EarthCARE Observations of Vertical Motion and Cloud Microphysical Structure in Tropical Cyclones

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Abstract. The Earth Cloud, Aerosol and Radiation Explorer (EarthCARE) ~~satellite mission~~ provides the first spaceborne Doppler radar measurements~~, enabling new insights into the vertical structure~~ of clouds and precipitation. ~~In this study, we~~ We construct a ~~dataset of EarthCARE overpasses of~~ tropical ~~cyclones (TCs)~~ cyclone (TC) dataset by collocating ~~satellite~~ 16 months of EarthCARE observations with the International Best Track Archive for Climate Stewardship ~~(IBTrACS). Based on 14 months of observations, we examine the radial structure of radar reflectivity, Doppler velocity, retrieved air motion, and cloud particle types.~~, comprising 101 intercepts of 28 TCs. The ~~results show a transition from convective-like structures in the eyewall to stratiform-like characteristics in the rainband region. The eyewall~~inner-core region exhibits ~~stronger updrafts,~~ enhanced reflectivity, ~~and~~stronger and more variable upward air motion, and a broader Doppler velocity ~~distributions. In contrast, the rainband region shows that weaker vertical motions and Doppler signals are more strongly influenced by hydrometeor fall speeds. We further evaluate TC simulations using the Nonhydrostatic ICosahedral Atmospheric Model (NICAM) with two different cloud microphysical configurations of hydrometeor fall speeds. Both experiments reproduce the overall TC structure but exhibit more confined distributions of radar reflectivity, Doppler velocity, and~~ distribution. Although based on only two independent intercepts, inner-core results show consistent Doppler and air velocity ~~compared to the observations. Differences~~structures. In the rainband region, the Doppler velocity distribution shifts toward more negative values, accompanied by more negative particle terminal velocities and a bright band near the melting level. Particle classifications show small ice dominates the upper troposphere, whereas snow extends toward more negative Doppler velocities between ~~the two simulations highlight the sensitivity of vertical structure to hydrometeor fall speeds.~~5 and 12 km. These results ~~indicates~~show that ~~EarthCARE~~regional variations in Doppler ~~observations provide valuable~~velocity reflect differences in both air motion and particle sedimentation. We conduct a preliminary single-case comparison for Hurricane Humberto using the Nonhydrostatic Icosahedral Atmospheric Model with two common microphysical configurations. Both configurations underestimate TC intensity and produce narrower distributions than observed. Compared with K21, T24 more closely reproduces observed upper-level structure, with gradual changes in radar reflectivity and Doppler velocity, and a broader cloud ice distribution. Because the comparison is limited to one case, it demonstrates sensitivity to the microphysical configurations rather than a general evaluation of model performance. Overall, EarthCARE provides complementary

constraints on ~~the coupling between dynamics and cloud~~vertical air motion, condensate properties, and particle sedimentation for evaluating TC microphysics ~~in TCs~~.

1 Introduction

Understanding vertical motion in cloud systems is crucial for weather forecasting and climate projection, but it has been difficult to observe at fine resolution globally. The Earth Cloud, Aerosol and Radiation Explorer (EarthCARE; Illingworth et al., 2015; Wehr et al., 2023) satellite mission enables observation of ~~vertical motion of clouds for the first time~~cloud particle's Doppler velocity from space by carrying a 94 GHz nadir-pointing Cloud Profiling Radar (CPR), the first spaceborne Doppler radar to observe cloud and precipitation particles' vertical motion. ~~The~~ EarthCARE also carries 355 nm ATmospheric LIDar (ATLID), with dual-polarization capability, providing information on particle shapes. The ~~unprecedented~~Doppler measurements from CPR ~~and ATLID observations~~ enable the estimation of hydrometeor fall speed and ~~inference~~the retrieval of vertical air motion across diverse cloud regimes (Roh et al., ~~2026). The detection of particle shapes by~~2025), while ATLID ~~further improves~~observations support the ~~understanding~~identification of cloud ~~microphysical processes~~particle types. EarthCARE sheds new light on studies of cloud dynamics and cloud microphysics, which were previously limited in their global observations.

Spaceborne observations have ~~enabled real-time~~long supported the monitoring of tropical cyclones (TCs) and ~~have revealed new~~provided insights into ~~TC~~their dynamics ~~before EarthCARE~~. A geostationary satellite image is used to estimate and forecast the TC intensity of a location (Dvorak, 1975, 1984). Combining cloud top temperature from the Moderate Resolution Imaging Spectroradiometer (MODIS) and cloud top height with CloudSat cloud profiles, Luo et al. (2008) developed a method to better estimate TC intensity. On the other hand, the CloudSat TC dataset (CSTC) has been released and is widely used to understand TC dynamics (Tourville et al., 2015). Using CSTC, Wu and Soden (2017) found that strengthening TCs have 20% higher ice water content (IWC) than weakening TCs. Wu et al. (2020) then showed that the intensification rate is correlated with IWC in rapidly intensifying TCs, suggesting that ~~rapid intensification~~enhanced IWC may be a precursor to ~~TC~~rapid intensification. Lee and Wing (2024) investigated the role of cloud-radiative feedback in intensifying weak TCs and found that cloud-radiative processes can drive the secondary circulation and enhance TC intensity. ~~The above~~These studies ~~demonstrated a breakthrough in TC understanding using~~ demonstrate the value of CloudSat radar observations ~~despite only~~for understanding TCs, although CloudSat provides radar reflectivity~~. In the era~~ without Doppler velocity. The Doppler capability of EarthCARE~~, by observing with~~ CPR therefore provides new information for examining the ~~two active sensors, CPR and ATLID, we can better understand the coupling~~relationship between ~~dynamics~~vertical motion and cloud microphysics in TCs.

In addition to dynamical processes, cloud microphysics plays a crucial role in determining TC structure and evolution. ~~For example, the~~The presence of supercooled liquid water ~~has important implications for latent heat release~~affects riming, freezing,

and hydrometeor growth in the upper levels. ~~Therefore, supercooled water is regarded as the target~~Project STORMFURY therefore attempted to ~~weaken~~modify TC structure and intensity by seeding ~~during STORMFURY~~ supercooled water (Willoughby et al., 1985). However, they reported that the changes in TC intensities are limited because TCs contain less supercooled water than expected. Black and Hallett (1986, 1999) showed that supercooled water is hard to find when the temperature is below -5 ℃ due to the efficient depletion by riming and freezing processes. In contrast, aircraft observations of Hurricane Bonnie revealed the presence of large graupel particles at high altitudes, implying in situ growth supported by deeply supercooled cloud droplets within TC updrafts (Black et al., 2003). These contrasting findings highlight the large uncertainties in the occurrence and vertical distribution of supercooled water in TCs. This underscores the need for observational constraints on cloud phase and its coupling with dynamical processes. The cloud particle types retrieved from EarthCARE provide the opportunity to examine the relationship between vertical motion and cloud microphysical structure in TCs, although they do not directly quantify the amount of supercooled liquid water.

Recent advances in computational power have enabled the use of global storm-resolving models (GSRMs) to study atmospheric phenomena (Satoh et al., 2019; Stevens et al., 2019). By explicitly resolving deep convection without cumulus parameterization, GSRMs provide explicit representations of the structure and variability of storm systems, including TCs. Judt et al. (2021) analyzed datasets from the nine GSRMs and showed that, while individual models can capture certain aspects of TC behavior, their representations vary across models. Baker et al. (2024) further demonstrated that GSRMs can simulate rapid intensification, which is ~~absent~~hard to be represented in ~~coarser~~ low-resolution conventional global climate models ~~with cumulus parameterization~~. GSRMs can also capture the sensitivity of the inner-core size to the intensification rate of TCs. These studies highlight the potential of GSRMs for simulating ~~TC~~TCs, but also indicate the need for further evaluation and development. In particular, observational constraints on both dynamical and cloud microphysical processes of TCs remain limited. The radar reflectivity and Doppler velocity observed by EarthCARE provide a unique opportunity to jointly evaluate and constrain these processes in GSRMs. ~~In~~ Roh et al. (~~2026), they~~2025) also argued that the ~~synergetic~~combined analysis of EarthCARE observations and GSRMs ~~could reveal~~can improve the ~~nature~~ understanding of cloud systems ~~whose understanding is limited solely by EarthCARE~~beyond what can be obtained from either observations or ~~GSRMs.~~ models alone.

This study ~~aims to apply unprecedented~~uses EarthCARE observations to investigate the dynamical and cloud microphysical structures of TCs, with a particular focus on vertical motion. We ~~co-locate~~collocate EarthCARE overpasses with TC tracks from the International Best Track Archive for Climate Stewardship (IBTrACS) to construct ~~the~~an EarthCARE- TC dataset following Tourville et al. (2015). ~~In this paper~~Using 16 months of observations, we ~~analyze 14-month statistics of TC structures observed by EarthCARE~~examine regional differences in radar reflectivity, Doppler velocity, retrieved air motion, and ~~then compare observed TC structures~~cloud particle types. We further investigate how air motion and particle sedimentation influence the Doppler velocity distributions in the inner-core, rainband, and outer regions. Finally, we conduct a preliminary single-case comparison with ~~those simulated by a global storm-resolving model, the Icosahedral~~ simulations from the

Nonhydrostatic Icosahedral Atmospheric Model (NICAM; Tomita and Satoh, 2004; Satoh et al., 2008, 2014~~).~~) to examine the sensitivity of the simulated cloud structure to two microphysical configurations with different hydrometeor fall-speed settings. The paper is organized as follows: Section 2 describes the data and method; Section 3 presents the results; Section 4 ~~evaluates the model~~presents the preliminary comparison for Hurricane Humberto; and Section 5 summarizes the ~~paper~~study.

2 Data and Methodology

2.1 Data

2.1.1 EarthCARE CPR and ATLID

The EarthCARE satellite is a joint mission developed by the European Space Agency (ESA) and the Japan Aerospace Exploration Agency (JAXA). In addition to CPR and ATLID, the EarthCARE satellite carries the Multi-Spectral Imager (MSI) and the Broadband Radiometer (BBR). CPR operates at 94 GHz (W-band) and provides the first spaceborne Doppler radar observation. ATLID is a 355-nm lidar equipped with dual-polarization capability, which enables the observation of particle shape. ~~The retrieved data from the above two sensors are used in this study.~~ We primarily use the JAXA level-2 cloud and precipitation microphysics retrievals from CPR (CPR_CLP; Sato et al., ~~2025), including radar reflectivity, Doppler velocity, air velocity, cloud water content, and cloud ice content.~~2025). We also adopt the cloud particle types from the JAXA level-2 CPR-ATLID Synergy Cloud Product (AC_CLP; Sato et al., 2025; Okamoto et al., 2024) to investigate the cloud microphysical structure in TCs and the relationship between vertical motion and cloud microphysics. Both CPR_CLP and AC_CLP ~~data are in~~products share the same horizontal (1 km) and vertical (0.~~5~~1 km) resolutions. We ~~used~~adopt the ~~data~~period covered by both products from 1 August 2024 to ~~31~~30 November 2025 ~~to colocate~~for collocation with TC tracks.

We use radar reflectivity, Doppler velocity, air velocity, terminal velocity, cloud water content, and cloud ice content from the CPR_CLP product, together with cloud particle types from the CPR-ATLID synergy product. Radar reflectivity and Doppler velocity are directly ~~observed variables, while~~obtained from observation with corrections following the ~~other quantities.~~ JAXA processing algorithm (Sato et al., 2025). Basic physical corrections, including clutter-echo and gaseous-attenuation corrections for radar reflectivity and Doppler unfolding for Doppler velocity, are applied before the level-2 retrievals. The CPR Doppler Nyquist velocity is approximately ±4.8 m s^{-1}, so velocities exceeding this range are aliased in the raw measurements and subsequently corrected through Doppler unfolding in the Level-2 processing. In this study, all vertical velocities are defined as positive upward, so particle fall velocities are negative.

Cloud water content, cloud ice content, and air velocity are retrieved ~~based on these measurements. For example, cloud~~ from the corrected CPR observations following the JAXA Level-2 retrieval algorithms (Sato et al., 2025). Cloud water and ice

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contents are ~~estimated~~calculated from radar reflectivity using empirical relationships (Sato et al., 2025). Air velocity is retrieved by estimating and removing the hydrometeor terminal velocity from the observed Doppler velocity (Sato et al., 2009; Sato et al., 2025). The measured Doppler velocity can be expressed as

$$V_D = V_{air} + V_{tz} \quad (1),$$

where V_{air} is the air velocity, and V_{tz} is the radar reflectivity-weighted terminal velocity of particles. V_{tz} depends on particle size, shape, orientation, and atmospheric conditions. Cloud microphysical properties and vertical motion are retrieved consistently using the observed radar quantities and assumed particle properties. The product also provides retrieved particle terminal velocities based on inferred particle properties. These represent particle fall speeds and are distinct from V_{tz}, which represents the radar-weighted sedimentation contribution to the measured Doppler velocity. In addition, we estimate V_{tz} as $V_D - V_{air}$. ~~and air and terminal velocities are derived by decomposing the Doppler velocity, as described by Sato et al. (2009). The~~in the following analysis. Finally, the cloud particle types are retrieved based on the combined use of CPR and ATLID observations. Cloud particles are categorized into 16 hydrometeor types: missing, clear, warm water, supercooled water, 3D-ice, 2D-plate, mixture of 3D-ice and 2D-plate, liquid drizzle, mixed-phase drizzle, rain, snow, water and liquid drizzle, water and rain, mixed phase, unknown, and melting layer (Okamoto et al., 2024). ~~These retrieval algorithms rely on assumptions regarding particle size distributions, shapes, and scattering properties, which may influence the accuracy of the derived variables in complex cloud conditions. Therefore, uncertainties remain in mixed-phase regions or under conditions of strong attenuation. To reduce uncertainties due to attenuation, we exclude grid points with radar reflectivity values smaller than −20 dBZ, where attenuation effects are significant.~~

These retrieved quantities are subject to uncertainties associated with assumptions regarding particle size, shape, and scattering properties. Retrievals of particle terminal velocity and vertical air motion can be particularly challenging when multiple hydrometeor populations coexist, especially in mixed-phase and melting regions. Strong precipitation can introduce additional uncertainties through radar attenuation and multiple scattering. These limitations are considered when interpreting the retrieved microphysical properties and vertical air motion in the following analyses.

2.1.2 IBTrACS

The TC tracks and TC intensities are adopted from the International Best Track Archive for Climate Stewardship (IBTrACS; Knapp et al., 2010). IBTrACS provides the best-estimated dataset by merging TC records from multiple operational agencies. In this study, we use Version 4r01 of the IBTrACS dataset (Gahtan et al., ~~2024~~2025). The 3-hourly TC position, maximum sustained wind speed, and radius of maximum wind (RMW) are based on the USA agency records. These data are used to identify TC cases intercepted by EarthCARE and to calculate the radial distance from the storm center for composite analyses.

2.1.3 IMERG

Precipitation data are obtained from the Integrated Multi-satellite Retrievals for GPM (IMERG) Final Run product (GPM_3IMERGHH, Version 07). IMERG provides global precipitation estimates by combining observations from multiple passive microwave sensors and infrared measurements, with gauge calibration applied in the Final Run product. The dataset has a temporal resolution of 30 minutes and a spatial resolution of 0.1° × 0.1°. In this study, IMERG data are used to characterize the precipitation structure associated with TCs.

2.2 Methodology

2.2.1 EarthCARE overpass of TCs

To construct a dataset of TC structures observed by EarthCARE, we first identify satellite overpasses that pass within 1000 km of a TC center, following Tourville et al. (2015). The TC position, maximum sustained wind, and RMW are interpolated from the 3-hourly IBTrACS data to the exact EarthCARE overpass time. For each EarthCARE radar profile ~~along the satellite track~~, the distance ~~to~~from the interpolated TC center is calculated and normalized by the corresponding RMW to account for ~~subsequent~~ differences in storm size among individual TCs. The sampled TCs have a mean RMW of 25.6 km and an interquartile range of 18.5-31.5 km, providing a physical scale for the normalized radial distance (Fig. S1). The statistical composites in this study are restricted to strong TCs of Category 3 intensity or higher. To focus the analysis on detectable cloud and precipitation signals, only grid points with reflectivity greater than −20 dBZ are retained for the composite and conditional sampling analyses. Radial-height bins with fewer than 100 valid samples are excluded from the composites.

Radial composites are constructed by collecting all valid EarthCARE profiles within each normalized radial bin. The dataset includes 101 EarthCARE intercept events from 28 TCs in the Northern Hemisphere. These intercepts provide 1,853 valid profiles within 15 RMW. Because the number of satellite intercepts differs substantially with radius, we examine both the number of independent intercept events and the number of valid profiles contributing to each radial bin (Fig. S2). Because the number of EarthCARE samples decreases substantially toward the TC center, all profiles within 2 RMW are combined into one radial bin, whereas 1-RMW bins are used from 2 to 15 RMW in the subsequent analyses. Sampling is particularly limited within 2 RMW, so individual-event mean vertical profiles are compared to assess the robustness of the inner-core statistics (Fig. S3). Although only two independent TC cases contribute to this region, they show consistent vertical structures in Doppler and air velocities and a similar vertical extent of radar echoes exceeding 0 dBZ, despite differences in radar reflectivity magnitude.

Figure 1 illustrates an example of the colocation for Hurricane Humberto on 28 September 2025 at 18:17 UTC. Humberto is an intense hurricane over the Atlantic Ocean, reaching Category 4 intensity (Fig. 1a). The EarthCARE ground track intersects

Humberto's eye, sampling both the eyewall and outer regions (Fig. 1b). At the time of the overpass, Humberto was undergoing an eyewall replacement process. The cross section of radar reflectivity (Fig. 1c) shows strong signals within ±100 km of the storm center, indicating substantial condensate in the eyewall and rainband regions. The Doppler velocity field (Fig. 1d) ~~reveals updraft~~shows distinct structures associated with the ~~double eyewall~~inner and outer eyewalls, with the closest passage to the inner eyewall located ~~near 9~~approximately 8 km ~~(closest point)~~from the TC center and the outer eyewall sampled near ±50 km. ~~Stronger~~Doppler velocities are less negative and more concentrated ~~upward Doppler velocity~~ in the inner eyewall ~~compared to~~than in the outer eyewall, suggesting a stronger contribution from upward air motion. Beyond ±100 km, isolated convection and anvil cloud structures are observed in the outer region. Figure 1e shows the retrieved cloud particle types from the CPR-ATLID synergy product. Rain dominates below the freezing level, while snow particles are associated with regions of enhanced reflectivity. In the upper troposphere, 3-D ice particles are prevalent, particularly in the anvil region. These cross sections demonstrate the capability of EarthCARE to capture the vertical structure of clouds and Doppler velocity within a TC.

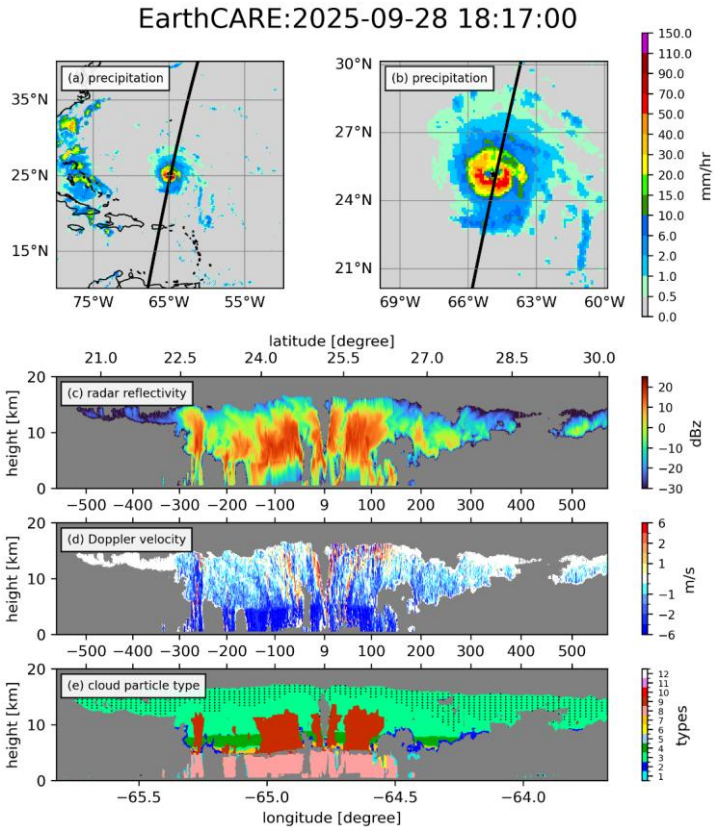


Figure 1. (a) and (b) ~~are~~show IMERG precipitation accumulated from 18Z to 19Z for large and small ~~domain~~domains, respectively. The black line indicates the ~~-~~track of EarthCARE overpass. (c) demonstrates the cross-section of radar reflectivity along the track in (b). (d) is the same but for Doppler velocity. (e) shows the retrieved cloud particle types: 1, warm water; 2, supercooled water; 3, 3-D ice; 4, 2-D plate; 5, mixture of 3-D ice and 2-D plate; 6, liquid drizzle; 7, mixed-phase drizzle; 8, rain; 9, snow; 10, water and liquid drizzle; 11, water and rain; and 12, mixed phase. The types of clear, melting layer, and missing are not shown here. Distances (km) from the TC center are indicated between panels (c)-(d) and (d)-(e).

2.2.2 NICAM hindcast simulations

NICAM is used to perform hindcast simulations in this study. The model is configured with a horizontal resolution of approximately 3.5 km and 78 vertical levels using a terrain-following coordinate. The vertical grid spacing increases from 66 m near the surface to 400 m at 3.3 km, remains constant up to 18 km, and then increases toward the model top at 50 km. Cloud microphysical processes are represented using the NICAM Single-moment Water 6 (NSW6; Tomita, 2008; Roh et al., 2014) scheme, which includes six prognostic hydrometeor species. Radiative transfer is calculated using the MSTRNX scheme based on the correlated k-distribution method (Sekiguchi and Nakajima, 2008). Surface processes are represented by the MATSIRO land surface model (Takata et al., 2003) and a slab ocean model, while subgrid-scale turbulence is parameterized using the Mellor-Yamada-Nakanishi-Niino level 2 scheme (MYNN2; Nakanishi & Niino, 2006; Noda et al., 2010).

The simulations are initialized at 00:00 UTC on ~~27~~26 September 2025 using operational atmospheric ~~initial conditions interpolated~~analysis from the ~~ERA5 reanalysis~~ECMWF Integrated Forecasting System (IFS) at approximately 9-km horizontal resolution, while sea surface temperature is nudged toward daily Optimum Interpolation Sea Surface Temperature (OISST) in the slab ocean model, with a 7-day relaxation time to prevent SST drift. Land initial conditions are taken from climatology derived from a low-resolution NICAM simulation. Each simulation is integrated for ~~2~~6 days, with output frequencies of ~~3~~6-hourly for three-dimensional variables and 1-hourly for two-dimensional fields. In this study, we use the Joint-Simulator for satellite sensors (J-Sim; Hashino et al., 2013; Roh et al., 2025) to ~~produce~~generate the EarthCARE CPR-like ~~signals of~~ radar reflectivity and Doppler velocity based on NICAM outputs, which can be directly compared to the EarthCARE signals.

~~Two simulations are performed with different cloud microphysical settings~~Two commonly used configurations of the NICAM NSW6 are evaluated: the HighResMIP-tuned configuration (Kodama et al., 2021; hereafter K21) and the global K-scale climate configuration (Takasuka et al., 2024; hereafter T24). ~~The~~These configurations represent alternative parameter choices that have been adopted in recent NICAM applications, and we compare them to assess their representation of the observed TC cloud and precipitation structure. A primary difference between K21 and T24 lies in the coefficients used to parameterize the terminal velocities of hydrometeors. K21 applies larger coefficients for terminal velocities of snow and rain, while cloud ice is assumed to be non-falling. In contrast, T24 uses smaller parameters for snow and rain and assigns a small constant fall speed (0.1 m s^{-1}) to cloud ice. Additionally, T24 incorporates lateral moisture mixing through the Leonard term. ~~Sensitivity experiments using~~ Comparison of these two ~~different cloud microphysics schemes provide an insightful~~NSW6 configurations provides a useful framework for examining how differences in hydrometeor terminal velocity settings influence the simulated radar reflectivity and Doppler velocity, ~~that is, the dynamics and cloud microphysics within a~~ and thus the representation of TC~~, respond to changes in terminal speeds of hydrometeors~~ cloud and precipitation structure.

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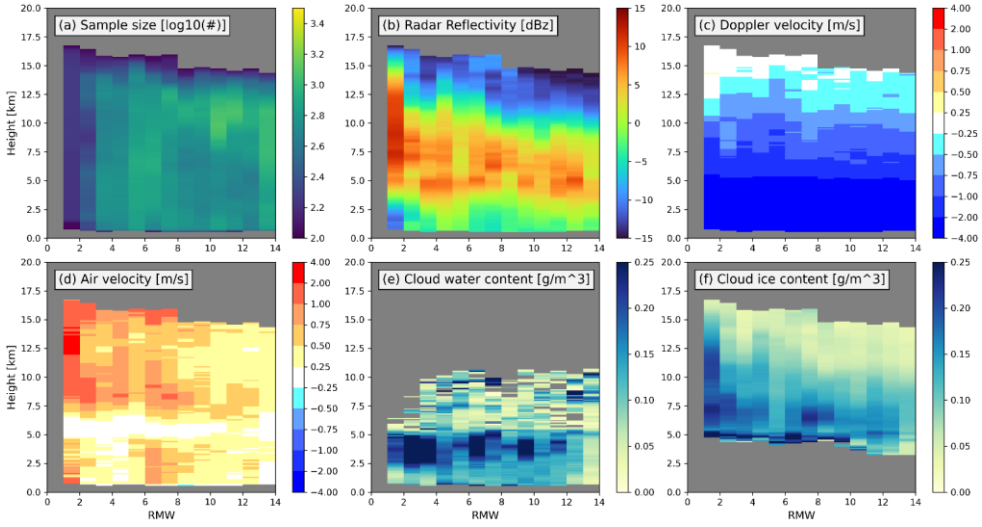


Figure 2. Radial composites ~~based on RMW~~as a function of normalized radial distance (RMW) for (a) sample size ~~[log10(#)],~~[#], (b) radar reflectivity [~~dBz~~dBZ], (c) Doppler velocity [m s^{-1}], (d) air velocity [m s^{-1}], (e) cloud water content [g m^{-3}~~],~~], and (f) cloud ice content [g m^{-3}~~]~~].

3 Observational Analysis

3.1 Radial Composites of Tropical Cyclones

Figure 2 presents the radial-height composite ~~structure~~structures observed by EarthCARE. Because of ~~strong TCs (maximum wind speed > 94 knots, Category 3 and above).~~the limited sampling in the inner-core region, all samples within 2 RMW are combined into a single radial bin, while 1-RMW bins are used farther outward. The sample ~~size indicates sufficient~~ count shows considerable observational coverage ~~from 2 to~~ outside 2 RMW, with generally sufficient sampling throughout the 2-15 RMW range (Fig. 2a). Radar reflectivity (Fig. 2b) reveals a coherent vertical structure characterized by enhanced echoes in the ~~eyewall~~inner-core region (~~RMW~~R < 2 RMW), where strong reflectivity extends to 12.5 km. The upper extent of strong reflectivity decreases sharply ~~at~~outside 2 RMW, ~~marking~~indicating the transition from the ~~eyewall~~inner-core to the ~~primary~~ rainband region. ~~A relative minimum in reflectivity at 5 RMW suggests a separation between the primary and outer rainband regions.~~ In the rainband region (2~~–~~ RMW ≤ R < 5 RMW), radar reflectivity above 5 km is slightly weaker than in the ~~eyewall~~inner-core region, while a pronounced reflectivity layer near 5 km corresponds to the melting layer. Beyond 5 RMW

~~(outer region), both the intensity and~~ , the vertical extent of reflectivity ~~decrease gradually~~generally decreases with increasing distance from the TC center. Overall, the composite structure derived from the EarthCARE ~~observation~~observations is consistent with the canonical organization of TCs, including a deep convective inner core and progressively weaker outer rainbands. Three radial regions are defined based on RMW: the ~~eyewall~~inner region (R < 2 RMW), the rainband region (2– RMW ≤ R < 5 RMW), and the outer region (5– RMW ≤ R < 15 RMW). The 5-RMW boundary is used as a practical threshold for the regional analysis rather than as a strict physical boundary. Sensitivity tests using 4 and 6 RMW as the boundary produce qualitatively similar results (see Supplement for details). These definitions are used throughout the following analysis.

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Doppler velocity shows predominantly negative values below 15 km (Fig. 2c), with a broadly similar vertical structure across radial regions. Above the freezing level (~5 km), Doppler velocity increases from approximately -2 m s^{-1} to near 0 m s^{-1} with height. Below the freezing level, Doppler velocities become more negative, reaching around -4 m s^{-1}, consistent with the contribution of liquid particle fall speeds in the lower troposphere. ~~Air vertical~~Vertical air velocity exhibits upward motion in the mid-to-upper troposphere (Fig. 2d). A layer of near-zero vertical velocity is observed around 5-7 km across all regions, in which the retrieval of vertical motion in mixed-phase conditions may be uncertain (see Section 42.1.1). Stronger upward motion is evident in the ~~eyewall~~inner-core region (R < 2 RMW) between approximately 7.5 and 15 km height, while upward motion is more confined to 7.5-12.5 km height in the rainband region. (2 RMW ≤ R < 5 RMW). Beyond 5 RMW, the magnitude of upward motion generally decreases. Notably, localized upward motion is also observed below the freezing layer in the ~~eyewall~~ inner-core region and in parts of the outer region ~~(~~between 6- and 8 RMW~~).~~ . The vertical structure of air motion in the ~~eyewall~~inner-core and outer regions resembles convective updrafts, except for a gap that may be due to retrieval uncertainties in the mixed-phase layer. On the other hand, the rainband region shows a more stratiform structure, characterized by the bright band signal and top-heavy vertical motions.

The distributions of the retrieved cloud water and cloud ice further illustrate the cloud microphysical structure of TCs (Fig. 2e and 2f). Cloud water is primarily confined to the lower troposphere below approximately 5 km, while cloud ice dominates the upper troposphere above this level. ~~Between 5-10 km, mixture of ice and liquid phases is presented, indicating the existence of supercooled water.~~ Within ~~the region~~R < 8 RMW ~~less than 8~~, cloud water is most pronounced between approximately 2.5 and 5 km, while the ~~occurrence~~amount decreases ~~both above and~~ below this layer. ~~Cloud water is also detected above 5 km, indicating the presence of supercooled liquid water up to approximately 10 km. However, its occurrence is relatively limited, suggesting that it does not dominate the composite structure at these levels.~~ Below approximately 2.5 km, cloud water retrieval may be affected by attenuation, potentially leading to an underestimation of liquid water content near the surface. The ~~distribution~~radial-height structure of cloud ice generally ~~follows~~matches that of radar reflectivity, with enhanced ice content in regions of stronger reflectivity. The distributions of cloud water and ice contents provide information on cloud microphysical structures in TCs for further model evaluations.

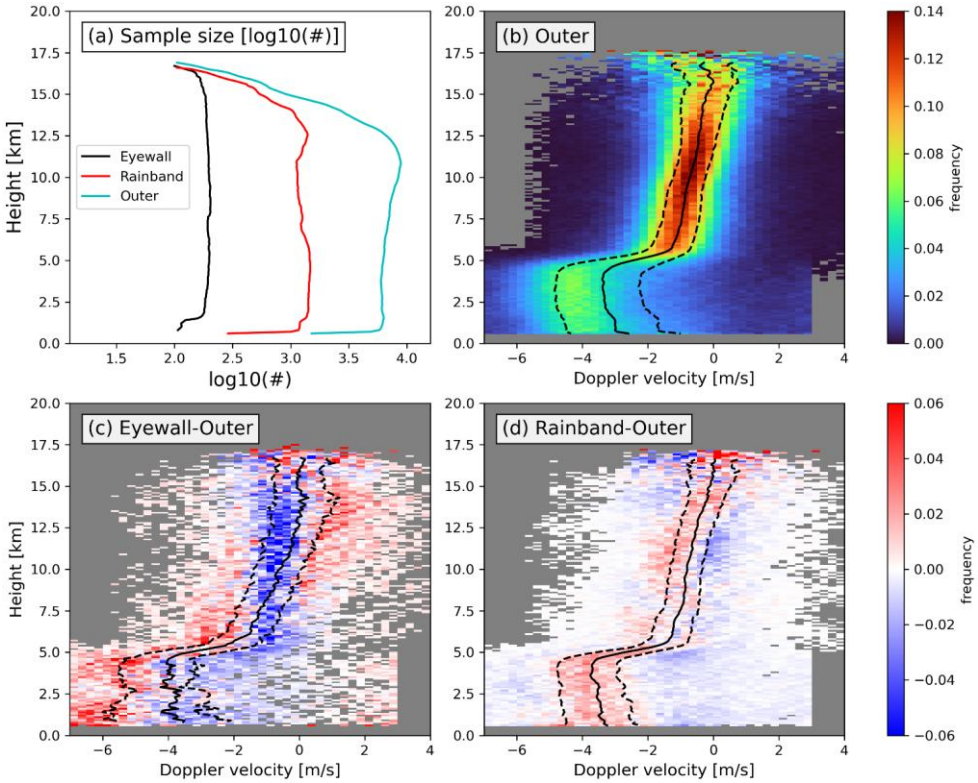


Figure 3. (a) ~~sample~~Sample size of three different regions. (b) PDF of Doppler velocity for the outer region (5~~<~~ RMW~~<~~ < R < 15 RMW). PDF differences of (c) ~~eyewall~~inner-core and (d) rainband regions~~, respectively, relative~~ with respect to the outer region. Solid lines represent the mean of Doppler velocity, while dashed lines indicate the interquartile range. The PDFs are normalized independently at each level.

3.2 Doppler and Vertical Air ~~velocity~~Velocity

Based on the structural differences identified in Fig. 2, the samples are divided into ~~eyewall~~inner-core, rainband, and outer regions to examine the distribution of ~~vertical motion~~Doppler velocity in more detail. The sample size in each region exceeds 100 across most vertical levels (Fig. 3a), providing sufficient ~~coverage for statistical analysis.~~ grid point-level coverage for

examining distributions of Doppler velocity. However, the samples in the inner-core region are obtained from only two independent EarthCARE intercept events (Fig. S2). The two events exhibit similar Doppler velocity characteristics (Fig. S3), suggesting that the distributions capture consistent features of the sampled inner-core structures, although they should not be interpreted as statistically representative of TCs in general. At each height, the Doppler velocity PDF is normalized independently using the valid samples at that level, so that each vertical level represents its own Doppler velocity distribution. For Fig. 3c and 3d, the normalized PDF of the outer region is subtracted from the normalized PDFs of the inner-core and rainband regions, respectively. Positive values therefore indicate Doppler velocity ranges with higher frequency than in the outer region, while negative values indicate lower frequency. Sensitivity tests using 4 and 6 RMW as the rainband-outer-region boundary show similar Doppler velocity distributions (Fig. S4 and S5), indicating that the main characteristics are insensitive to the exact choice of this boundary.

The Doppler velocity probability density function (PDF) in the outer region is used as a reference (Fig. 3b). A ~~sharp~~ transition in Doppler velocity at around 5 km in height ~~indicates~~is consistent with the melting level~~, which separates~~ and the transition between predominantly ice- and liquid-phase particle layers. Above the melting level, the PDF is relatively symmetric and concentrated within the interquartile range~~, resembling a near-normal distribution.~~. In contrast, below the melting level, the PDF becomes broader and skewed toward negative velocities, with a mean around −3 m s^{-1}~~-1~~ and a peak near −4 m s^{-1}~~-1~~. The ~~eyewall~~inner-core region exhibits a substantially broader distribution compared to the outer region (Fig. 3c). Below the melting level, the ~~distribution shifts with enhanced~~ frequency ~~at both~~ increases toward more negative ~~(−6 m s^{-1})~~ velocities~~.~~, including values around −6 m s^{-1}. Between 5 and 7.5 km, the PDF shifts to ~~a~~ more negative ~~region~~values. Above 7.5 km, the frequency decreases within the interquartile range and increases toward ~~higher~~less negative and more positive Doppler velocities, ~~suggesting enhanced upward motion~~indicating greater variability in the observed hydrometeor Doppler velocities. In the rainband region (Fig. 3d), the Doppler velocity distribution is systematically shifted toward more negative values relative to the outer region. The frequency increases on the negative side and decreases on the positive side across most altitudes. To summarize, the Doppler velocity distributions exhibit distinct characteristics across radial regions: a broadened distribution in the ~~eyewall~~sampled inner-core region, a negatively shifted distribution in the rainband region, and a relatively narrow distribution in the outer region.

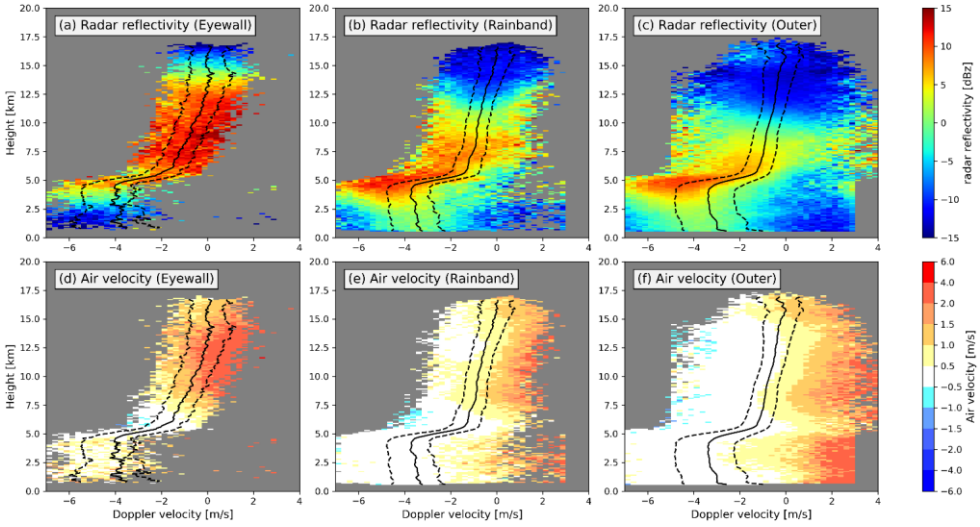


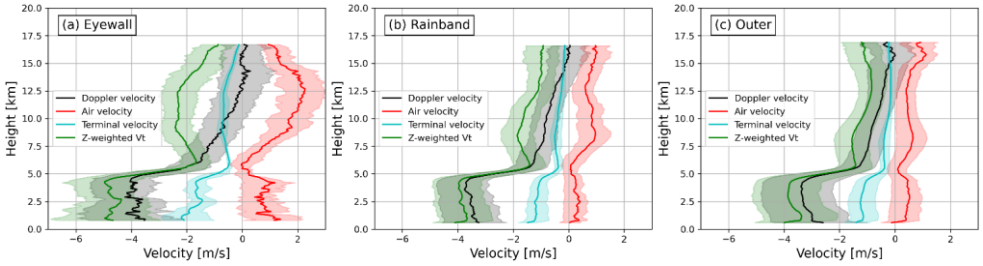
Figure 4. ~~The~~Conditional composite of radar reflectivity (a, b, and c) and air velocity (d, e, and f) on the Doppler velocity bins for (a and d) ~~eyewall~~inner-core, (b and e) rainband, and (c and f) outer regions. Solid lines represent the mean of Doppler velocity, while dashed lines indicate interquartile range. ~~We eliminate the points where sample size less than 5~~Shading is shown only for bins containing more than five samples.

We examine the conditional distributions of radar reflectivity and ~~air~~ vertical air velocity (Fig. 4~~).~~) to further understand the cloud and dynamical structures associated with different Doppler velocity ranges. In the ~~eyewall~~inner-core region, enhanced radar reflectivity is primarily observed above the freezing level, while weaker signals below are likely influenced by attenuation from overlying dense clouds (Fig. 4a). Strong reflectivity is ~~preferentially~~ associated with Doppler velocities greater than the upper quartile, indicating that ~~cloud particles tend~~enhanced reflectivity tends to ~~coincide with upward anomalies of~~occur at more positive Doppler ~~velocity. This behavior is consistent with convective updraft structures~~velocities. In the rainband region, strong reflectivity is mainly located at Doppler velocities smaller than the mean around the freezing level (Fig. 4b). Above 6 km, enhanced reflectivity ~~is generally associated with Doppler velocities below the upper quartile, suggesting that Doppler velocity in the rainband is contributed by the particle falling.~~occurs in the region where Doppler velocities are lower than the mean value. The significant signal near the freezing level indicates a radar-bright band, consistent with stratiform precipitation. In the outer region, reflectivity is generally weaker than in the rainband and is largely confined

near the freezing level (Fig. 4c). The relatively enhanced reflectivity in the rainband may reflect larger particle sizes and/or greater particle concentrations compared with the outer region.

The To further interpret the regional differences in Doppler velocity, we next examine the conditional distributions of air retrieved vertical velocity show consistent differences across regions. air velocity. Because Doppler velocity reflects the combined effects of air motion and particle fall speed, these differences cannot be attributed to either component from the Doppler velocity PDFs alone. In the eyewall inner-core region, upward motion above the freezing level within the interquartile range reaches approximately 1 – 2 m s^{-1}, and stronger updrafts (>2 m s^{-1}) occur at Doppler velocities greater than the upper quartile (Fig. 4d). These updrafts tend to coincide with regions of enhanced reflectivity., which is consistent with convective updraft structures. The more positive Doppler velocities in the sampled upper inner-core region coincide with stronger upward air motion, indicating that upward air motion is associated with the more positive side of the Doppler velocity distribution at these levels. In contrast, in the rainband, vertical motion within air velocity in the interquartile range rainband region is weaker (approximately 0.5 m s^{-1}) and shows little correspondence with regions of strong reflectivity (Fig. $^{-1}$) over most of the interquartile range (Fig. 4e). In the outer region, vertical motion is generally weak across the Doppler velocity range (Fig. 4f). Below the freezing level, weak upward motion is observed in the eyewall across a wide range of Doppler The retrieved air velocities, whereas in the rainband and outer regions, upward motion primarily occurs are broadly similar over most of the Doppler velocity range, with noticeable differences mainly at Doppler velocities greater than the upper quartile. In addition, radar reflectivity is generally stronger within the interquartile range in the rainband region. These results suggest that the systematic negative shift of the rainband Doppler velocity distribution relative to the outer region is more closely related to differences in particle fall speed. Overall, these results indicate that the eyewall is characterized by strong coupling between upward regional differences in Doppler velocity arise from different combinations of air motion and precipitation, particle fall speed. More positive Doppler velocities are associated with the stronger upward air motion in the upper inner-core region. In contrast, the negative shift in the rainband compared to the outer region is more consistent with convective structures, while the rainband and outer regions exhibit features more consistent with stratiform precipitation, including a pronounced bright band and weaker coupling between reflectivity and differences in particle fall speed rather than vertical air motion.

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(a) Eyewall
(b) Rainband
(c) Outer
Doppler velocity
Air velocity
Terminal velocity
Z-weighted Vt
Height [km]
Velocity [m/s]

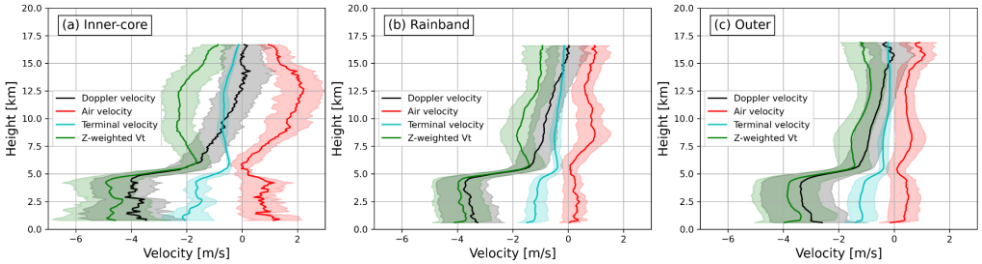


Figure 5. The means and interquartile ranges of Doppler velocity, air velocity, terminal velocity, and radar reflectivity-weighted terminal velocity (V_{tz}) in (a) ~~eyewall~~inner-core, (b) rainband, and (c) outer regions.

~~We further quantify the relative contributions of air motion and particle fall speed, which vary across three regions (Fig. 5). Doppler velocity is defined as~~ We further separate Doppler velocity into air velocity and radar reflectivity-weighted terminal velocity to examine the regional differences in more detail (Fig. 5). We also use the retrieved terminal velocity to interpret our results. The retrieved particle terminal velocity represents the estimated falling speed of particles, while the radar reflectivity-weighted terminal velocity represents the particle falling motion as reflected in the observed Doppler velocity. In the inner-core region, upward air motion above approximately 7 km is stronger and more variable than in the rainband and outer regions (Fig. 5a). The radar reflectivity-weighted terminal velocity is negative at these levels, but the stronger upward air motion partly offsets the particle falling motion, resulting in Doppler velocities closer to 0 m s^{-1}. This is consistent with the enhanced frequency of more positive Doppler velocities in the upper inner-core region shown in Fig. 3c. In the rainband region, vertical air velocity is weaker than in the inner-core region and is similar to that in the outer region in the ice-phase layer (Fig. 5b and c). In contrast, the radar reflectivity-weighted terminal velocity is slightly more negative in the rainband than in the outer region. The retrieved particle terminal velocity also shows slightly more negative values in the rainband, supporting the interpretation that particles in the rainband tend to fall faster. Because particle terminal velocity depends on particle size as well as shape, density, and other particle properties, the slightly faster terminal velocity is associated with the presence of somewhat larger and/or denser particles. This result is also consistent with the stronger radar reflectivity in the rainband shown in Fig. 4b. These features help explain the systematic shift of the rainband Doppler velocity distribution toward more negative values compared to the outer region (Fig. 3d). Below the melting level, both radar reflectivity-weighted terminal velocity and retrieved particle terminal velocity become substantially more negative in all three regions, while regional differences in vertical air velocity are relatively small. Overall, the separation of Doppler velocity shows that the more positive Doppler velocities in the upper levels in the sampled inner-core region are associated with stronger upward air motion. In contrast, the

negative shift in the rainband relative to the outer region is associated with slightly faster particle terminal velocities, while their vertical air motions remain similar.

Airborne and ground-based Doppler radar observations provide a useful context for the vertical air motions observed by EarthCARE. Black et al. (1996) found that more than 70% of vertical velocities in eyewall, rainband, and stratiform regions of seven hurricanes were within -2 to 2 m s^{-1}, while the eyewall exhibited the broadest distribution and approximately 5% of the vertical velocities exceeded 5 m s^{-1}. In our EarthCARE observations, vertical air velocities in the sampled inner-core region are mostly around 1-2 m s^{-1} above the freezing level, with stronger upward motions exceeding 2 m s^{-1} occurring on the more positive side of the Doppler velocity distribution. Thus, although the strongest updrafts reported by airborne radar are not well represented in the present EarthCARE composite, the broader distribution and stronger upward air motion in the inner-core region are qualitatively consistent with previous observations. Ground-based dual-Doppler observations of Hurricane Ike also identified localized eyewall updrafts with a mean peak upward velocity of approximately 8.3 m s^{-1} associated with mesovortices (Wingo and Knupp, 2016), further illustrating that localized eyewall updrafts can be substantially stronger than the composite values observed here.

For the rainband region, the EarthCARE composite is dominated by weaker upward motion of approximately 0.5 m s^{-1} and a pronounced bright band, indicating mainly stratiform-like characteristics in the sampled profiles. Airborne Doppler radar studies, however, have shown that localized convective updrafts can be embedded within TC rainbands (Hence and Houze, 2008; Barron et al., 2022). Barron et al. (2022) reported that the modal maximum velocity of identified rainband convective updrafts was approximately 1-2 m s^{-1}, with 2-3 m s^{-1} updrafts also frequently observed at larger normalized radii. The weaker motions in our composite therefore should not be interpreted as evidence that convective elements are absent from rainbands. Instead, these elements are intermittent and occupy only part of the rainband area, while the limited number of independent EarthCARE intercepts and the narrow nadir sampling make them difficult to isolate in the present analysis. The EarthCARE composite therefore mainly represents the more frequently sampled stratiform component of the rainband, and additional observations will be needed to better characterize the embedded convective elements. Overall, the EarthCARE results are qualitatively consistent with previous Doppler radar observations, while differences in sampling should be considered when comparing the magnitude of vertical motion.

$$V_D = V_{air} + V_{tz} + E \quad (1),$$

where V_{air} is the air velocity, V_{tz} is the radar reflectivity-weighted terminal velocity of particles, and E is the uncertainty from observation and retrieval processes. Here we show the terminal velocity, which is retrieved from V_{tz} depending on particle size, shape, orientation, and temperature. V_{tz} is not provided in the CPR product, so we use an estimate of $V_D - V_{air}$ for interpretation. In the eyewall region, terminal velocities above 6 km are slightly larger and exhibit a broader interquartile range

than in the rainband and outer regions (Fig. 5a), indicating a large variability of ice particle size. Consequently, V_{tz} is more negative, reflecting the contribution of larger and faster-falling particles. The negative V_{tz} is offset by strong upward air motion, which results in the Doppler velocity close to 0 m s^{-1}. In the rainband region, the air vertical motion is weaker than in the eyewall region (Fig. 5b) and is not large enough to offset the contribution from ice particle terminal velocity, which is slightly faster than that in the outer region. As a result, the overall PDF of Doppler velocity in ice phase shifts toward more negative values compared to the outer region (Fig. 3d). In the outer region, the terminal velocity of ice particles is slowest and has the smallest interquartile range among the three regions (Fig. 5c). The air vertical velocity is also weakest, leading to intermediate values of Doppler velocity. Below the freezing level, Doppler velocity is mainly controlled by the fall speed of liquid particles, while the contribution from air motion is limited. The air motion in the rainband region is the weakest among the three regions. Overall, in the eyewall region, strong updrafts, faster terminal velocities, and the greater variance in terminal velocity are consistent with convective characteristics. In contrast, in the rainband region, weaker air motion below the freezing level and the presence of a bright band are more consistent with stratiform characteristics.

3.3 Cloud Particle Type

We investigate the distribution of cloud particle types, retrieved from both CPR and ATLID, to further understandexamine the cloud microphysical structures in TCs. The radial-height frequency diagrams of different particle types are shown in Fig. 6. We first categorize these cloudthe retrieved particle types into 5five groups: small ice particles, snow particles, rain particles, small liquid, droplets, and mixed-phase, snow, and rain groups. The small particles. Small ice particle group (Fig. 6a) includesparticles include 3D ice, 2D plates, and mixtures of these types, while the small droplets include warm water, liquid drizzle, water and liquid drizzle, and water and rain. The mixed-phase group (Fig. 6c) includes supercooled water, mixed-phase drizzle, and mixed-phase typesparticles. At each radial-distance-height bin, particle frequency is calculated as the number of samples classified into each particle group divided by the total number of valid particle classifications in that bin. Therefore, the frequencies of the five groups sum to one in each bin. The distribution of cloud particle types exhibits a clear vertically stratified structure. Small ice particles dominate above 12 km across all regions (Fig. 6a). Between 5 and 12 km, snow particles are most prominent in the eyewallsampled inner-core region, whereas the rainband region contains a mixture of small ice particles and snow (Fig. 6b). This pattern is consistent with the difference in terminal velocities identified between the eyewall and rainband regions (Fig. 5a and 5b). In the outer region, the occurrenceThe frequency of snow particles decreases toward the outer region and is largely confined below 10 km. Mixed-phase, while the frequency of small ice particles mainly occur between 5 and 7.5 km (Fig. 6c), which may contributeincreases. This outward transition from snow to the uncertainty in retrieving both terminal velocity and air motion. Thesesmall ice particles are more frequently observedis consistent with the slightly faster retrieved particle terminal velocities in the rainband compared with the outer region (shown in Fig. 5<RMW<10).. Below the freezing level (~5 km), rain is the dominant hydrometeor type (Fig. S16c). Small liquid particles, including warm water, water and liquid drizzle, water and rain, and liquid drizzle,droplets are rare within RMW < 5 but show

~~a slight~~an increase in occurrence in the outer region (Fig. 6d). Mixed-phase particle type mainly occurs between 5 and 7.5 km and is more frequently observed in the outer region (Fig. 6e). The outward shift from snow toward small ice particles provides additional evidence of regional differences in particle properties between the rainband and outer regions.

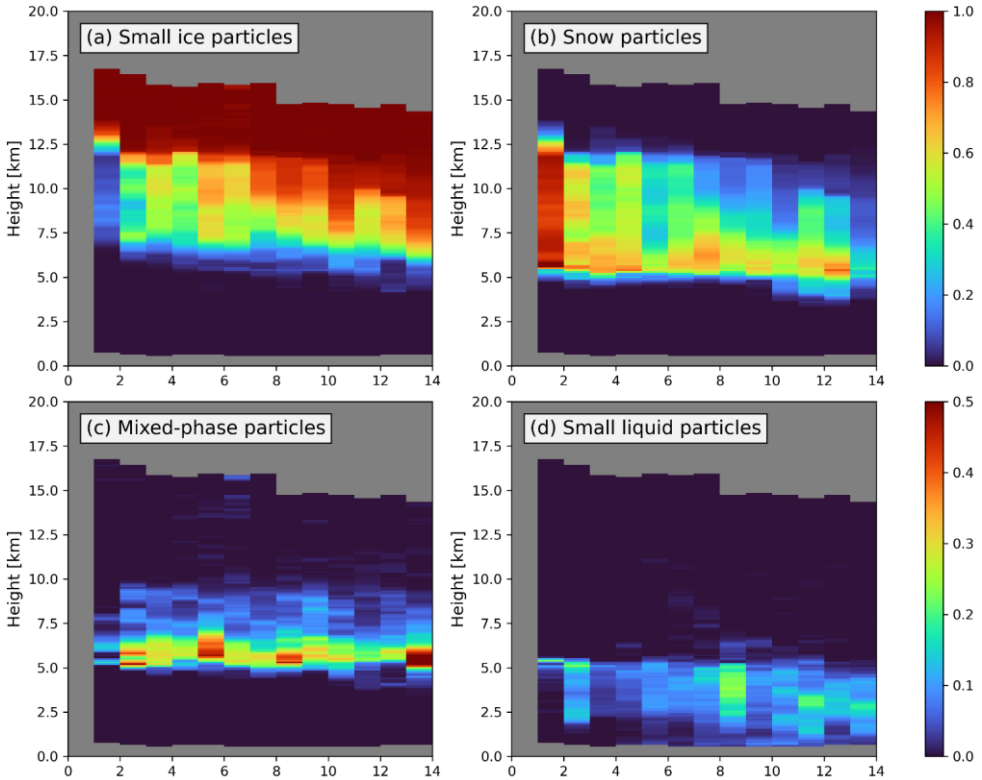


Figure 6. ~~RMW~~Radial-height frequency diagram of (a) small ice particles, (b) snow particles, (c) ~~mixed-phase, and~~rain particles, (d) small ~~liquid~~droplets, and (e) mixed-phase particles.

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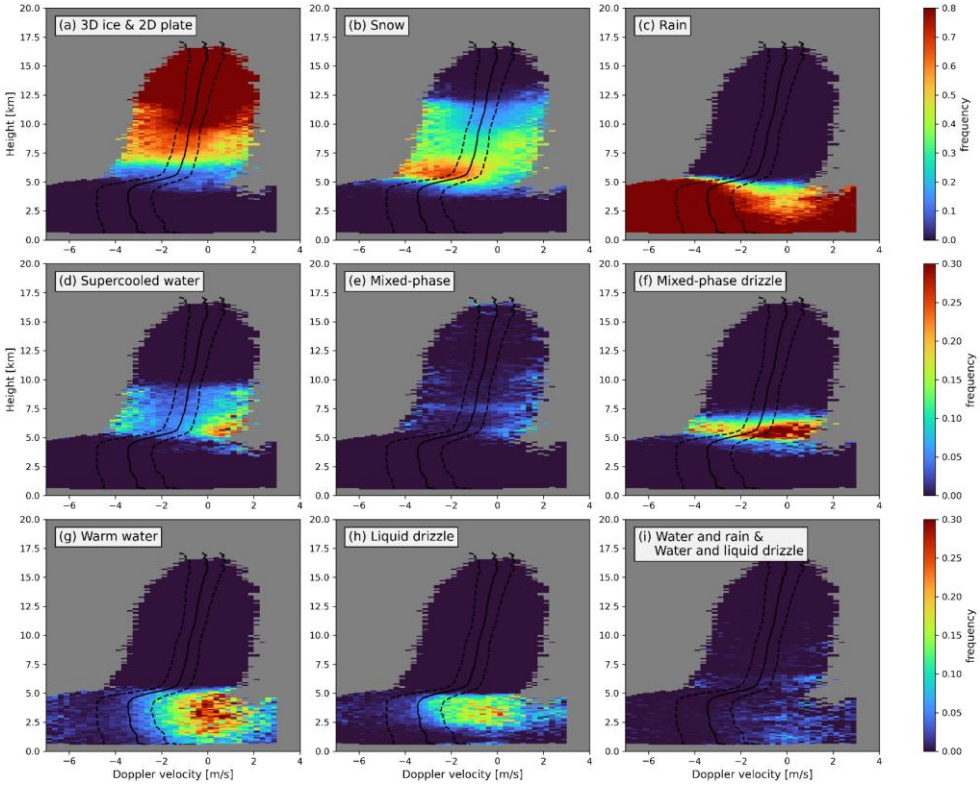


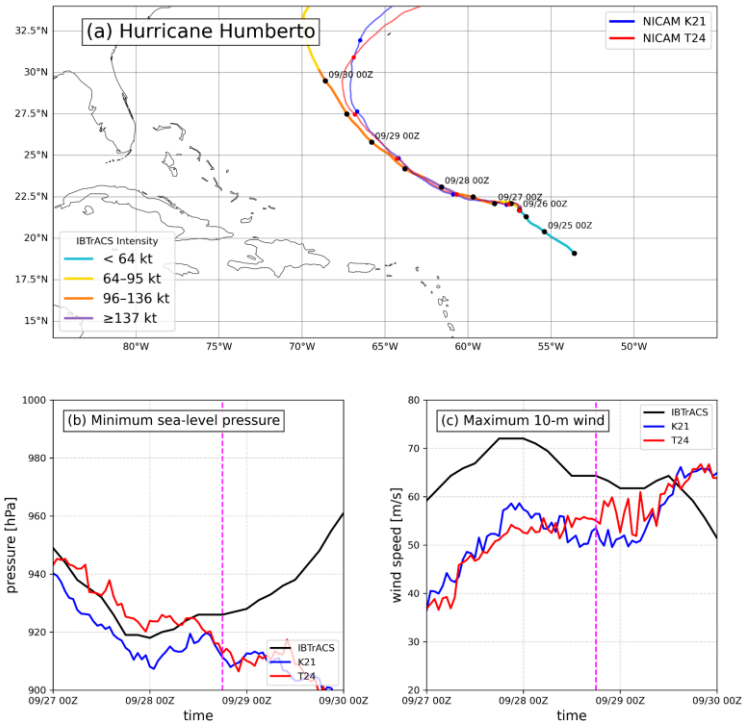
Figure 7. Frequency diagrams of (a) ~~3D~~small ice ~~& 2D plate~~particles, (b) snow particles, (c) rain particles, (d) ~~supercooled water~~small droplets, (e) mixed-phase~~, (f) mixed-phase drizzle, (g) warm water, (h) liquid drizzle, and (i) water & rain~~ particles on the ~~DPF~~PDF of Doppler velocity. Solid lines indicate the mean Doppler velocity, while dashed lines indicate the interquartile range.

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We further project the frequency diagrams onto Doppler velocity PDFs to investigate the relationship between Doppler velocity and cloud particle types. Because the sample ~~size~~sizes in the ~~eyewall region is~~inner-core and rainband regions are insufficient for ~~conditional sampling~~constructing separate frequency diagrams, all three regions are combined to construct the frequency diagrams in Doppler velocity space (Fig. ~~7). The upper panels show the dominant cloud particle types: small ice particles, snow, and rain. The combination of 3D ice and 2D plates dominates~~7). Small ice particles dominate above 7.5 km, except in regions beyond the upper quartile of Doppler velocity (Fig. 7a). In these regions, snow ~~and supercooled water~~particles are present, although with lower frequency (Fig. ~~7b~~7b). Snow particles are mainly found between approximately 5 and 12 km and ~~7d~~extend toward more negative Doppler velocities than small ice particles (Fig. 7b). Below the freezing level, rain is the dominant particle type (Fig. 7c). However, its frequency decreases in the region of Doppler velocity close to 0 m s^{-1}, where small liquid droplets become more evident (Fig. 7d). Mixed-phase particles are concentrated near and above the melting level and exhibit a distribution across a broad range of Doppler velocities (Fig. 7e). ~~warm water and liquid drizzle become more evident (Fig. 7g and 7h).~~Enhanced frequencies occur on both the more negative and less negative (or near-zero) sides of the Doppler velocity distribution. The less negative side overlaps with Doppler velocity ranges where stronger upward air motion is identified in Fig. 4, while the more negative side is consistent with faster particle falling. These results suggest that mixed-phase particles occur under two different conditions: regions with upward air motion or faster ice particle falling. The different cloud particle types occupy distinct parts of the Doppler velocity distribution, which provides the relationship between cloud particle properties, vertical air motion, and particle falling motion in TCs for evaluating cloud microphysics in models.

~~The lower panels of Fig. 7 highlight particle types that mainly occur beyond the upper quartile, corresponding to upward motion identified in Fig. 4. Mixed-phase particles are relatively rare but exhibit a distribution along the edges of the Doppler velocity PDF (Fig.~~

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~~7e). Mixed-phase drizzle frequently occurs slightly above the freezing level, but is also found in regions beyond the lower quartile (Fig. 7f). All mixed-phase particles, including supercooled water, mixed phase, and mixed-phase drizzle, indicates enhanced occurrences at both more negative and less negative (or near-zero) Doppler velocities. The more negative Doppler velocities are associated with larger hydrometeor fall speeds, likely reflecting enhanced particle growth processes such as riming. On the other hand, the less negative or near-zero Doppler velocities correspond to upward air motion. The coexistence of these two regimes suggests that mixed-phase processes are closely linked to dynamical conditions. In particular, the occurrence of supercooled water and mixed-phase particles in regions of upward motion implies that riming processes are likely enhanced within convective updrafts, where supercooled liquid water is available. The combined water and rain category occurs infrequently at lower levels (Fig. 7i). These results show that the occurrence of different particle types is systematically~~

~~linked to Doppler velocity, reinforcing that Doppler velocity provides constraints on both particle phase and vertical structure, as well as the coupling between dynamical and microphysical processes in TCs.~~

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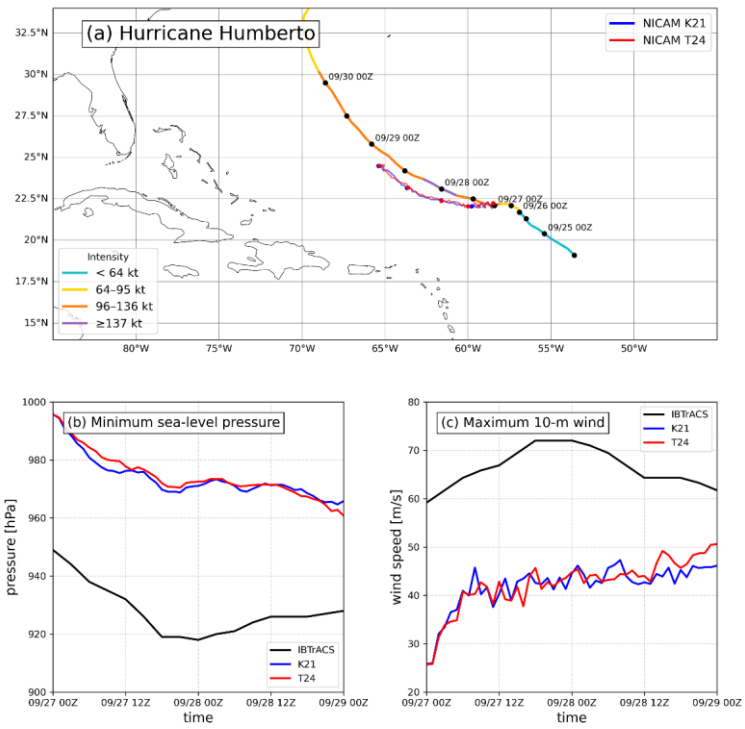


Figure 8. (a) Tracks of IBTrACS, K21, and T24. The colored segments along the IBTrACS track indicate the observed storm-intensity categories. Time evolutions of (b) minimum sea-level pressure and (c) maximum near-surface wind. The vertical dashed pink lines indicate the timing that EarthCARE intercept with hurricane Humberto.

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4 Model Evaluation

~~4.1 Simulated Hurricane~~

As a ~~representative~~ case study, we conduct NICAM hindcast simulations of Hurricane Humberto and evaluate the results using EarthCARE observations (Fig. ~~1). Figure 8 compares~~1). The simulations are initialized at 00:00 UTC on 26 September 2025 using the ECMWF IFS operational analysis, as described in Section 2.2.2. Figure 8 compares the simulated track and intensity evolution of Hurricane Humberto with IBTrACS data. Both simulations reproduce the observed track reasonably well (Fig. 8a), although a ~~slight southward~~southeastward bias is present. ~~The storm~~ However, the observed intensity evolution is ~~substantially underestimated in~~ not fully reproduced. At the time of the EarthCARE overpass, both simulations~~, with higher central pressure and~~ produce lower minimum sea-level pressures but weaker maximum ~~wind speeds~~10-m winds than IBTrACS (Fig. 8b and c). ~~The~~ The simulated storms also continue to intensify after the observed storm begins to weaken. K21 and T24 produce similar tracks and overall intensity evolutions, although the track ~~bias~~biases and intensity underestimation ~~may be partly related to limitations in the initial conditions and initialization procedure. In particular, the coarse resolution of the ERA5 reanalysis (0.25°) does not fully capture the intensity of Humberto, with the minimum sea-level pressure slightly below 1000 hPa (Fig. 8b), and spin-up effects remain a known challenge for the NICAM simulations. Despite these limitations, the two simulations~~are present. Their comparable storm states provide a useful basis for examining how the two NSW6 configurations affect the EarthCARE-observable cloud structures. Nevertheless, the comparison ~~with EarthCARE observations. The differences between K21 and T24 are relatively small, with T24 producing slightly stronger winds and lower central pressure during the final 6 hours of the simulations~~is interpreted as a case-study assessment rather than a general evaluation of NICAM performance for TCs.

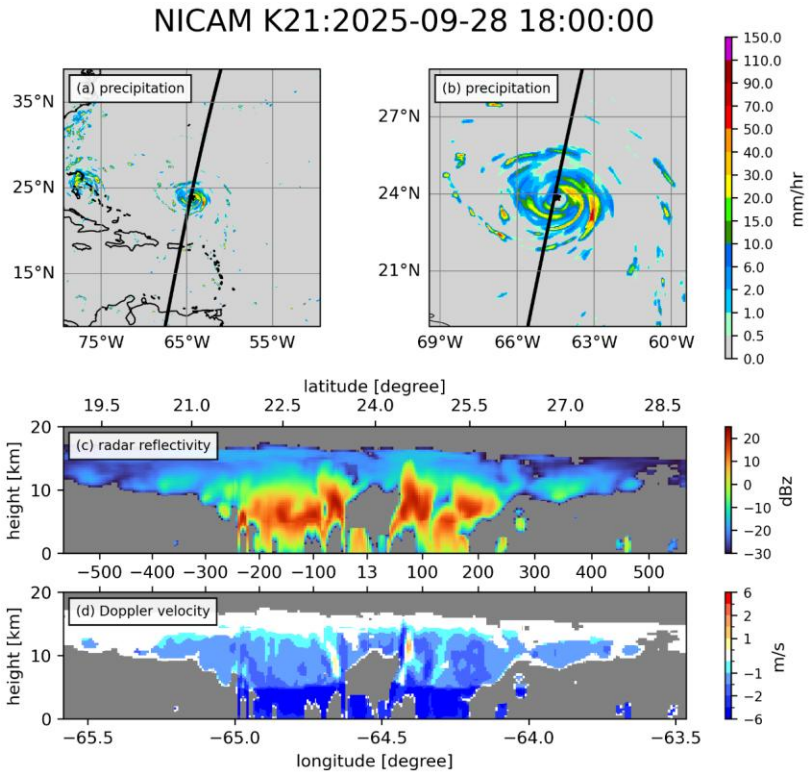


Figure 9. (a) and (b) are NICAM K21 precipitation accumulated from 18Z to 19Z for large and small domain, respectively. The black line indicates the track of EarthCARE overpass with ~~0~~1.5-degree eastward shift to intersect the simulated eyewall. (c) demonstrates the cross-section of simulated radar reflectivity in (b). (d) is the same but for simulated Doppler velocity.

Figure 9 shows the simulated radar reflectivity and Doppler velocity generated by the J-Sim along the EarthCARE overpass. To facilitate comparison, the EarthCARE overpass is shifted ~~0~~1.5° eastward to intersect the simulated eyewall (Fig. 9a). Here, we present results from K21, while those from T24 are provided in the ~~supporting information.~~supplement (Fig. S6). The simulated precipitation pattern is sparser than that in the IMERG observations, and the rainfall intensity in the eyewall region is weaker in K21 (Fig. 9b and 1b). Despite this, the simulated radar reflectivity captures the overall storm structure, including deep convective and stratiform regions extending into the upper troposphere (Fig. 9c). Compared to observations, the simulated

reflectivity is generally stronger but vertically confined below 10 km (Fig. 9c and 1c). Below the freezing level, radar reflectivity is substantially attenuated in both observations and simulations. The simulated Doppler velocity shows more negative values above the freezing level compared to observations (Fig. 9d and 1d). NICAM reproduces the overall TC structure, but ~~notable~~ discrepancies remain in both the intensity and vertical structure ~~when~~ compared with EarthCARE observations.

We compare the ~~joint~~ PDFs of radar reflectivity, Doppler velocity, and air velocity between EarthCARE observations and NICAM simulations (Fig. 10). ~~Here, we~~To reduce differences in sampling geometry, only ~~use~~NICAM data along the EarthCARE-like transect are used in the main comparison. In addition, the EarthCARE profiles are averaged using a 3.5-km moving window along the satellite track to approximate the horizontal resolution of NICAM before constructing the PDFs. Both the EarthCARE and NICAM PDFs are constructed using only the cross-~~section of data to perform statistics to fairly compare with EarthCARE, and the result~~sectional data for Hurricane Humberto at the time of the EarthCARE overpass. At each height, the PDF is normalized independently using the valid samples at that level. The results using all ~~data in NICAM can be found in the supplement~~NICAM samples within 300 km of the Humberto center are provided in the Supplement (Fig. ~~S2~~S7 and ~~S3~~S8). The observed distributions exhibit a broad spread across all variables, reflecting substantial variability in both dynamical and cloud microphysical processes. In contrast, the simulated PDFs are much more confined. We focus on the structure above the freezing level because the signal is significantly attenuated below this level.

Figure 10a shows that the EarthCARE PDF has a peak occurrence between 10 and 15 ~~dBz~~dBZ and develops a double-peaked structure with increasing height. One peak remains near 10 ~~dBz~~dBZ and sharply shifts toward lower reflectivity at 12.5 km, while the other one tilts from about 5 dBz at 7 km to −10 ~~dBz~~dBZ at 12.5 km. In both K21 and T24, the PDF peaks occur between 15 and 20 dBz at around 6 km, indicating an overestimation of radar reflectivity (Fig. 10b and 10c). The overestimation of radar reflectivity in T24 is more pronounced compared to K21. Moreover, the simulated reflectivity does not reproduce the double-peaked structure observed by EarthCARE. ~~With sufficient sampling, T24 tends to reproduce a double-peaked structure; however,~~When all NICAM samples within 300 km of the ~~separation between the two peaks is less distinct in the PDF~~Humberto center are used, both K21 and T24 still exhibit single-peak distributions (Fig. ~~S2~~S7). With increasing height, the peak in K21 shifts rapidly from ~15 ~~dBz~~dBZ at 6 km to ~~−15 dBz~~10 dBZ at 12 km. The peak in T24 remains near 15 ~~dBz~~dBZ up to 8 km and decreases more gradually, reaching −10 ~~dBz~~dBZ at around 14 km. However, T24 exhibits a narrower PDF between 8 and ~~12.5~~15 km compared to K21. These results suggest that the smaller terminal velocity coefficients in T24, which reduce particle fall speeds, ~~can improve the PDF structure with~~ contribute to a more gradual vertical transition~~, even though its PDF becomes~~ in radar reflectivity above approximately 8 km. Meanwhile, the narrower ~~than K21~~PDF in T24 may be partly related to the enhanced lateral mixing associated with the Leonard term, which tends to reduce horizontal variability.

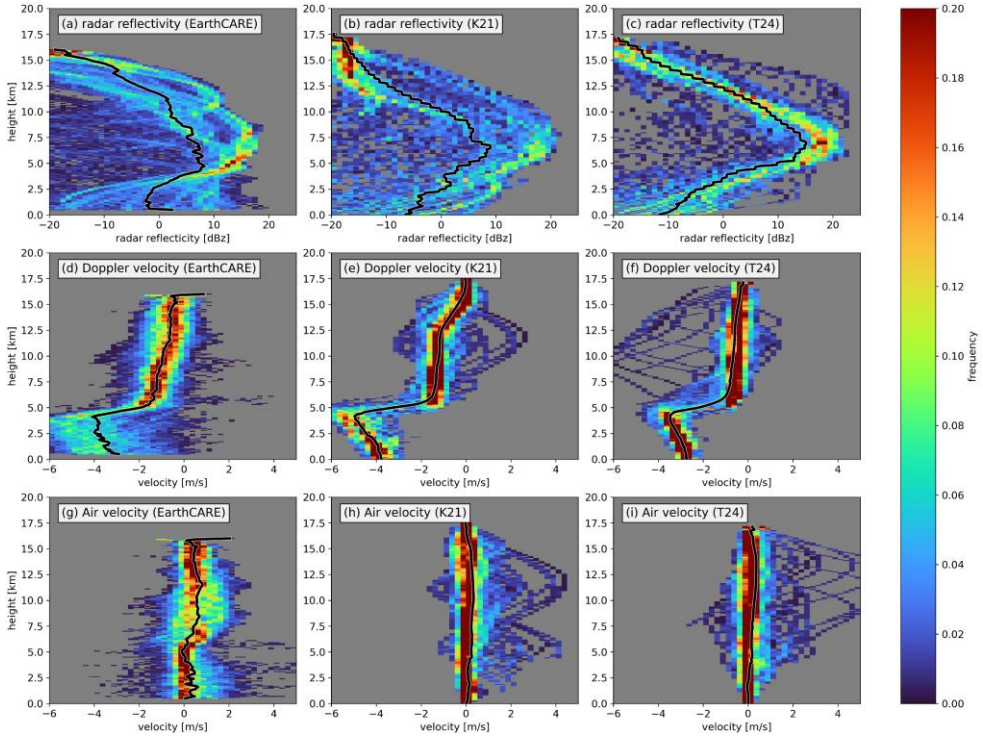


Figure 10. Radar reflectivity PDF of (a) EarthCARE, (b) K21, and (c) T24. Doppler velocity PDF of (d) EarthCARE, (e) K21, and (f) T24. Air velocity PDF of (g) EarthCARE, (h) K21, and (i) T24. The black lines are the mean of each variable.

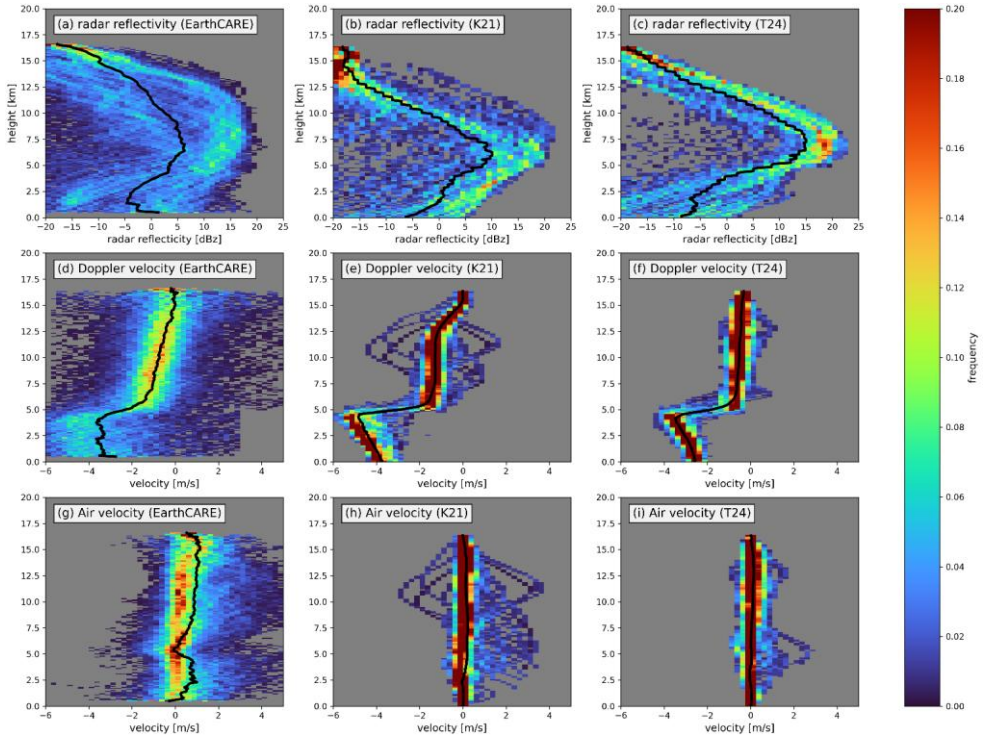
The PDF of Doppler velocity observed by EarthCARE shifts from about −1.5 m s^{-1} at 5 km to −0.5 m s^{-1} at 15 km (Fig. 10d). In K21, the peak of the PDF is well captured near −1.5 m s^{-1} at 5 km, but the peak remains near −1.5 m s^{-1} from 5 to 12.5 km and then rapidly shifts toward −0.5 m s^{-1} (Fig. 10e). ~~The result suggests an overestimation of~~ This behavior is consistent with overly large ice particle terminal velocities above the freezing level. In contrast, the peak in T24 remains around −0.5 m s^{-1} throughout most of the vertical range in ice phase (Fig. 10f). T24 shows closer agreement with EarthCARE in the upper levels, although its Doppler velocity is less negative than observed near the freezing level. These differences indicate that changes in the terminal velocity coefficients substantially affect the vertical structure of Doppler velocity.

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On the other hand, the PDFs of air velocity in both K21 and T24 are much narrower than those observed by EarthCARE (Fig. 10g–i). This suggests that the simulations underestimate the variability of vertical air motion. We note that part of the broader spread in the observed Doppler velocity may arise from observational uncertainties, such as beamwidth-related variability and multiple scattering. In addition, the retrieval of air motion is more uncertain in mixed-phase regions and under strong attenuation. These factors may contribute to the wider observed distributions. ~~However, such uncertainties are unlikely to fully account for~~Nevertheless, the ~~marked reduction in variability in~~simulated PDFs remain narrower after the ~~simulations.~~EarthCARE observations are averaged to the NICAM resolution even though all NICAM samples are used to construct PDFs (Fig. S7). These results suggest that the simulations produce ~~overly constrained structures~~more confined distributions of radar reflectivity ~~and,~~ Doppler velocity, ~~which~~and air velocity. The underestimation of variabilities may be related to both limited resolution and the parameterized representation of cloud microphysical processes. ~~We further note that the simulations do not exhibit double peaks in~~The EarthCARE air velocity ~~with~~distribution also shows a local minimum near the melting level~~, a characteristic of the EarthCARE air velocity retrieval data~~ that is not reproduced by the simulations (Figs. 5~~,~~ and 10g~~). This is why we infer that the~~ i). Because air-velocity retrieval ~~may~~is more uncertain under mixed-phase conditions, this particular difference should be ~~subject~~interpreted cautiously and should not be attributed solely to ~~uncertainties near the melting level~~model bias.

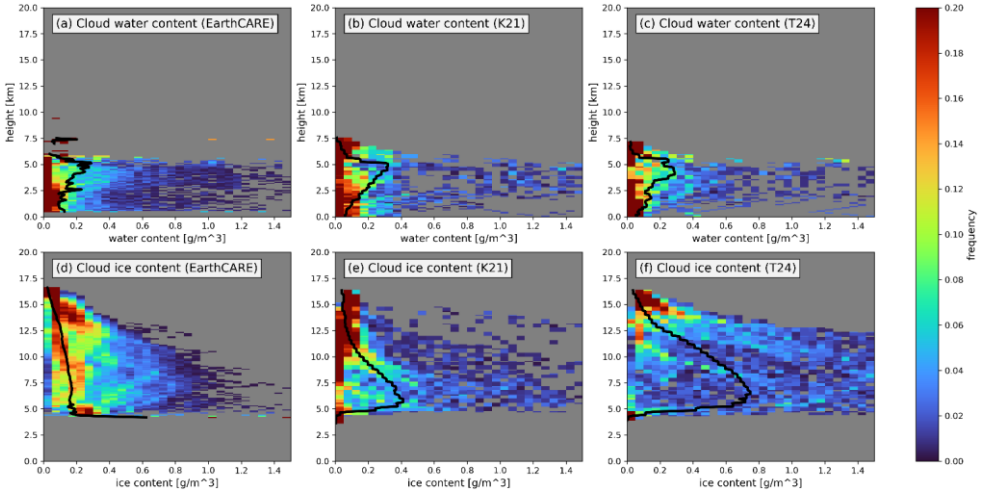
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~~Figure 10. Radar reflectivity PDF of (a) EarthCARE, (b) K21, and (c) T24. Doppler velocity PDF of (d) EarthCARE, (e) K21, and (f) T24. Air velocity PDF of (g) EarthCARE, (h) K21, and (i) T24. The black lines are the mean of each variable.~~



We further evaluate the distributions of cloud water and ice content in NICAM simulations. The same cross-sectional sampling and horizontal averaging used in Fig. 10 are applied. Cloudy grid points with at least 0.001 g m^{-3} of liquid or ice water content are sampled to construct the PDFs (Fig. 11). The liquid water content retrieved from EarthCARE is generally smaller than 0.1 g m^{-3}, with a long tail extending ~~toward~~beyond 1 g m^{-3} (Fig. 11a). Both K21 and T24 capture this general pattern, although the frequency of the long tail is lower than in the observations (Fig. 11b and 11c). The mean profiles in K21 and T24 follow the observed structure reasonably well below 6 km. Above this level, liquid clouds are rarely observed, whereas non-negligible liquid water content persists in both simulations. This may suggest that NICAM tends to produce excessive supercooled liquid water. However, due to uncertainties in retrievals within mixed-phase regions, it is difficult to determine whether this represents a model bias.

Above the freezing level, the PDF of cloud ice content from EarthCARE at 5 km exhibits a skewed distribution with a long tail ~~toward~~extending beyond 1 g m^{-3}. With increasing height, the PDFs become more concentrated around ~0.1 g m^{-3} (Fig. 11d). In K21, the PDF peaks near 0.05 g m^{-3}, and the skewed structure is mainly confined between 5 and 10 km (Fig. 11e), which is narrower compared to the observation. In contrast, T24 exhibits a much broader PDF without a distinct peak, with ice content spanning from ~0.05 g m^{-3} to ~~beyond~~at least 1.5 g m^{-3} (Fig. 11f). Both K21 and T24 overestimate the mean ice content relative to EarthCARE~~.~~, with a larger overestimation in T24 between approximately 5 and 12 km. These results ~~indicate~~suggest that ~~reduced~~the modified terminal velocity ~~coefficients~~settings in T24 ~~enhance~~may contribute to the ~~variability~~broader distribution of cloud ice content, although ~~the~~its mean values remain overestimated. The comparison suggests that hydrometeor fall speed strongly influences the variability and the vertical distribution of cloud ice, which in turn affects the simulated reflectivity and Doppler velocity. ~~The observational constraints offer guidance for improving the representation of cloud microphysical processes in models.~~



Overall, this preliminary case study shows that T24 agrees better with EarthCARE in several upper-level features. T24 shows a more gradual vertical transition in radar reflectivity. It also does not show the rapid upper-level shift in Doppler velocity found in K21. In addition, T24 produces greater variability in cloud ice content between 5 and 12 km. Based on these results, we recommend T24 as the baseline configuration for future NICAM simulations of TCs, although T24 still overestimates radar reflectivity near the freezing level and cloud ice content.

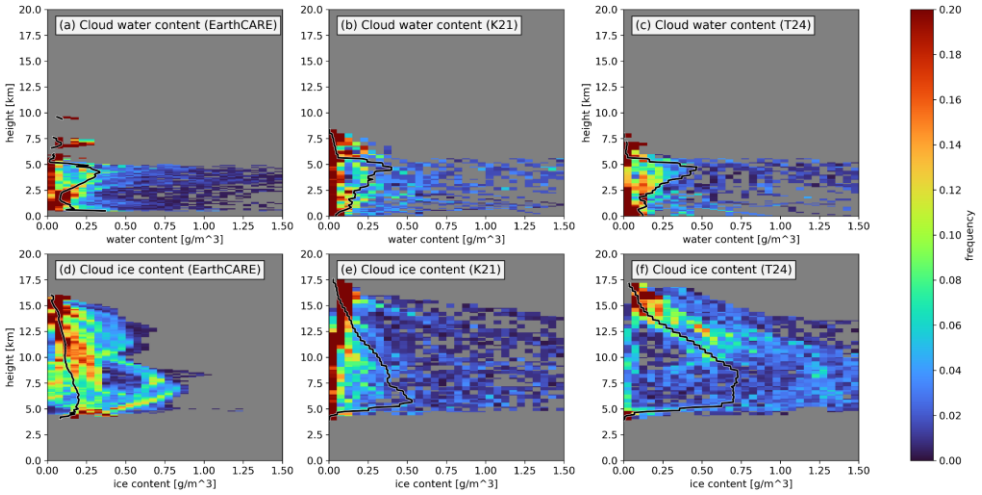


Figure 11. Cloud water content PDF of (a) EarthCARE, (b) K21, and (c) T24. Cloud ice content PDF of (d) EarthCARE, (e) K21, and (f) T24. The black lines are the mean of each variable.

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45 Summary

This study uses ~~unprecedented~~ EarthCARE observations to investigate the dynamical and cloud microphysical structures of TCs. By ~~co-locating~~collocating EarthCARE overpasses with TC tracks, we ~~construct statistics of the radial-height structures of~~ identify 101 intercept events from 28 TCs, including 1,853 valid profiles within 15 RMW. Although the inner-core composite is based on only two independent intercept cases, both cases show similar vertical structures in Doppler and air velocities. These observations are used to construct radial-height statistics of radar reflectivity, Doppler velocity, air vertical motion, and cloud particle types. ~~This provides a unique opportunity to examine the coupling between dynamics and cloud microphysics in TCs, which would not be possible without Doppler velocity observations from space. The observational results reveal a transition in TC structure from convective in the eyewall region to stratiform in the rainband region. The eyewall is characterized by strong updrafts,~~ The inner-core region exhibits enhanced reflectivity, stronger and ~~broader variability in Doppler velocity. In contrast, the rainband region exhibits weaker vertical motion, a significant bright band signal near the melting level, and Doppler velocity distributions~~ more ~~strongly influenced by~~variable upward air motion, and a broader Doppler velocity distribution. In the rainband region, the Doppler velocity distribution shifts toward more negative values,

accompanied by slightly more negative particle terminal ~~velocity.~~velocities and a pronounced bright band near the melting level. The outer region generally ~~shows~~exhibits weaker ~~signals than the rainband region. These results indicate that~~reflectivity and narrower Doppler velocity ~~provides an effective constraint on the relative contributions of~~and air motion ~~and hydrometeor fall speed, linking dynamical and cloud microphysical processes across different TC regions. The distributions of~~distributions. These regional differences demonstrate how EarthCARE observations can help distinguish the influences of air motion and particle sedimentation on the regional variations in Doppler velocity PDFs.

The retrieved cloud particle types ~~further support the transition between the eyewall and rainband regions, consistent with the observed transition from a convective to a stratiform regime.~~ provide additional information for interpreting the Doppler velocity distributions. Small ice particles dominate the upper troposphere, whereas snow particles occur mainly between approximately 5 and 12 km and extend toward more negative Doppler velocities. Below the freezing level, rain dominates at more negative Doppler velocities, while small liquid droplets become more evident near zero Doppler velocity. Mixed-phase particles occur mainly near and above the melting level and span a broad range of Doppler velocities. Their distribution overlaps with both less negative Doppler velocities associated with stronger upward air motion and more negative velocities associated with faster particle falling. However, mixed-phase retrievals remain uncertain when multiple hydrometeor populations coexist.

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~~The analysis of cloud particle types in TCs provides a new perspective on cloud microphysical structure and its relationship with Doppler velocity, although uncertainties remain in the retrieval. In particular, our results suggest that mixed-phase particles occur more frequently than previously reported, even above 6 km where temperatures are below −5°C, which contrasts with earlier studies (e.g., Black et al., 1999). The increased occurrence of mixed-phase particles implies that supercooled water may be more prevalent in TCs than inferred from earlier aircraft observations (e.g., Willoughby et al., 1985). EarthCARE offers a unique opportunity to better understand the amount of supercooled water in TCs and associated structure of air motions. Further comparisons with ground-based radar observations will help to reduce uncertainties and improve the robustness of these findings.~~

~~The~~As a preliminary single-case evaluation, NICAM hindcast simulations of Hurricane Humberto reproduce ~~TC tracks~~the storm track and overall ~~TC~~cloud structure~~,~~ but underestimate the TC intensity. The simulated distributions of radar reflectivity, Doppler velocity, and air vertical motion are generally more confined than those observed by EarthCARE, ~~suggesting limited variability in both dynamical and cloud microphysical fields. Differences between~~ indicating that the simulations ~~with two different terminal velocity settings in the cloud microphysics scheme further highlight the role of hydrometeor fall speed in shaping the~~ underestimate the observed variability. The two microphysical configurations produce different vertical ~~structure of~~structures of radar reflectivity, Doppler velocity, and cloud ice content, demonstrating their sensitivity to the assumed hydrometeor fall speeds. T24 agrees better with EarthCARE in upper-level features, including a more gradual vertical

transition in radar reflectivity and Doppler velocity. These results suggest that cloud microphysical assumptions, particularly those related to particle fall speeds, strongly control the simulated structure and variability of clouds in TCs. The improvements in track and intensity remain limited in this case, and the simulated results may depend on the large-scale environment, the internal TC structure and the spin-up processes. We will investigate additional TC cases with various lead times to enable a more robust statistical comparisongreater variability in cloud ice content. Nevertheless, it overestimates reflectivity near the freezing level and cloud ice content. Because the comparison is based on a single TC case and the simulated storm intensity is underestimated, these results should not be interpreted as a general evaluation of NICAM performance.

In conclusion, this study presents a newan observational perspective on contrastingregional differences in TC dynamics and cloud microphysical structures in TCs using EarthCARE observations. The hindcast simulation results for Humberto and their comparison with EarthCARE observations highlight the importance of representing both the variability and the vertical structure of cloud and precipitation processes in models. The observationalprovides complementary constraints offer valuable guidance for improvingfor model development. Radar reflectivity is sensitive to particle size distributions, while cloud water and ice contents provide information on condensate mass. Comparing Doppler velocity with retrieved air velocity can further help evaluate particle sedimentation and terminal-velocity settings. Although these retrieved quantities are not fully independent because they share radar inputs and retrieval assumptions, their combined evaluation can help identify microphysical settings that improve the representation of cloud microphysical processesboth particle distributions and sedimentation. This study compares two commonly used configurations within the single-moment NSW6 scheme to isolate the sensitivity to their couplingdifferent falling speed assumptions. Future studies will examine the terminal velocities of individual hydrometeor species, compare NSW6 with dynamics in a global km-scale storm-resolving model.the double-moment NDW6 scheme (Seiki and Nakajima, 2014), and evaluate the sensitivity of simulated vertical motions to model resolution.

Code and data availability

The EarthCARE data used in this study are available from the JAXA G-Portal (https://gportal.jaxa.jp/gpr/index/index), including CPR (https://doi.org/10.57746/EO.01jdvd2gqq34e6yz9p8kfe68x5) and CPR-ATLID synergistic (https://doi.org/10.57746/EO.01jkwjeg2y0bqndnsvjvaaskaw) Level-2 products. IMERG dataset can be found in https://gpm.nasa.gov/data/imerg, and 3-year IBTrACS is downloadedavailable from https://doi.org/10.25921/82ty-9e16. J-Sim used to generate satellite-like signals from NICAM outputs is available from JAXA (https://www.eorc.jaxa.jp/theme/Joint-Simulator/userform/js_userform.html). The processed dataset supporting the findings

of this study is publicly available at figshare repository (~~https://doi.org/10.6084/m9.figshare.32142271).~~https://doi.org/10.6084/m9.figshare.32142271.v2).

Supplement link

Team list

Author contributions

J.-D. H.: Conceptualization, Methodology, Formal analysis, Data curation, Investigation, Writing – original draft.
W. R.: Conceptualization, Methodology, Formal analysis, Writing – review & editing.
T. M.: Conceptualization, Supervision, Writing – review & editing.
M. S.: Conceptualization, Supervision, Funding acquisition, Writing – review & editing.
~~T. M.: Conceptualization, Supervision, Writing – review & editing.~~

Competing interests

The authors declare that they have no conflict of interest.

Disclaimer

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Review statement

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