallow stratus or stratocumulus.

Line 447. “theoretical W-band terminal velocity” -> “theoretical terminal velocity”. Terminal velocity should not be band-dependent.

Thank you for the comment. It is true that terminal velocity itself does not depend on radar frequency. However, the figure shows the reflectivity weighted terminal velocity (V_t) obtained from Eq. (4), which is band-dependent. We have revised the manuscript to clarify this point by changing the expression “theoretical W-band terminal velocity” to “theoretical Z_W – V_t relationship.”, not only at the original Line 447 but also in other instances where similar wording was used throughout the manuscript.