

## Response to referee

RC2: 'Comment on egusphere-2025-3596', Anonymous Referee #2

This work analyses Ku-, Ka-, and W-band radar measurements of precipitating clouds using a one-year dataset of matchup EarthCARE and GPM observations. Following a quick demonstration of two case studies, statistical properties of radar reflectivity and Doppler velocity profiles are investigated for different particle phases (liquid/solid) and different precipitation types (shallow/convective/stratiform). A new method is devised to evaluate the vertical air motion in raining layers by subtracting the terminal velocity deduced by DPR-derived DSD from the EarthCARE Doppler velocity.

This is a well written paper presenting robust analysis results that align with theoretical expectations and physical intuition. The authors' effort to construct a matchup EarthCARE and GPM dataset should be applauded and will be welcomed by the cloud/precipitation science community. I suggest a few revisions that are mostly minor in nature with the possible exception of the first point. Otherwise I would recommend that the paper be published in AMT.

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.

Main comments -----

1. JAXA's EarthCARE CPR Level-2 cloud product (L2a CPR\_CLP) contains its own vertical air motion estimated from Doppler velocity. The CPR reflectivity (and hence DSD estimates crucial for  $V_t$  and  $V_{air}$  as well) is subject to heavy attenuation for intense rain as the authors pointed out (ll. 210-211). That being said, a substantial number of CPR reflectivities would be still usable, being not entirely washed out by attenuation even beneath the 0-degree level as far as I can tell from Fig. 2c and 3c. This means that there would be plenty of simultaneous measurements available for both EarthCARE-provided  $V_{air}$  and GPM Dm estimates.

I am curious how consistent the  $V_t$  estimates are between the CPR standard product and the current method using DPR-derived DSD. You would find discrepancies because the CPR\_CLP relies on its own built-in DSD assumption which is not guaranteed to accord with DPR Dm. An additional plot or two comparing the CPR-only and DPR-based  $V_t$  and  $V_{air}$  estimates would tell us how reliable the CPR products are, offering useful information for EarthCARE algorithm developers and interested users.

We thank the reviewer for this insightful suggestion, which enhances the value of the estimated  $V_{air}$  in our study. As you pointed out, the EarthCARE standard product, CPR\_CLP, estimates  $V_{air}$  based on its own built-in DSD

assumptions and scattering database. Comparing these estimates with those derived from the DPR-based DSD provides useful information for both algorithm developers and users in evaluating the consistency and validity of each retrieval approach. Accordingly, we conducted a new analysis comparing  $V_{\text{air}}$  retrievals from CPR\_CLP with our results. Figure 11 shows histograms of  $V_{\text{air}}$  for deep stratiform and deep convective precipitation, separately for the temperature ranges corresponding to snow ( $-10\text{ }^{\circ}\text{C} < T < 0\text{ }^{\circ}\text{C}$ ) and rain ( $T > 4\text{ }^{\circ}\text{C}$ ). Along with, Table 2 shows the mean and standard deviation of each histograms shown in Fig. 11. Based on these results, we have added a discussion in new Section 3.5 to the revised manuscript as follows:

Line 568–608

### 3.5 Comparison of vertical motions with single-sensor observations by the CPR

CPR\_CLP, one of JAXA's EarthCARE Level-2a standard products, provides its own estimates of  $V_{\text{air}}$ , which are derived solely from single-sensor observations by the CPR (Sato et al. 2025). Both the method implemented in CPR\_CLP and the CPR-DPR combined approach presented in this study are based on the same fundamental concept of calculating  $V_{\text{air}}$  by subtracting the  $V_t$  from the  $V_d$ . However, the two methods differ in how  $V_t$  is determined: the CPR\_CLP estimates it from a particle size distribution (PSD) inferred using only the CPR-measured  $Z_w$  and  $V_d$ , whereas the present method uses the PSD derived from the 2A.DPR algorithm. Because of this difference in the underlying PSDs and scattering database, discrepancies between the two  $V_{\text{air}}$  estimates are expected. Therefore, in this section, we compare the two  $V_{\text{air}}$  estimates to assess the consistency and reliability of the retrieved  $V_{\text{air}}$ , as well as the implicit assumptions regarding  $V_t$  and PSD within each algorithm. Since the CPR\_CLP product does not provide the quantity corresponding to  $V_t$ , the comparison focuses solely on  $V_{\text{air}}$ .

Figure 11 shows histograms of  $V_{\text{air}}$  for deep stratiform and deep convective precipitation, separately for the temperature ranges corresponding to snow ( $-10\text{ }^{\circ}\text{C} < T < 0\text{ }^{\circ}\text{C}$ ) and rain ( $T > 4\text{ }^{\circ}\text{C}$ ). Table 2 summarizes the mean and standard deviation of the  $V_{\text{air}}$  histograms shown in Fig. 11 for each retrieval method. Overall, the histograms exhibit smaller standard deviation in stratiform cases ( $0.5\text{--}0.9\text{ m s}^{-1}$ ) and larger standard deviation in convective cases ( $0.9\text{--}1.6\text{ m s}^{-1}$ ), likely associated with turbulent motions.

For the snow layers (Figs. 11a and 11b), weak upward motions appear on average in both types ( $0.3\text{--}0.6\text{ m s}^{-1}$ ), likely associated with latent heat release during ice particle growth. On the other hand, some discrepancies exist between the two  $V_{\text{air}}$  estimates, probably due to the radar frequency and assumptions about ice particle properties. The CPR\_CLP algorithm accounts for scattering from ice particles with various shapes and orientations, whereas the DPR algorithm assumes simple spherical particles with a fixed bulk density of  $0.10\text{--}0.13\text{ g cm}^{-3}$ . The peak of the  $V_{\text{air}}$  distribution from the DPR-based method is about  $0.3\text{ m s}^{-1}$  higher than that from CPR\_CLP, suggesting a positive bias. This difference may indicate that the DPR-based PSD retrieval does not fully capture the contribution from smaller particles with slow  $V_t$  compared with the W-band CPR-based retrieval. On the other hand, for convective precipitation, the DPR-derived  $V_{\text{air}}$  shows a larger proportion of downward motions ( $< -1\text{ m s}^{-1}$ ) than the CPR\_CLP  $V_{\text{air}}$ . This is likely because convective cases include more dense particles, such as graupel or hail, with densities exceeding  $0.3\text{ g cm}^{-3}$ , which are not represented in the current 2A.DPR algorithm.

For the rain layers (Figs. 11c and 11d), the DPR-based method and CPR\_CLP show more similar  $V_{\text{air}}$  histograms than in the snow cases. For stratiform precipitation, the mean  $V_{\text{air}}$  is close to  $0\text{ m s}^{-1}$ , whereas for convective precipitation, it shows stronger upward motion of about  $1\text{ m s}^{-1}$  with a larger variance. The two histograms agree well for strong upward motion ( $V_{\text{air}} > 1\text{ m s}^{-1}$ ); however, for  $V_{\text{air}} < 1\text{ m s}^{-1}$ , the CPR\_CLP  $V_{\text{air}}$  shows a distinct peak around  $0\text{ m s}^{-1}$ , while the DPR-based  $V_{\text{air}}$  exhibits a smoother distribution. Despite such several differences, both methods yield comparable  $V_{\text{air}}$  histograms overall.

While further validation is still needed, the approach presented in this study provides useful reference information for evaluating the validity of vertical air motion retrieval, which can otherwise only be obtained by specific ground-based vertically pointing radars where direct observational data are extremely limited.

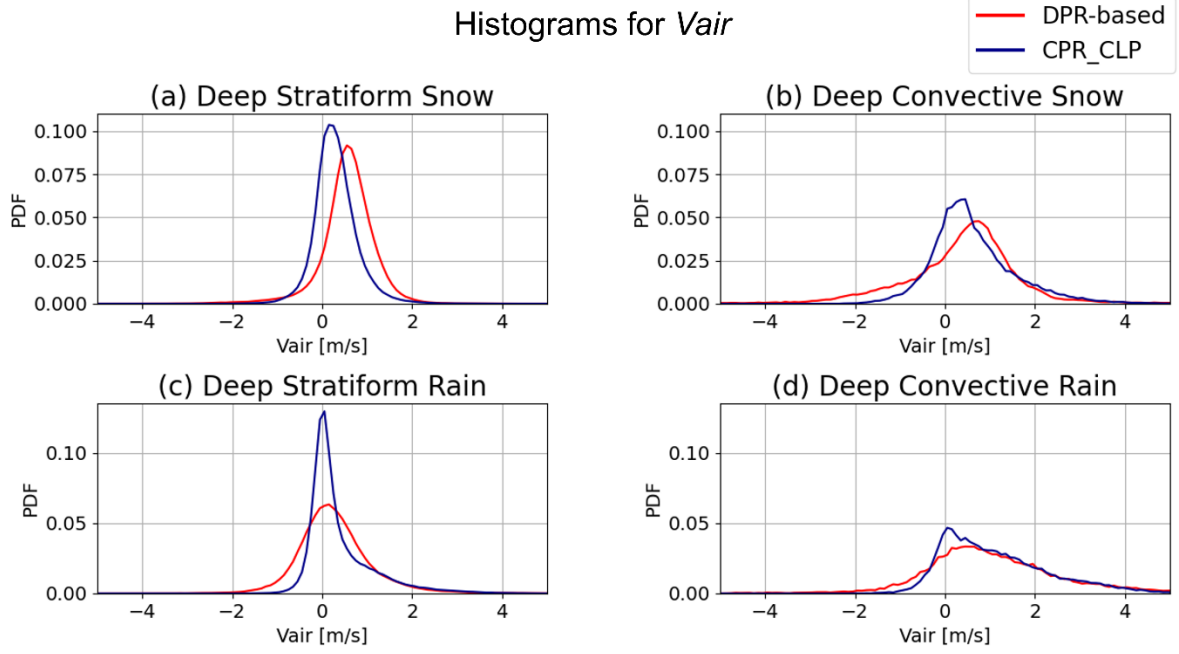


Figure 1: Histograms  $V_{air}$  calculated using the CPR-DPR combined method proposed in this study, and that using CPR\_CLP (a, b) for the temperature range from  $-10^{\circ}\text{C}$  to  $0^{\circ}\text{C}$  (snow) and (c, d) for the temperature above  $4^{\circ}\text{C}$  (rain). (a, c) deep stratiform and (b, d) deep convective types. Each histogram is normalized by the total number of samples for each precipitation type.

Table 2: The mean and standard deviation of each  $V_{air}$  histogram shown in Fig. 11.

| Indicator          | $V_{air}$ retrieval method | Snow ( $-10^{\circ}\text{C} < T < 0^{\circ}\text{C}$ ) |               | Rain ( $T > 4^{\circ}\text{C}$ ) |               |
|--------------------|----------------------------|--------------------------------------------------------|---------------|----------------------------------|---------------|
|                    |                            | a) Stratiform                                          | b) Convective | c) Stratiform                    | d) Convective |
| Mean               | DPR-based                  | 0.561                                                  | 0.356         | 0.279                            | 1.112         |
|                    | CPR_CLP                    | 0.302                                                  | 0.621         | 0.375                            | 1.126         |
| Standard deviation | DPR-based                  | 0.638                                                  | 1.366         | 0.874                            | 1.631         |
|                    | CPR_CLP                    | 0.487                                                  | 0.945         | 0.738                            | 1.198         |

Furthermore, we have added the following discussion to the summary in Section 4:

Line 646–652

In addition, we compared the  $V_{air}$  estimated using the DPR-derived PSD with that estimated solely from CPR measurements in the CPR\_CLP product. The two estimates show consistent characteristics, exhibiting smaller variability with values concentrated around  $0 \text{ m s}^{-1}$  for stratiform cases and larger variability for convective cases, likely associated with turbulent motions. On the other hand, a systematic bias is found between the two in the snow layer, which can be attributed to differences in the microphysical assumptions and observational characteristics due to radar frequency. Such information is expected to be valuable for improving both algorithms and for providing reference data to validate vertical velocity retrievals, which are otherwise extremely limited in direct observations.

2. In the paper,  $V_t$  and  $V_{air}$  are shown only for rain layers (Fig. 10). Why not add  $V_t$  and  $V_{air}$  for solid precipitation too (Fig. 9)? The DPR Dm might not be as reliable for snow as for rain because the KuPR is not

sensitive enough to small frozen hydrometeors, but a comparison with the CPR\_CLP product would be worth studying for solid precipitation as well.

We appreciate the reviewer's suggestion. As you pointed out, including the results for ice-phase precipitation allows for a more comprehensive discussion, including the limitations of DSD retrievals by DPR in snow. Therefore, we attempted to estimate  $V_{\text{air}}$  based on DPR-derived DSDs for snow in the temperature range from  $-10^{\circ}\text{C}$  to  $0^{\circ}\text{C}$ . The results and related discussion have been incorporated into the revised manuscript at Line 568–608, as described in our response to the previous comment.

In addition, we have added the following description to Section 2 regarding the assumed snow particle size distribution and terminal fall velocity used in the DPR for the calculation of  $V_t$ :

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:

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

$$c(\rho) = \sqrt{\frac{\rho_0}{\rho}} = \sqrt{\frac{\rho_0 RT}{p}}. \quad (6)$$

Here, the unit of  $D$  is millimeters,  $\rho$  denotes the ambient air density,  $\rho_0$  is the standard air density (set to  $1.225 \text{ kg m}^{-3}$ ),  $R$  is the specific gas constant for dry air ( $287 \text{ J kg}^{-1} \text{ K}^{-1}$ ), and  $p$  and  $T$  represent pressure and temperature obtained from auxiliary data. The backscattering cross-section  $\sigma_b$  was derived from Mie scattering calculations for spherical raindrops at W-band frequency.

For snow,  $\sigma_b$  and  $v_t$  was calculated in the same manner as in the 2A.DPR algorithm, assuming homogeneous spherical particles with a density of  $0.10\text{--}0.13 \text{ g cm}^{-3}$  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:

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

where  $D_s$  is the unmelted snow particle diameter in mm, and  $\rho_s$  is the density of snow particles in  $\text{g cm}^{-3}$ . On the other hand, ice particles can take various shapes, sizes, and densities, such as those of snow, graupel, and hail. Because  $\sigma_b$  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.

Specific points -----

3. I. 55: and The TRMM -> and the TRMM

We have modified the sentence as follows:

Line 55

The Tropical Rainfall Measuring Mission (TRMM) satellite was launched in 1997, and it carried the world's first spaceborne Ku-band (13.8 GHz) radar, Precipitation Radar (PR)

4. I. 73: weaker hydrometeors -> smaller hydrometeors

We have revised the manuscript as suggested.

5. I. 135: are more frequently appear -> more frequently appear

We have revised the manuscript as suggested.

6. II. 144-146: I am puzzled by the claim that "only data from the HS mode are used". The KaHS mode has been reassigned to match the outer KuPR swath to complement the inner KaMS swath since the scan pattern was changed in May 2018. As far as I can tell from Figs. 2 and 3, the whole DPR swath (that is, both MS and HS modes) seems to be analysed in this work.

As pointed out, KaHS is used in Figures 2 and 3. Our intention was to indicate that only KaHS was used in the statistical analysis presented in Section 3.2 and thereafter. We have revised the text to make this point clear as follows:

Line 151–153

In this study, only data from the HS mode are used in the statistical analysis from Section 3.2 onward,

7. I. 153: which calculated -> which were calculated

We have revised the manuscript as suggested.

8. I. 156: "equatorial" region may be better replaced by low- and mid-latitude regions. 65S-N is much wider than the equatorial region.

We have revised the manuscript as suggested.

9. I. 170: samplings -> samples

We have revised the manuscript as suggested.

10. Figure 4c/d: Why are the KuPR and KaPR CFEDs sharply (presumably artificially) cut off above a certain level, with a temperature threshold around -42C for Ku and -35C for Ka?

The DPR has lower sensitivity than the CPR, and therefore, in the upper regions, there are many cases where echoes are detected by the CPR but not by the DPR. Consequently, the sample size in the colder temperature range in Figs. 4c and 4d is considerably smaller than that for the CPR. To avoid misinterpretation, temperature ranges with fewer than 1000 samples are not shown. The following note has been added to clarify this point.

Lines 314–316

Because the sensitivity of the DPR is lower than that of the CPR, the number of samples in the colder temperature range in Figs. 4c and 4d is considerably smaller than that for the CPR. To avoid misinterpretation, temperature ranges with fewer than 1000 samples are not shown.

11. I. 303: "However" does not really fit the context here. Please try "On the other hand" or "In contrast" instead.

We have revised the manuscript as suggested.

12. Figure 6: The joint histogram of Ku- and W-band Z reminds me of Fig. 8 of Stephens and Wood (2007, DOI: 10.1175/MWR3321.1). They showed CFADs separated for different cloud types, which also bears resemblance to the present work. I just thought this might be worth a brief discussion.

We appreciate the reviewer's suggestion. The classification based on precipitation and cloud-top height by Stephens and Wood (2007, hereafter SW07), as well as their subsequent analysis using joint histograms, is closely related to our approach and supports our interpretation. Therefore, we have added acknowledgments to SW07 and the related study by Masunaga et al. (2005), along with a brief discussion of the similarity to SW07, in Section 3.3 of the revised manuscript as follows:

Line 399–410

The cloud top height (CTH) and precipitation top height (PTH) are key variables that characterize the developmental stage of precipitation systems (Masunaga et al., 2005, hereafter M05; Stephens and Wood 2007, hereafter SW07; Takahashi and Luo, 2014; Kikuchi and Suzuki, 2018). M05 first categorized precipitation systems using CTH–PTH joint histograms constructed by deriving the PTH from the 18-dBZ echo top observed by the TRMM PR and the CTH from the 11- $\mu\text{m}$  brightness temperature observed by the Visible Infrared Scanner (VIRS) onboard TRMM. SW07 improved upon this approach by incorporating millimeter-wavelength radar observations, which allowed them to better represent multilayer cloud structures, whereas VIRS observations can capture only the uppermost cloud layer. Following these studies, this work assumes that the ETH retrieved from CPR corresponds to the CTH, and that from KuPR corresponds to the PTH. The joint histograms of temperature at CTH and temperature at PTH for stratiform and convective precipitation determined by 2A.DPR algorithm, respectively, are shown in Fig. 6. The histograms are reminiscent of the histograms presented by M05 (their Fig. 1) and SW07 (their Fig. 8).

Line 464–468

SW07 has classified cloud types using a similar approach based on ground-based Ka-band radar observations and presented comparable histograms of Z as a function of height (their Fig. 10). Although the attenuation conditions differ—since their observations are made from the ground upward, whereas the present study is based on spaceborne downward-looking radar measurements—the vertical profiles of  $Z_W$  in each category (Fig. 7a–d) exhibit similar characteristics. This study extends their findings by introducing an additional perspective through the use of  $V_d$ .

13. I.375: "Intense" deep convection (DC-I) could be misleading, given that higher echo tops do not necessarily guarantee more intense convection (e.g., Hamada et al., 2015, DOI: 10.1038/ncomms7213). Something like Tall deep convection (DC-T) may be a safer alternative.

We thank the reviewer for this careful comment. As pointed out, a high precipitation top height does not necessarily indicate strong precipitation. As suggested, we have changed the name from *Intense deep convective (DC-I)* to *Tall deep convective (DC-T)*, and replaced the corresponding terminology throughout the manuscript.

14. I. 394: is generally low -> are generally low

We have revised the manuscript as suggested.

15. l. 415: Here again, "However" may be better rephrased by "By contrast" etc.

We have revised the manuscript as suggested.