Author's response to reviewer 1

RC1: 'Comment on amt-2024-99', Anonymous Referee #1, 03 Jul 2024

This paper provides a brief overview of the radar-only, radar-lidar and radar-lidar-radiometer cloud and precipitation retrieval products from the JAXA Level 2 production model, with illustrations of key variables based on numerical forecast models and CloudSat/CALIPSO. The results in this paper are well-presented and summarises a long record of work with CloudSat/CALIPSO and other instruments in preparation for EarthCARE. While we appreciate concise papers, ultimately the paper does not provide enough of a detailed description of the algorithm(s), nor a consistent view of the data products in question. I recommend this paper for major revisions to address these issues.

We are sincerely grateful to all reviewers for their careful reading of the manuscript and useful comments that have allowed us to improve its quality. In our revised manuscript, we have made corrections and added a better overview and major details of the algorithms and products based on comments by the reviewers. Below are the reviewers' comments in blue text followed by our replies in black text.

Major comments

1. The names of the products (i.e. C-CLP, AC-CLP, ACM-CLP) have typically been given in the paper titles within this special issue, and this would help the user to navigate through the special issue as well as the EarthCARE L2 data products.

   Product names have been added to the title as follows; JAXA Level 2 cloud and precipitation microphysics retrievals based on EarthCARE CPR, ATLID, and MSI: The C-CLP, AC-CLP, ACM-CLP products

2. There's a fundamental ambiguity in the Abstract, which isn't resolved within the paper. We read that, (L16-17) "these products provide a detailed view of [cloud properties] as well as vertical velocity information", but then in the final sentence, (L20) "Level 2 velocity-related products will be described in a future paper." Please make it very clear from the abstract onward that the vertical velocity products are not described in the present paper.

   We have deleted "as well as vertical velocity information" (L16–17) and edited the final sentence to read: JAXA Level 2 velocity-related products (i.e., CPR_VVL, AC_VVL, and ACM_VVL) such as hydrometeor fall speed and air vertical velocity will be described in a future paper. (L21-22)

3. Table 1 is key to detailing the production model represented within this paper. The "standard" version of each L2 product are given, and also "research" versions of each product which contain vertical velocity information (i.e. retrieved precipitation mass flux, in-cloud vertical air velocity). This is ambiguous: are the existing products to be updated at a later date to include these additional variables, or are additional products to be released? Asked another way: it's not clear from Table 1 or from the text of this paper whether the JAXA L2 production model as described in Eisinger et al. (2024) is accurate: in Figure 3 of Eisinger et al (2024) the C-CLP, AC-CLP and

ACM-CLP products will provide the "standard" quantities relating to cloud mask, phase, shape and cloud microphysics, while additional "research" L2 data products with different names will provide complementary information: e.g. C-RAS for CPR retrievals of rain and snow properties, C-VVL for vertical velocity; ACM-ICE for ice cloud effective radius as described in Eisinger et al. (2024). In Table 1, the titles of the three last columns indicate that all of these variables fall under "C-CLP", "AC-CLP" and "ACM-CLP", and no other products are named. Please resolve this ambiguity, while citing the Eisinger et al. (2024) paper which was intended as a centralised resource for understanding the full range of products available.

The JAXA L2 products summarized by Eisinger et al. (2024) are correct. Table 1 and the corresponding text have been updated for consistency with Eisinger et al. (2024). The main research products (C-RAS, AC_RAS, ACM_RAS, CPR_VVL, AC_VVL, and ACM_VVL products) have been added to Table 1 and the text. The C-CLP, AC-CLP, and ACM-CLP products include both cloud and precipitation microphysics, but are reported only as cloud microphysics, whereas C-RAS, AC_RAS, and ACM_RAS include precipitation-only products using Doppler velocity. The C-CLP, AC-CLP, and ACM-CLP products will eventually be updated using Doppler velocity. For ACM_CLP, this update will be included in ACM_CDP, which is processed by JAXA Laboratories (LR), but results fulfilling the release criteria could be added to the ACM-CLP products. ACM-ICE is under consideration.

Subsection 2.1.1 is added in the paper as follows;

"2.1.1 Primary cloud products

Standard cloud property (CLP) products (i.e., CPR_CLP, AC_CLP, and ACM_CLP) include a cloud mask, cloud particle type, cloud particle habit category, cloud microphysics, cloud optical thickness, and cloud water/ice paths (Table 1). The microphysical properties of all hydrometeor types in the standard products are reported in the cloud microphysics product, and precipitation-sized particles are not separated into precipitation products. JAXA L2 research cloud products include velocity-related products such as sedimentation velocity and air vertical velocity (Sato et al., 2009), which are designated CPR_VVL, AC_VVL, and ACM_VVL; precipitation-only products (e.g., rain and snow rates; CPR_RAS, AC_RAS, and ACM_RAS) (Table 1). Details of these research products will be reported in a future paper. All products are reported using the Joint Standard Grid (JSG) with 1-km horizontal and 100-m vertical grid spacing. Note that CPR_CLP, AC_CLP, and ACM_CLP are produced with and without the use of L2 CPR Doppler velocity to show the effect of additional information obtained from Doppler velocity. The version without Doppler velocity will eventually be updated based on the version using Doppler velocity. Similarly, research products will be developed through RAS and VVL, and results fulfilling the release criteria may be added to the standard products (i.e., CPR_CLP, AC_CLP, and ACM_CLP) for release."

4. The algorithm description section 2.3 of this paper is very dense and difficult to understand.

- It begins by citing the ATBD, but a link to this document is not provided—and in any case, I would ask that the authors provide some recapitulation of the main detail provided in the ATBD within this paper, or in the citations within. As in other papers in this special issue, this should provide at least an overview of the algorithm, the key physical assumptions, etc.

The descriptions of the L2 cloud algorithms in section 2.3 have been improved to provide a better overview and major details of the algorithms. The reference to ATBD has been replaced by Okamoto et al. (2024b), which is a better reference for the interrelations among algorithms and products, corresponding to the subjects covered in this paper. A general summary of the JAXA L2 cloud microphysics algorithms is added in subsection 2.1.3

- It would be helpful to break the description into paragraphs at least, but even more helpfully into sub-sections: cloud mask, phase discrimination, cloud microphysics. Here it would also be useful to provide a description of the intended use of Doppler measurements for vertical velocity products, even if they are to be more fully described in a later paper.

Thank you for your suggestion.

The text in section 2.3 has been divided into subsections related to the preprocessing algorithms for cloud microphysics retrieval (i.e., subsection 2.3.1 Preprocessing for cloud microphysics retrieval; 2.3.1.1Cloud mask; 2.3.1.2 Cloud type; 2.3.1.3 Cloud particle category (CPC)), and cloud microphysics retrieval algorithms (i.e., 2.3.2 Cloud microphysics; 2.3.2.1 Ice cloud microphysics; 2.3.2.2 Liquid cloud microphysics).

The intended use of Doppler velocity has been added to subsections 2.3.1 and 2.3.2 for cloud preprocessing and microphysics retrieval and subsection 2.3.3 for air vertical velocity (i.e., 2.3.3 Intended use of Doppler measurements for air vertical velocity and terminal velocity products).

The following subsections has been added in the paper:

"2.3 Description of the JAXA Level 2 cloud microphysics product

The following section provides a brief overview and highlights of the standard JAXA L2 cloud microphysics products.

2.3.1 Preprocessing for cloud microphysics retrieval

2.3.1.1 Cloud mask

The ATLID-only cloud mask is processed by the ATLID_CLA algorithm (Nishizawa et al., 2024), the CPR-only cloud mask is processed by the CPR_CLP algorithm (Okamoto et al., 2024a), and the MSI-only cloud mask is processed by the MSI_CLP algorithm (Nakajima et al., 2019). For ATLID, aerosol, cloud, and surface components are discriminated from clear pixel when the Mie backscattering coefficient is significant compared to the noise level (Nishizawa et al., 2024). A cloud mask scheme is then applied; this scheme includes a vertically variable threshold value for the Mie backscattering coefficient (or particle backscattering coefficient when the Rayleigh backscattering coefficient is significant), as well as a spatial continuity test to exclude noisy pixels. The lack of sufficient surface signal is used to identify fully attenuated ATLID pixels below aerosol or cloud layers. Similarly, the CPR cloud mask scheme considers noise level, continuity testing, and surface echo information to determine sufficient radar echo power for cloud and precipitation analysis, as well as full attenuation of the radar signal. The AC_CLP synergy cloud mask scheme merges the single active sensor cloud mask results from ATLID_CLA and CPR_CLP, and then flags cloudy pixels in ATLID, CPR, or both. MSI cloud mask information is not used for the ACM_CLP cloud mask. The AC_CLP and ACM_CLP cloud mask products are currently identical.

2.3.1.2 Cloud type

The ATLID cloud type scheme (ATLID_CLA) uses δ, β_{att}, and temperature to identify the cloud phase and ice particle orientation, which is designated as two-dimensional (2D) ice, three-dimensional (3D) ice or mixed 2D and 3D ice (Okamoto et al., 2024a). The CPR cloud type scheme (CPR_CLP) uses mainly Z_e (along with its vertical profile) and temperature to discriminate the hydrometeor phase, ice particle orientation, precipitation type (snow, drizzle, or rain) and melting layer (Okamoto et al., 2024a). The AC_CLP synergy cloud type scheme combines ATLID_CLA with CPR_CLP and reclassifies the cloud type when estimates from the two sensors differ according to the classification rule specified by Kikuchi et al. (2017). The differing particle size sensitivity of CPR and ATLID aid in the identification of mixed-phase clouds and mixed cloud-precipitation types (i.e., cloud water + drizzle or cloud water + rain). The ACM_CLP and AC_CLP cloud types are identical. In addition, Doppler velocity will be used to improve differentiation between snow and rain and between cloud and drizzle. Further details of the cloud mask and cloud particle type products were reviewed by Nishizawa et al. (2024) and Okamoto et al. (2024a).

2.3.1.3 Cloud particle category (CPC)

After applying the cloud mask and cloud phase discrimination schemes (Okamoto et al., 2024a), one of the main products of the EarthCARE JAXA L2 cloud product is the cloud particle category product, which enables more detailed comprehensive exploration of the ice particle habit category contained within each JSG grid. Among cloud particle categories, the liquid-phase types are the same as those in the cloud type product (subsection 2.3.1.2). Ice particles are further categorized based on ATLID lidar ratio and depolarization ratio diagrams (Okamoto et al., 2019; 2020; Sato and Okamoto, 2023). This information is anticipated to be instrumental for general remote sensing applications (Van Diedenhoven, 2018; Letu et al., 2016) and the development of ice optical parameterization (Li et al., 2022) and hydrometeor sedimentation velocity parameterization for use in numerical models. The retrieved ice particle habit categories include horizontally oriented 2D plates and their assemblages, 2D columns and their assemblages, bullet rosettes and 3D-oriented aggregate types, droxtal/compact types, Voronoi/irregular/roughened types, and fractal-type snow aggregates (Ishimoto et al., 2008, 2012). ATLID-only CPC is used to train the CPR-based algorithm for ice particle category retrieval from Z_e and temperature information in regions with CPR-only measurements. The CPR-only CPC product is obtained from CPR_CLP.

CPR_CLP, and ATLID-only CPC are combined to produce the synergy AC_CLP CPC product. For ice categories, ATLID-only CPC estimates are used when both CPR_CLP CPC and ATLID-only CPC estimates are available for the same JSG grid. The Doppler velocity will be further used to improve category identification, particularly for snow types (e.g., graupel or hail).

2.3.2 Cloud microphysics

In CPR_CLP, ACP_CLP, and ACM_CLP, forward models corresponding to the derived cloud particle categories are used to analyze the observations from each sensor, and microphysics corresponding to each category are thus obtained. The single scattering properties of ice particles with various shapes and orientations are calculated using physical optics (Borovoi et al., 2012) and modified geometrical optics integral equation methods (Masuda et al., 2012) for ATLID specification (Okamoto et al., 2019), and discrete dipole approximation and finite-difference time domain (FDTD) methods for CPR wavelength (Sato et al., 2011; Ishimoto et al., 2008, 2012); Mie theory is used for the liquid phase and multiple scattering effects are estimated based on Sato et al. (2018, 2019).

The total effective radius for cloud and precipitation information is given as:

$$\mathrm{r_{eff}} = \int r_{eq}^{3} \frac{dn(r_{eq})}{dr_{eq}} dr_{eq} \Big/ \int r_{eq}^{2} \frac{dn(r_{eq})}{dr_{eq}} dr_{eq} \qquad (1)$$

where r_{eq} is the melted mass equivalent radius to a sphere, dn/dr_{eq} is the size distribution function. For both ice- and liquid-phase clouds, a maximum of two different particle size distributions (i=1,2) can be considered within one JSG grid to handle the presence of cloud and precipitation modes, i.e., $\frac{dn(r_{eq})}{dr_{eq}} = \sum_{i=1}^{2} \frac{dn_i(r_{eq})}{dr_{eq}}$. The corresponding effective radius is given as:

$$\mathrm{r_{eff,i}} = \int r_{eq}^{3} \frac{dn_i(r_{eq})}{dr_{eq}} dr_{eq} \Big/ \int r_{eq}^{2} \frac{dn_i(r_{eq})}{dr_{eq}} dr_{eq} \qquad (i = 1,2) \qquad (2)$$

For dn_i/dr_{eq}, a modified gamma size distribution,

$$\frac{dn_i(r_{eq})}{dr_{eq}} = \frac{No,i}{\Gamma(p) r_{m,i}} \left(\frac{r_{eq}}{r_{m,i}}\right)^{p-1} exp\left(-\frac{r_{eq}}{r_{m,i}}\right) \qquad (i = 1,2) \qquad (3)$$

in which r_m is the characteristic radius and the dispersion value is p = 2 (Okamoto, 2002; Sato and Okamoto, 2011), is employed for cloud ice, snow, and rain in cold precipitation. A log-normal size distribution,

$$\frac{dn_i(r_{eq})}{dr_{eq}} = \frac{No,i}{\sqrt{2\pi} r_{eq} ln\sigma} exp\left\{-\frac{\left[ln(r_{eq}/r_{o,i})\right]^2}{2(ln\sigma)^2}\right\} \qquad (i = 1,2) \qquad (4)$$

in which r_o is the mode radius and the standard deviation of the distribution is σ = 1.5 (Okamoto, 2002), is assumed for warm water, super-cooled liquid, and warm precipitation.

In the following, general approaches for cloud microphysics retrievals are explained based on the AC_CLP cloud microphysics algorithm, which are common to CPR_CLP and ACM_CLP cloud microphysics algorithms.

2.3.2.1 Ice cloud microphysics

For ice clouds, a lidar-only cloud region, lidar–radar overlap cloud region, and radar-only region generally exist for ice and liquid precipitation. An algorithm to retrieve microphysical properties that considers a mixture of two particle types at maximum (i.e., 2D and 3D ice) has been developed for ice cloud regions observed with CloudSat and CALIPSO synergy (Okamoto et al., 2010) using Z_e, the attenuated backscattering coefficient β, and the depolarization ratio. A framework to extend the applicability of the microphysics retrieval algorithm from the cloud region to the entire precipitation region in the vertical column was developed to efficiently reflect information from the lidar–radar overlap region to the microphysics retrieved in the CloudSat- or CALIPSO-only region (Sato et al., 2011, 2020). The relationships between microphysical properties (r_{eff} and IWC) and β or Z_e in the vertical cloud grids of the lidar–radar overlap region were derived for each profile and used to estimate the microphysical properties in the radar- or lidar-only cloud region (Sato et al., 2011). The EarthCARE JAXA L2 cloud microphysics retrieval algorithms extend these algorithms in the following three aspects: (1) the spatial variability of the microphysics and observables are considered to derive more reliable relationships among cloud microphysics and observables, (2) the microphysics estimates in the ice precipitation region far from the lidar–radar overlap region of a precipitation system are further improved by extending the microphysics estimates from the precipitation region upward rather than downward from the lidar–radar region (Heymsfield et al., 2018), and (3) single-size mode for cloud ice is considered for lidar-only cloud region and lidar–radar overlap cloud region, while two different size modes for cloud ice and ice precipitation (snow) are considered for the CPR-only region existing from the bottom altitude of the lidar–radar overlap region to the top altitude of the melting level. The PIA is used to correct the attenuation of Z_e. (Iguchi et al., 2000).

Specifically, for (1), the L2 cloud microphysics algorithm uses r_{eff} and IWC for all horizontal and vertical grids within the radar–lidar overlap region embedded in each cloud system to obtain robust relationships of cloud microphysics with Z_e and β (e.g., Z_e–IWC relationships, $Z_{e,1}= a_1 IWC_1^{b1}$ are determined for each record, where Z_e [mm^6 m^{-3}] and IWC [g m^{-3}]). These relationships are derived for each record using all data within each cloud system (or within a single EarthCARE orbit frame when a sufficient number of points cannot be obtained to derive the statistics) weighted by distance from the target profile record and are used to provide initial estimates of cloud ice microphysics based on Z_e or β in the CPR-only (ice cloud and ice precipitation) or ATLID-only (ice cloud) regions, respectively.

For (2), the relationship between the microphysics and observables is expected to change from the cloud region to the precipitation region. Because lidar signals are fully attenuated at optically thick precipitation region, new relationships for ice precipitation are derived using CPR data. In this process, CPR data at melting levels or layers around the ice–liquid interfaces of a precipitation system are used. At the top of the melting level, it is assumed that only precipitation mode exists (Z_e=$Z_{e,2}$), and during melting, the mass in each size bin (i.e., r_{eff}) remains constant across several successive layers (Heymsfield et al., 2018). For a given r_{eff}, dBZ_e changes due to the different scattering properties for ice and liquid. Therefore, r_{eff} and IWC (or LWC) are derived and the relationships ($Z_{e,2}= a_2 IWC_2^{b2}$) can be established for ice precipitation (snow) holding the coefficient b_2 at the value derived in (1) (b_2=b_1) for each record.

For (3), $Z_{e,1}$ and $Z_{e,2}$ for the two size modes (cloud ice and snow) in the CPR-only ice precipitation region at each vertical grid ($Z_{e,1} + Z_{e,2} = Z_e$) are determined as follows. The ratio $IWC_2/(IWC_1+IWC_2)$ =$IWC_2/IWC=A$ increases linearly from 0 at the bottom of the lidar–radar overlap region to 1 at the top of the melting level. A is given as, $A = \int_{h}^{ht} Z_e\, dh \; / \int_{hm}^{ht} Z_e\, dh$, with a range of 0 to 1, where the integrated Z_e from the bottom altitude of the lidar–radar overlap region (h_t) to a certain altitude h below h_t within the CPR-only ice precipitation region ($\int_{h}^{ht} Z_e\, dh$) is normalized using the value integrated to the melting level altitude h_m ($\int_{hm}^{ht} Z_e\, dh$). As the Z_e–IWC relationships for both cloud ice and snow are derived, determining the vertical profile of IWC_2/IWC is equivalent to providing the relationship between $Z_{e,1}$ and $Z_{e,2}$ for each vertical grid. Therefore IWC_i, $r_{eff,i}$ (i=1,2) and other microphysical properties are derived for each JSG grid (Table 1).

In microphysics retrieval for convective/stratiform rain below the melting level, only the precipitation size mode is assumed to exist. The r_{eff} and LWC obtained at the rain top altitude of each observation record described in (2) are used to derive the No and x values of the Marshall–Palmer size distribution ($dn/dD = No\ e^{-\Lambda D}$ [m^{-4}], where D is the particle diameter, $\Lambda = xR^{0.21}$ [cm^{-1}] and R is the rain rate in mm/hr, which is a function of LWC and r_{eff}) (Marshall and Palmer, 1948). No and x are assumed to be constant within the vertical profile for rain in a given record and are used to determine the vertical profiles of LWC and r_{eff} for the modified gamma size distribution associated with each Z_e value in the rain region.

Generally, for the same Z_e, when the mass mixing ratio of the small mode to total IWC is overestimated (underestimated), optical thickness will be overestimated (underestimated); in the 3-sensor ACM_CLP algorithm, the mass mixing ratio of the two size modes is further constrained by the optical thickness obtained from the MSI. When only a single size mode is present, the r_{eff} and IWC of the single mode are adjusted to be consistent with MSI optical thickness retrievals. Doppler velocity is expected to effectively improve particle sizing in regions of ice and liquid precipitation, as well as in the breakup of large snow particles during melting (e.g., Fujiyoshi et al., 2023).

2.3.2.2 Liquid cloud microphysics

A two-size-mode approach similar to the ice cloud microphysics retrieval process is used for water clouds, which considers the coexistence of cloud particles and drizzle. CPR_CLP derives the liquid microphysics corresponding to each size mode from CPR-only scheme. In AC_CLP and ACM_CLP, for JSG grids with ATLID observables, ATLID δ and β_{att} (or σ_{ext}) are used to derive $r_{eff,1}$ and LWC_1 for cloud water or super-cooled water (Sato et al., 2018, 2019; Sato and Okamoto, 2020). As ATLID is expected to provide a better estimate of the cloud mode than CPR, for the CPR and ATLID overlap region, the ATLID cloud microphysics and $Z_{e,1}$ estimate are used for microphysics estimation of the drizzle mode.

In water clouds, *in situ* and ground-based radar measurements have shown that cloud particles and drizzle-sized particles can coexist above −35 dBZ_e (Baedi et al., 2000). Except at very small (< −35 dBZ_e) and large values of Z_e, where only a single mode is likely to occur, the cloud mode can dominate LWC and r_{eff}, whereas the precipitation mode can dominate Z_e (Baedi et al., 2000; Krasnov and Russchenberg, 2005). For this reason, in general, the dependence of total LWC on Z_e differs significantly from results derived for only cloud particles (LWC_1 and $Z_{e,1}$) or only drizzle-sized particles (LWC_2 and $Z_{e,2}$) (Baedi et al., 2000). PIA is sensitive to total LWC, and in the CPR-only microphysics retrieval scheme, the Z_e–LWC relationship ($Z_e= a\mathrm{LWC}^b$, where Z_e [mm^6 m^{-3}] and LWC [g m^{-3}]) and LWC for the cloud+drizzle mode for the JSG grids within each record are determined from PIA and Z_e assuming that b = 5.17 (Baedi et al., 2000). The power b_i of the Z_e–LWC relationship for clouds and drizzles are reported to have similar values and assumed to be fixed (i.e., b_1~1.17; Baedi et al., 2000, Fox and Illingworth, 1997, b_2~1.58; Krasnov and Russchenberg, 2002), while the coefficients a_i in the Z_e–LWC relationship could differ between clouds and drizzles by several orders of magnitude reflecting the size distribution difference (Khain et al., 2008). As CPR Z_e is more sensitive to the drizzle mode (i.e., $Z_{e,2}$), the a_1 coefficient for cloud mode is assumed to be initially fixed at reported value (a_1=0.015; Baedi et al., 2000), and a_2 is derived for each Z_e and LWC profile, given that $LWC_1 + LWC_2 = LWC$ and $Z_{e,1} + Z_{e,2} = Z_e$. Finally, $Z_{e,i}$, $r_{eff,i}$, LWC_i (i=1,2), and other microphysical properties such as the number concentration and particle fall speed are derived for the two size modes.

The liquid cloud microphysics are further constrained by the ATLID observables for the AC_CLP and ACM_CLP algorithms, and the MSI for the ACM_CLP algorithm. Doppler information will be used to improve the microphysics estimates of the precipitation (drizzle) mode.

2.3.3 Intended use of Doppler measurements for air vertical velocity and terminal velocity products

The Doppler velocity is intended to be used in at least two approaches; air vertical velocity will be determined by subtracting the Z_e-weighted particle fall speed corresponding to each cloud particle category obtained without the use of Doppler velocity, and simultaneous retrieval of air vertical velocity and microphysics through an approach similar to that described by Sato et al. (2009), which considers the difference between the vertical structures of Z_e (reflecting cloud microphysics) and V_D (which is affected by air vertical velocity and cloud microphysics) to extract the air vertical velocity component. "

Minor comments

- L91: please provide a DOI for the ATBD

The reference to ATBD has been replaced by Okamoto et al. (2024b) (reply to major comment 4). This reference is cited in section 2.2.

- L119: what are the two different size distributions?

The description for particle size distributions is provided in subsection 2.3.1 in the revised manuscript. A modified gamma size distribution is assumed for cloud ice and snow, and a log-normal size distribution is assumed for warm water, super-cooled liquid, and warm precipitation. For both ice- and liquid-phase clouds, a maximum of two different particle size distributions can be considered within one JSG grid to handle the presence of multiple cloud modes (i.e., cloud ice, cloud water, or super-cooled water), precipitation modes (drizzle, rain, or snow), and cloud particles of differing phases. Therefore, two different effective radii with corresponding ice water or liquid water content and other microphysical properties are derived for each active sensor grid within a vertical profile. The retrieval procedure of the two size modes are provided in subsections 2.3.2.1 and 2.3.2.2.

Author's response to reviewer 2

RC2: Review "JAXA Level 2 cloud and ..." by Kaori Sato et al.

The paper provides a high-level summary of JAXA level 2 cloud and precipitation microphysical property products, which can help users effectively select suitable products for research and application in the future. The paper is well organized and presented. However, as I commented below, a few aspects could be improved.

We are sincerely grateful to all reviewers for their careful reading of the manuscript and useful comments that have allowed us to improve its quality. In our revised manuscript, we have made corrections and added subsections in section 2 to provide a better overview of the products and major details of the algorithms and products based on comments by the reviewers. Below are the reviewers' comments in blue text followed by our replies in black text.

Major issues:

1. EarthCARE radar provides Doppler velocity measurements, the sum of hydrometer falling speed and air vertical velocity. The potential of providing air vertical velocity estimation in convective clouds is exciting. The paper used several names to discuss air vertical velocity. For example, in the first paragraph, 'vertical velocity' and 'air motion' refer to the same parameter (to my understanding). But we think about 'air motion' in 3-D. In Table 1, you list the "Cloud air velocity" product, better called "Air vertical velocity." It will be great to use a consistent statement for retrieved air vertical velocity in the paper.

We have improved the manuscript by using the term "air vertical velocity" throughout the paper and in Table 1.

2. It would be beneficial to provide a paragraph or two in section 2.1 to place JAXA level 2 cloud products in the context of space-based multi-sensor cloud remote sensing and the reasoning for three cloud products. Although it is not possible to go into details of each algorithm, it could be helpful to provide a high-level summary of available information and challenges, general approaches, and additional information used to constrain retrievals to help readers better understand uncertainties in the products.

Following the reviewer's suggestion, we have explained the rationale for using three cloud products and a high-level summary of the JAXA L2 cloud microphysics algorithms in Section 2.1. These additions to subsections 2.1.2 (Rationale for producing three products) and 2.1.3 (Summary of available information, challenges, general approaches, and additional information used to constrain retrievals) provide a better overview of the products. We have further improved the description of our general approach to microphysics retrieval in Section 2.3.

The following subsections has been added in the paper:

"2.1.2 Rationale for producing three products

The CPR standalone (CPR) algorithm is considered to produce the simplest and most stable products, which are not affected by the observation and retrieval performance of other sensors, but with relatively higher uncertainty due to the small number of observables. The CPR–ATLID synergy (AC) cloud algorithm, and the CPR–ATLID–MSI (ACM) algorithm are generally considered to produce more reliable estimates of cloud microphysics and can handle more complicated scenes in terms of cloud phase with more observables and greater sensitivity. Notably, the degree of improvement in multi-sensor retrievals can be affected by many factors (e.g., day/night differences in ATLID and MSI observations).

The JAXA L2 cloud microphysics algorithms for the CPR standalone, 2-sensor, and 3-sensor synergy products share the same basic algorithms and assumptions. Less synergetic algorithms are developed and trained with more synergetic algorithms (e.g., the CPR standalone algorithm relative to 2- and 3-sensor algorithms, and the 2-sensor algorithm relative to the 3-sensor algorithm). A comparison of the three products and careful investigation of the causes underlying differences in the retrieval results according to different synergy levels will contribute to the development of better algorithms and more reliable global cloud microphysical products. The release of these three products by JAXA supports the development of retrieval algorithms allowing for the consistent treatment and integration of comprehensive long-term, spatially dense observations from active sensors on various platforms with differing sensitivity levels to create homogenous microphysics data. Collocated lidar and cloud radar measurements will not always be possible in future missions; therefore, single-sensor algorithms that are consistent with synergetic algorithms are needed (e.g., to process cloud radar data from CloudSat, EarthCARE, and future missions with single CPR measurements)

2.1.3. Summary of available information, challenges, general approaches, and additional information used to constrain retrievals

For cloud microphysics, CPR_CLP and ACM_CLP share the same basic algorithm architecture as AC_CLP, whereas in CPR_CLP, the ATLID observables are simulated based on observations to drive AC_CLP-like retrieval. ACM_CLP has additional steps to handle inputs from the MSI. Further, the framework of ice and water microphysics retrieval algorithms have similar structure. For these algorithms, a maximum of two size modes in each JSG are used to treat coexistence of cloud ice and snow in the ice phase, cloud liquid and ice (or snow) in the mixed phase, and cloud liquid and liquid precipitation in the liquid phase. Cloud ice microphysics are generally retrieved by CPR-ATLID synergy, whereas ice and liquid precipitation are often retrieved by CPR alone due to the attenuation of ATLID signals, and cloud liquid is retrieved through either ATLID-only or CPR-only retrieval schemes, as lidar and cloud radar are considered to be sensitive to different portions of the particle size distribution, particularly for water clouds.

Cloud microphysics retrieval in CPR-only regions involves challenges in producing effective radius (r_{eff}) and ice water content (IWC) or liquid water content (LWC) solely from radar reflectivity (Z_e) constrained by pulse-integrated attenuation (PIA) when Doppler velocity is not used. The dependence of Z_e on cloud microphysical properties reflects cloud physical processes (e.g., Khain et al., 2008). A single size mode cannot explain the transition stage between cloud and precipitation (Krasnov and Russchenberg, 2002). Therefore, a methodology to consider two size modes in each JSG is developed for a better interpretation of Z_e profiles in both ice- and liquid-clouds. Z_e is less sensitive to cloud particles in the presence of large particles, and the additional information of MSI optical thickness is effective for constraining cloud r_{eff} and LWC (or IWC) derived from AC_CLP in the ACM_CLP scheme. For CPR_CLP, the same microphysics retrieval scheme employed by AC_CLP for the CPR-only detected cloud region is used. To run the AC_CLP scheme, the statistical relationships between lidar observables and Z_e for the water and ice phases are derived from CALIPSO and CloudSat long-term observations and applied to create ATLID-like observations (Okamoto et al., 2020) as a function of Z_e that is fully attenuated in optically thick regions, realistically recreating observations. The current version of ATLID-like inputs will be replaced by inputs directly derived from ATLID and CPR observations. Currently, the ATLID-like input is used for only for the ice phase. For liquid cloud microphysics, ATLID-only and CPR-only retrievals are obtained and combined in the AC_CLP algorithm due to the differing sensitivity of the sensors to cloud particle size. For CPR_CLP, the CPR-only retrieval without the ATLID-like input is conducted for liquid cloud microphysics.

2.3.2 Cloud microphysics

In CPR_CLP, ACP_CLP, and ACM_CLP, forward models corresponding to the derived cloud particle categories are used to analyze the observations from each sensor, and microphysics corresponding to each category are thus obtained. The single scattering properties of ice particles with various shapes and orientations are calculated using physical optics (Borovoi et al., 2012) and modified geometrical optics integral equation methods (Masuda et al., 2012) for ATLID specification (Okamoto et al., 2019), and discrete dipole approximation and finite-difference time domain (FDTD) methods for CPR wavelength (Sato et al., 2011; Ishimoto et al., 2008, 2012); Mie theory is used for the liquid phase and multiple scattering effects are estimated based on Sato et al. (2018, 2019).

The total effective radius for cloud and precipitation information is given as:

$$r_{\mathrm{eff}}=\int r_{eq}^{3}\frac{dn(r_{eq})}{dr_{eq}}dr_{eq}\Big/\int r_{eq}^{2}\frac{dn(r_{eq})}{dr_{eq}}dr_{eq} \qquad (1)$$

where r_{eq} is the melted mass equivalent radius to a sphere, dn/dr_{eq} is the size distribution function. For both ice- and liquid-phase clouds, a maximum of two different particle size distributions (i=1,2) can be considered within one JSG grid to handle the presence of cloud and precipitation modes, i.e., $\frac{dn(r_{eq})}{dr_{eq}} = \sum_{i=1}^{2}\frac{dn_i(r_{eq})}{dr_{eq}}$. The corresponding effective radius is given as:

$$r_{\mathrm{eff,i}}=\int r_{eq}^{3}\frac{dn_i(r_{eq})}{dr_{eq}}dr_{eq}\Big/\int r_{eq}^{2}\frac{dn_i(r_{eq})}{dr_{eq}}dr_{eq} \quad (i=1,2) \qquad (2)$$

For dn_i/dr_{eq}, a modified gamma size distribution,

$$\frac{dn_i(r_{eq})}{dr_{eq}} = \frac{No,i}{\Gamma(p)r_{m,i}}\left(\frac{r_{eq}}{r_{m,i}}\right)^{p-1} exp\left(-\frac{r_{eq}}{r_{m,i}}\right) \quad (i=1,2) \qquad (3)$$

in which r_m is the characteristic radius and the dispersion value is $p = 2$ (Okamoto, 2002; Sato and Okamoto, 2011), is employed for cloud ice, snow, and rain in cold precipitation. A log-normal size distribution,

$$\frac{dn_i(r_{eq})}{dr_{eq}} = \frac{No,i}{\sqrt{2\pi}r_{eq}ln\sigma} exp\left\{-\frac{\left[ln(r_{eq}/r_{o,i})\right]^2}{2(ln\sigma)^2}\right\} \quad (i=1,2) \qquad (4)$$

in which r_o is the mode radius and the standard deviation of the distribution is $\sigma = 1.5$ (Okamoto, 2002), is assumed for warm water, super-cooled liquid, and warm precipitation.

In the following, general approaches for cloud microphysics retrievals are explained based on the AC_CLP cloud microphysics algorithm, which are common to CPR_CLP and ACM_CLP cloud microphysics algorithms.

2.3.2.1 Ice cloud microphysics

For ice clouds, a lidar-only cloud region, lidar–radar overlap cloud region, and radar-only region generally exist for ice and liquid precipitation. An algorithm to retrieve microphysical properties that considers a mixture of two particle types at maximum (i.e., 2D and 3D ice) has been developed for ice cloud regions observed with CloudSat and CALIPSO synergy (Okamoto et al., 2010) using Z_e, the attenuated backscattering coefficient β, and the depolarization ratio. A framework to extend the applicability of the microphysics retrieval algorithm from the cloud region to the entire precipitation region in the vertical column was developed to efficiently reflect information from the lidar–radar overlap region to the microphysics retrieved in the CloudSat- or CALIPSO-only region (Sato et al., 2011, 2020). The relationships between microphysical properties (r_{eff} and IWC) and β or Z_e in the vertical cloud grids of the lidar–radar overlap region were derived for each profile and used to estimate the microphysical properties in the radar- or lidar-only cloud region (Sato et al., 2011). The EarthCARE JAXA L2 cloud microphysics retrieval algorithms extend these algorithms in the following three aspects: (1) the spatial variability of the microphysics and observables are considered to derive more reliable relationships among cloud microphysics and observables, (2) the microphysics estimates in the ice precipitation region far from the lidar–radar overlap region of a precipitation system are further improved by extending the microphysics estimates from the precipitation region upward rather than downward from the lidar–radar region (Heymsfield et al., 2018), and (3) single-size mode for cloud ice is considered for lidar-only cloud region and lidar–radar overlap cloud region, while two different size modes for cloud ice and ice precipitation (snow) are considered for the CPR-only region existing from the bottom altitude of the lidar–radar overlap region to the top altitude of the melting level. The PIA is used to correct the attenuation of Z_e. (Iguchi et al., 2000).

Specifically, for (1), the L2 cloud microphysics algorithm uses r_{eff} and IWC for all horizontal and vertical grids within the radar–lidar overlap region embedded in each cloud system to obtain robust relationships of cloud microphysics with Z_e and β (e.g., Z_e–IWC relationships, $Z_{e,1}= a_1 IWC_1^{b1}$ are determined for each record, where Z_e [mm^6 m^{-3}] and IWC [g m^{-3}]). These relationships are derived for each record using all data within each cloud system (or within a single EarthCARE orbit frame when a sufficient number of points cannot be obtained to derive the statistics) weighted by distance from the target profile record and are used to provide initial estimates of cloud ice microphysics based on Z_e or β in the CPR-only (ice cloud and ice precipitation) or ATLID-only (ice cloud) regions, respectively.

For (2), the relationship between the microphysics and observables is expected to change from the cloud region to the precipitation region. Because lidar signals are fully attenuated at optically thick precipitation region, new relationships for ice precipitation are derived using CPR data. In this process, CPR data at melting levels or layers around the ice–liquid interfaces of a precipitation system are used. At the top of the melting level, it is assumed that only precipitation mode exists (Z_e=$Z_{e,2}$), and during melting, the mass in each size bin (i.e., r_{eff}) remains constant across several successive layers (Heymsfield et al., 2018). For a given r_{eff}, dBZ_e changes due to the different scattering properties for ice and liquid. Therefore, r_{eff} and IWC (or LWC) are derived and the relationships ($Z_{e,2}= a_2 IWC_2^{b_2}$) can be established for ice precipitation (snow) holding the coefficient b_2 at the value derived in (1) ($b_2=b_1$) for each record.

For (3), $Z_{e,1}$ and $Z_{e,2}$ for the two size modes (cloud ice and snow) in the CPR-only ice precipitation region at each vertical grid ($Z_{e,1} + Z_{e,2} = Z_e$) are determined as follows. The ratio $IWC_2/(IWC_1+IWC_2)$ $=IWC_2/IWC=A$ increases linearly from 0 at the bottom of the lidar–radar overlap region to 1 at the top of the melting level. A is given as, $A = \int_{\mathrm{h}}^{\mathrm{ht}} Z_e\, dh / \int_{\mathrm{hm}}^{\mathrm{ht}} Z_e\, dh$, with a range of 0 to 1, where the integrated Z_e from the bottom altitude of the lidar–radar overlap region (h_t) to a certain altitude h below h_t within the CPR-only ice precipitation region ($\int_{\mathrm{h}}^{\mathrm{ht}} Z_e\, dh$) is normalized using the value integrated to the melting level altitude h_m ($\int_{\mathrm{hm}}^{\mathrm{ht}} Z_e\, dh$). As the Z_e–IWC relationships for both cloud ice and snow are derived, determining the vertical profile of IWC_2/IWC is equivalent to providing the relationship between $Z_{e,1}$ and $Z_{e,2}$ for each vertical grid. Therefore IWC_i, $r_{eff,i}$ (i=1,2) and other microphysical properties are derived for each JSG grid (Table 1).

In microphysics retrieval for convective/stratiform rain below the melting level, only the precipitation size mode is assumed to exist. The r_{eff} and LWC obtained at the rain top altitude of each observation record described in (2) are used to derive the No and x values of the Marshall–Palmer size distribution ($dn/dD = No\ e^{-\Lambda D}$ [m^{-4}], where D is the particle diameter, $\Lambda = xR^{0.21}$ [cm^{-1}] and R is the rain rate in mm/hr, which is a function of LWC and r_{eff}) (Marshall and Palmer, 1948). No and x are assumed to be constant within the vertical profile for rain in a given record and are used to determine the vertical profiles of LWC and r_{eff} for the modified gamma size distribution associated with each Z_e value in the rain region.

Generally, for the same Z_e, when the mass mixing ratio of the small mode to total IWC is overestimated (underestimated), optical thickness will be overestimated (underestimated); in the 3-sensor ACM_CLP algorithm, the mass mixing ratio of the two size modes is further constrained by the optical thickness obtained from the MSI. When only a single size mode is present, the r_{eff} and IWC of the single mode are adjusted to be consistent with MSI optical thickness retrievals. Doppler velocity is expected to effectively improve particle sizing in regions of ice and liquid precipitation, as well as in the breakup of large snow particles during melting (e.g., Fujiyoshi et al., 2023).

2.3.2.2 Liquid cloud microphysics

A two-size-mode approach similar to the ice cloud microphysics retrieval process is used for water clouds, which considers the coexistence of cloud particles and drizzle. CPR_CLP derives the liquid microphysics corresponding to each size mode from CPR-only scheme. In AC_CLP and ACM_CLP, for JSG grids with ATLID observables, ATLID δ and β_{att} (or σ_{ext}) are used to derive $r_{eff,1}$ and LWC_1 for cloud water or super-cooled water (Sato et al., 2018, 2019; Sato and Okamoto, 2020). As ATLID is expected to provide a better estimate of the cloud mode than CPR, for the CPR and ATLID overlap region, the ATLID cloud microphysics and $Z_{e,1}$ estimate are used for microphysics estimation of the drizzle mode.

In water clouds, *in situ* and ground-based radar measurements have shown that cloud particles and drizzle-sized particles can coexist above −35 dBZ_e (Baedi et al., 2000). Except at very small (< −35 dBZ_e) and large values of Z_e, where only a single mode is likely to occur, the cloud mode can dominate LWC and r_{eff}, whereas the precipitation mode can dominate Z_e (Baedi et al., 2000; Krasnov and Russchenberg, 2005). For this reason, in general, the dependence of total

LWC on Z_e differs significantly from results derived for only cloud particles (LWC_1 and $Z_{e,1}$) or only drizzle-sized particles (LWC_2 and $Z_{e,2}$) (Baedi et al., 2000). PIA is sensitive to total LWC, and in the CPR-only microphysics retrieval scheme, the Z_e–LWC relationship ($Z_e = a\mathrm{LWC}^b$, where Z_e [$\mathrm{mm}^6\ \mathrm{m}^{-3}$] and LWC [$\mathrm{g\ m}^{-3}$]) and LWC for the cloud+drizzle mode for the JSG grids within each record are determined from PIA and Z_e assuming that b = 5.17 (Baedi et al., 2000). The power b_i of the Z_e–LWC relationship for clouds and drizzles are reported to have similar values and assumed to be fixed (i.e., $b_1 \sim 1.17$; Baedi et al., 2000, Fox and Illingworth, 1997, $b_2 \sim 1.58$; Krasnov and Russchenberg, 2002), while the coefficients a_i in the Z_e–LWC relationship could differ between clouds and drizzles by several orders of magnitude reflecting the size distribution difference (Khain et al., 2008). As CPR Z_e is more sensitive to the drizzle mode (i.e., $Z_{e,2}$), the a_1 coefficient for cloud mode is assumed to be initially fixed at reported value ($a_1=0.015$; Baedi et al., 2000), and a_2 is derived for each Z_e and LWC profile, given that $LWC_1 + LWC_2 = LWC$ and $Z_{e,1} + Z_{e,2} = Z_e$. Finally, $Z_{e,i}$, $r_{\mathrm{eff},i}$, LWC_i (i=1,2), and other microphysical properties such as the number concentration and particle fall speed are derived for the two size modes.

The liquid cloud microphysics are further constrained by the ATLID observables for the AC_CLP and ACM_CLP algorithms, and the MSI for the ACM_CLP algorithm. Doppler information will be used to improve the microphysics estimates of the precipitation (drizzle) mode.“

3. About processing flow (Section 2.2): The processing flow given in Fig. 1 is helpful in understanding the relationships among the three products. However, parameters under the two horizontal arrows could be better described in the text and positioned in the figure. In the summary, three processing chains (L2a, L2b, L2c) are mentioned but could be discussed in this section.

Figure 1 has been improved, and corresponding text explaining the connections (inputs and outputs) of the three processing chains has been added to Section 2.2 (Processing flow of the JAXA Level 2 cloud microphysics product) as:

“The L2 cloud algorithms are processed in the following order: CPR_CLP, AC_CLP, and ACM_CLP. The cloud mask, cloud type, and cloud particle category products from each algorithm are passed to the high-order synergy algorithms. The CPR-only cloud mask, cloud type, and cloud particle category products from L2a CPR_CLP are input to the L2b AC_CLP algorithm, and these CPR-only derived products are combined with the ATLID-only cloud mask, cloud type, and cloud particle category to produce synergy CPR-ATLID products. These products are then applied to the AC_CLP algorithm to derive cloud microphysics products. The AC_CLP cloud mask, cloud type, and cloud particle category products are further passed to the ACM_CLP algorithm and used for 3-sensor microphysics retrieval. The MSI is not currently used to improve the cloud mask, type, and category products; therefore, these products from ACM_CLP are the same as those from AC_CLP.”

Minor issues:

1. Line 24: add " and cloud dynamics" after "hydrometer formation"

   We added " and cloud dynamics".

2. Line 42: Does "the EarthCARE L2" mean JAXA L2 here?

   Yes. We corrected it to “EarthCARE JAXA L2”.

3. Line 102-104: This sentence could be incorrectly stated. Do you mean that ATLID-based results are used to train a CPR-based algorithm to provide retrievals in regions with CPR only measurements?

   Yes. We have rephrased it as; ATLID-only CPC is used to train the CPR-based algorithm for ice particle category retrieval from Z_e and temperature information in regions with CPR-only measurements. (Line 193-194)

4. Line 129: "Eight frames" and "15 frames" are inconsistent here. One of the "frames" needs to be replaced with a different word.

   Eight frames represent one orbit, and we used 15 frames for evaluation, corresponding to nearly two orbits. We have clarified this information in the text as, “The simulated L1 data for an EarthCARE orbit are divided into eight frames, and 15 frames, corresponding to nearly 2 orbits, are simulated to include representative cloud and aerosol scenes around the world." (Line 320-321)

5. In Figure 3, there are fewer clouds horizontally in simulated ATLID measurements, which is puzzling because ATLID should be more sensitive to CPR in cloud detection.

   The ATLID L2a cloud backscatter product for the cloud scenes in this study (Figure 3) is processed by the JAXA L2 ATLID algorithm (Nishizawa et al., 2024). Nishizawa et al., (2024) applied the JAXA ATLID L2 feature mask algorithm to the simulated EarthCARE L1 data and found that the cloud mask scheme appeared to reasonably extract cloudy pixels from the original output of ATLID signals produced by the model. The misidentification of the cloud layers was relatively low (approximately 10%). The effective radius/ice water content of the simulated ice clouds in Figure 3 were sometimes relatively large/small near cloud tops (Figures 4 and 5), and the corresponding ATLID backscattering coefficient could be weak to be detected.

Nishizawa, T., Kudo, R., Oikawa, E., Higurashi, A., Jin, Y., Sugimoto, N., Sato, K., and Okamoto, H.: Algorithm to retrieve aerosol optical properties using lidar measurements on board the EarthCARE satellite, Atmos. Meas. Tech. Discuss. [preprint], https://doi.org/10.5194/amt-2024-100, in review, 2024.

6. Figure 3 caption: add "(left column)" after "Ze measurements" and "(right column)" afte "product" to better separate CPR and ATLID measurements.

   We included them.

7. The layout of different panels between simulations and retrieval for Fig. 6 differs from Figs. 4 and 5. It would be better if they were consistent.

   The layout of Fig.6 is modified to be consistent with Figs.4 and 5.

8. Line 182: Fig. 7b and Fig. 7c should be switched.

   Fig. 7b and Fig. 7c are switched.

9. Line 218: change "Doppler information" to "radar Doppler velocity measurements".

   We have changed it.

   Thank you for your suggestions.