

## RESEARCH ARTICLE

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## Key Points:

- Climatology of the vertical profiles of polarimetric radar variables and microphysical parameters is documented for different storm types
- Areas of high ice water content (IWC) in clouds are characterized by high values of specific differential phase combined with low reflectivity
- Tropical clouds have smaller size ice in higher concentration compared to their continental counterparts with comparable IWC

## Supporting Information:

Supporting Information may be found in the online version of this article.

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# Climatology of the Vertical Profiles of Polarimetric Radar Variables and Retrieved Microphysical Parameters in Continental/Tropical MCSs and Landfalling Hurricanes

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**Abstract** Most existing cloud models tend to overestimate the size of cloud ice particles and underestimate their concentration. This emphasizes the need to provide a reliable observational reference to optimize cloud model performance, particularly in areas of high concentration of ice at high altitudes. The dual-polarization radars give the community a unique opportunity to quantify cloud ice with a good accuracy using polarimetric radar retrievals. In this study, we utilize the network of operational WSR-88D radars to build a climatology of the vertical profiles of radar variables, such as radar reflectivity  $Z$ , differential reflectivity  $Z_{DR}$ , and specific differential phase  $K_{DP}$  as well as the radar-retrieved vertical profiles of ice water content (IWC) above the melting layer and liquid water content below it, mean volume diameter  $D_m$ , and total number concentration  $N_t$  of ice and liquid particles. Such climatology was created for continental/marine mesoscale convective systems (MCSs) and tropical cyclones including hurricanes. The dataset includes 13 continental MCSs, 10 marine MCSs, and 11 tropical cyclones. Separate statistics of the “background” vertical profiles and the ones associated with high IWC aloft have been obtained in the course of this study. It is shown that continental MCSs exhibit larger size of ice in lower concentration aloft compared to the marine MCSs and especially tropical cyclones/hurricanes. A combination of high  $K_{DP}$  and low  $Z$  aloft signifies lower  $D_m$ , higher  $N_t$ , and often substantial IWC.

## 1. Introduction

Modern operational radar networks around the world are equipped with Doppler polarimetric radars which demonstrate their efficiency in improving data quality, quantitative precipitation estimation, hydrometeor classification, and severe weather warnings (Bringi & Chandrasekar, 2001; Kumjian, 2018; Ryzhkov & Zrnicek, 2019; Zhang, 2016). In addition to the radar reflectivity  $Z$ , polarimetric radars directly measure differential reflectivity  $Z_{DR}$  which is a difference between the reflectivities at orthogonal polarizations, differential phase  $\Phi_{DP}$  which is the difference between the phases of reflected signals at orthogonal polarizations, and cross-correlation coefficient  $\rho_{HV}$  between orthogonally polarized radar returns. A very important polarimetric variable, specific differential phase  $K_{DP}$ , is estimated from a radial profile of  $\Phi_{DP}$  as a half of the radial derivative of  $\Phi_{DP}$ . Polarimetric radar measurements can be efficiently utilized for retrievals of key microphysical variables, such as precipitation fluxes, liquid water content (LWC) or ice water content (IWC), particle characteristic sizes, and their number concentrations.

Polarimetric weather radars also offer a unique opportunity to optimize numerical weather prediction (NWP) models (Ryzhkov et al., 2020). The inability of existing microphysical parameterization schemes in the NWP models to adequately capture the complexity of various microphysical processes is commonly blamed as a main source of forecast uncertainties (e.g., Fan et al., 2017; Morrison et al., 2015, 2020). Because the polarimetric radars are capable of distinguishing between hydrometeors with different microphysical properties and identifying “polarimetric fingerprints” of various microphysical processes, they are a powerful resource for optimization of cloud models (e.g., Kennedy & Rutledge, 2011; Kumjian et al., 2013, 2014; Kumjian & Ryzhkov, 2009, 2010, 2012; Ryzhkov et al., 2013).

Reliable radar microphysical retrievals provide important references for the optimization of microphysical parameterizations in NWP models because these retrievals yield estimates of LWC/IWC, mean volume diameter  $D_m$ , and total number concentration  $N_t$  of hydrometeors over large regions of a storm. It is known that existing NWP models tend to ubiquitously overestimate the size of ice and underestimate its number concentration, particularly

in the areas of high-altitude ice in significant concentration with high IWC (HIWC; e.g., Fridlind et al., 2015; Huang et al., 2021; Stanford et al., 2017). One of the possible reasons for such persistent model biases is that the secondary ice production (SIP) may not be appropriately accounted for in the models (Korolev & Leisner, 2020).

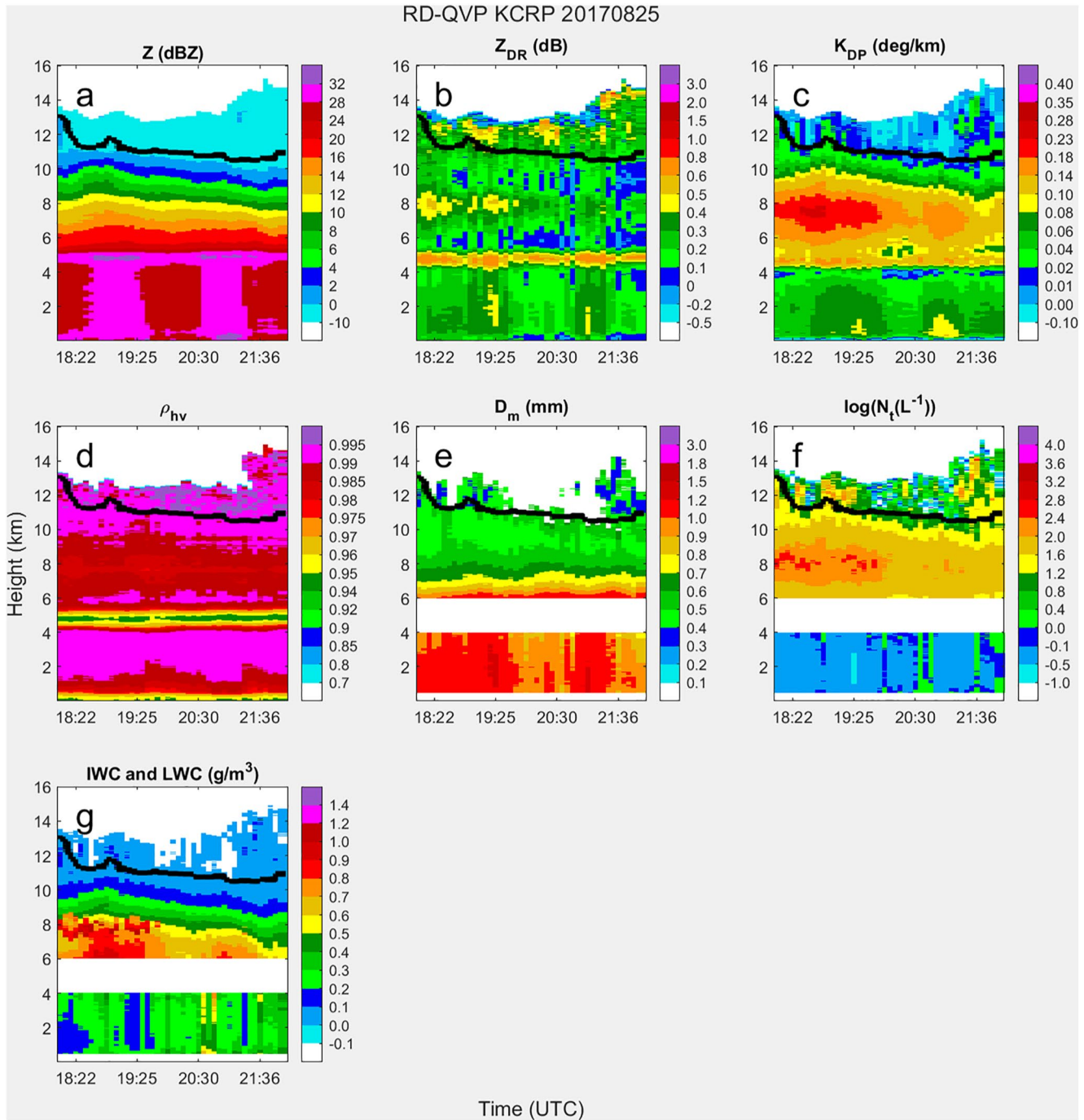
Significant differences were documented between microphysical characteristics of maritime tropical and midlatitude continental storms. These are rooted in the differences in vertical profiles of humidity, cloud condensation nuclei (CCN) concentrations, strengths of updrafts, and possibly SIP mechanisms among other factors. A bulk of tropical rain forms primarily via a warm rain process with ice playing a relatively minor role in its production compared to the midlatitude storms where a good portion of rain is generated from melting graupel. In stronger convective updrafts typical for continental storms, most of a secondary ice is likely produced via collision-induced breakup whereas freezing drop shattering may be a dominant SIP mechanism in tropical maritime updrafts (Khain & Pinsky, 2018). It is hard to quantify ice within the convective updrafts even with polarimetric radars but it is much easier to estimate multiple ice attributes after it is advected into the stratiform part of the storm where graupel/hail is not common and where the suggested polarimetric retrievals are quite accurate. Because tropical and continental ice and rain are formed via different microphysical processes, it would be instrumental to statistically compare vertical profiles of their radar and microphysical characteristics using a unified approach based on the observations with a multitude of operational WSR-88D weather radars. This is one of the main objectives of this study.

Polarimetric radar retrievals in pure rain are pretty well established. For the rain rate estimation, a novel method based on specific attenuation  $A$  and specific differential phase  $K_{DP}$  introduced by Ryzhkov et al. (2013) proved to be quite efficient at  $S$  band as its validation using the United States National Weather Service WSR-88D radars demonstrated (Zhang et al., 2020). LWC can be effectively estimated using both the radar reflectivity  $Z$  and differential reflectivity  $Z_{DR}$  (see Ryzhkov & Zrnica, 2019; Zhang, 2016). The mean volume diameter of raindrops  $D_m$  is traditionally estimated from  $Z_{DR}$  (e.g., Brandes et al., 2004; Bringi et al., 2009; Cao et al., 2008; Zhang et al., 2001). The overviews of the polarimetric retrievals in rain can be found in Zhang (2016) and Ryzhkov and Zrnica (2019).

Radar retrievals in ice are much more difficult than in rain due to tremendous diversity of ice habits. Until recently, radar reflectivity  $Z$  was the only radar parameter used for estimating snowfall rate  $S$ , IWC, and size of the ice particles (Hogan et al., 2006; Kalina et al., 2017; Matrosov & Heymsfield, 2017; Protat et al., 2016; Tian et al., 2016). Because radar reflectivity is heavily weighted by a few largest snowflakes in the particle size spectrum, the  $Z$ -based retrievals are notoriously inaccurate for ice. It is known that the existing IWC( $Z$ ) relations generally tend to significantly underestimate IWC in areas of very high concentrations of small ice crystals at high altitudes. The underestimation of IWC presents potential icing hazard to aircrafts. Such ice with significant IWC is routinely reported in tropical cyclones, thunderstorm anvils, and stratiform parts of mesoscale convective systems (MCS) by in situ microphysical measurements onboard research aircrafts (Heymsfield et al., 2009; Leroy et al., 2017; McFarquhar & Heymsfield 1996; Rosenfeld & Woodley, 2000; Strapp et al., 2016).

First attempts to improve the radar estimates of IWC using polarimetric measurements were made in the studies of Vivekanandan et al. (1994) and Ryzhkov et al. (1998) followed by recent publications by Ryzhkov et al. (2018), Ryzhkov and Zrnica (2019), and Bukovcic et al. (2018, 2020) where some alternative polarimetric relations for determination of IWC were introduced. In addition, the polarimetric retrieval relations for the mean volume diameter of ice particles  $D_m$  and their total number concentration  $N_t$  have been suggested in Ryzhkov et al. (2018) and Ryzhkov and Zrnica (2019).

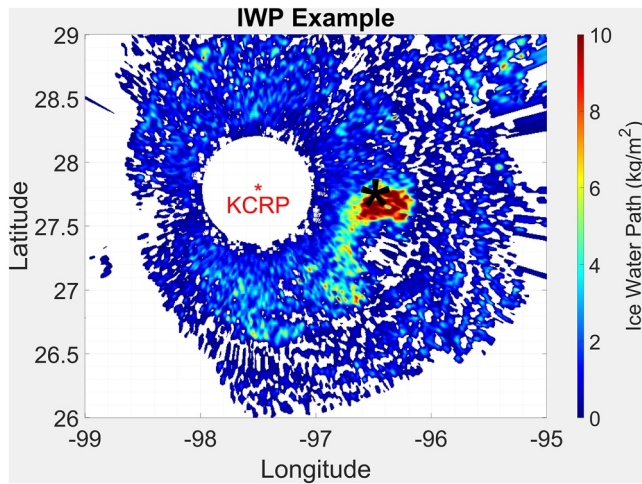
Polarimetric relations for ice contain specific differential phase  $K_{DP}$ . If the density-size inverse dependence of ice/snow particles is assumed, then  $K_{DP}$  is approximately proportional to the first moment of the particle size distribution (PSD) which is much closer to IWC (which is a second moment of PSD) than radar reflectivity  $Z$  which is proportional to the fourth moment of PSD of ice/snow. A bulk of snow mass is contained at the lower end of its size spectrum whereas  $Z$  is primarily sensitive to its upper end containing a few largest snowflakes. Because  $Z$  is determined by the fourth moment of PSD and  $K_{DP}$  by its first moment, their ratio is proportional to the cube of the mean volume diameter  $D_m$  and is independent of the total number concentration  $N_t$ . Therefore,  $D_m$  can be estimated from the cubic root of the  $Z/K_{DP}$  ratio. If the reflectivity difference  $Z_{dp} = Z_h - Z_v = Z_h (1 - Z_{dr}^{-1})$  is utilized instead of  $Z$  in the ratio with  $K_{DP}$  then the corresponding estimates become insensitive to the variability of



**Figure 1.** RD-QVP time series between 1800 UTC and 2200 UTC 25 August 2017 near Corpus Christi, Texas (KCRP), WSR-88D radar. (a)  $Z$ , (b)  $Z_{DR}$ , (c)  $K_{DP}$ , (d)  $\rho_{hv}$ , (e)  $D_m$ , (f)  $N_t$ , and (g) IWC/LWC. Black line represents the 10 dB SNR contour and pixels above this line are not used for CFAD calculations.

the particle shapes and orientations. Once  $D_m$  is calculated, the total number concentration  $N_t$  can be determined from the combination of  $Z$  and  $D_m$ .

The quality of the polarimetric retrievals of IWC has been evaluated using in situ microphysical measurements onboard research aircrafts (Kedzuef et al., 2021; Murphy et al., 2020; Nguyen et al., 2019; Ryzhkov et al., 1998) and at the surface (Bukovic et al., 2018, 2020), whereas the corresponding retrievals of  $D_m$  and  $N_t$  have been validated by Murphy et al. (2020) and Kedzuef et al. (2021). These initial verification tests showed good promise,



**Figure 2.** An example of ice water path (IWP) near Copper Christi, TX during the landfall of Hurricane Harvey on 25 August 2017 at 1812 UTC. Black asterisk denotes the center of moving HIWC area.

and the polarimetric radar retrievals in ice and rain have already been utilized in a number of recent observational studies (e.g., Homeyer et al., 2021; Hu et al., 2020; Troemel et al., 2019; Wu et al., 2021).

A cursory comparison of the vertical profiles of polarimetric variables and derived microphysical parameters in the stratiform parts of the continental MCS (Murphy et al., 2020) and tropical cyclones (Homeyer et al., 2021; Hu et al., 2020) indicates that HIWC is more typical for marine weather systems that are generally characterized by lower values of  $D_m$  and higher values of  $N_t$  in high-altitude ice. However, previous studies were either case studies or only covered a limited number of storms. The community needs to know whether the results from those studies are broadly applicable for validating numerical simulations. The operational network of polarimetric WSR-88D radars provides a unique opportunity to build a climatology of the radar and microphysical patterns in cloud and precipitation systems over the CONUS using both inland and coastal radars that are capable of observing marine MCSs and landfalling hurricanes.

Several novel methodologies for processing and visualizing radar data have been introduced recently which can help to facilitate such comprehensive statistical analysis. These methodologies include the quasi-vertical profiles (QVP; Ryzhkov et al., 2016), range-defined QVP (RD-QVP; Tobin & Kumjian, 2017), enhanced and slanted vertical profiles, respectively (Bukovcic et al., 2017), columnar vertical profiles (CVP; Murphy et al., 2020), and GridRad (Homeyer & Bowman, 2017) techniques and products.

In this study, we perform a systematic analysis of the vertical profiles of polarimetric radar variables and microphysical parameters, such as LWC/IWC,  $D_m$ , and  $N_t$  using multiple WSR-88D radars and the RD-QVP and CVP data processing techniques for various types of weather systems including continental/marine MCSs and tropical cyclones. Overall, 34 storms have been examined. The primary objective is to quantify the vertical profiles of the radar and derived microphysical variables and their differences between the three types of weather systems: continental MCSs, marine MCSs, and tropical cyclones. We anticipate this study will comprise a needed climatology which can serve as a reference against which the cloud models' outputs can be evaluated.

### 1.1. Radar Microphysical Retrieval Algorithms

The radar retrieval equations for computing microphysical variables in rain and ice which we utilize in our study can be found in Ryzhkov and Zrnic (2019, Chapter 11), Ryzhkov et al. (2020), Bukovcic et al. (2018, 2020), and Carlin et al. (2021). These equations are listed herein.

For radar microphysical retrievals in pure rain, the following formulas for LWC, median volume diameter  $D_0$ , and total number concentration of raindrops  $N_t$  have been used:

$$LWC = 1.38 \times 10^{-3} \times 10^{(0.1Z - 2.43Z_{DR} + 1.12Z_{DR}^2 - 0.176Z_{DR}^3)}, \quad (1)$$

$$D_0 = 0.717 + 1.48Z_{DR} - 0.725Z_{DR}^2 + 0.171Z_{DR}^3, \quad (2)$$

$$\log(N_t) = -2.37 + 0.1Z - 2.89Z_{DR} + 1.28Z_{DR}^2 - 0.213Z_{DR}^3, \quad (3)$$

where LWC is expressed in  $\text{g m}^{-3}$ ,  $D_0$  is in mm,  $N_t$  is in  $\text{L}^{-1}$ ,  $Z$  is in dBZ, and differential reflectivity  $Z_{DR}$  is in dB. Equations 1 and 3 have been derived using simulations based on a large disdrometer dataset in Oklahoma and Equation 2 was suggested by Brandes et al. (2004). It has to be mentioned that the median volume diameter of raindrops  $D_0$  is quite close to its mean volume diameter  $D_m$  which is the ratio of the fourth and third moments of the raindrop size distribution:

$$D_0 = \frac{3.67 + \mu}{4 + \mu} D_m, \quad (4)$$

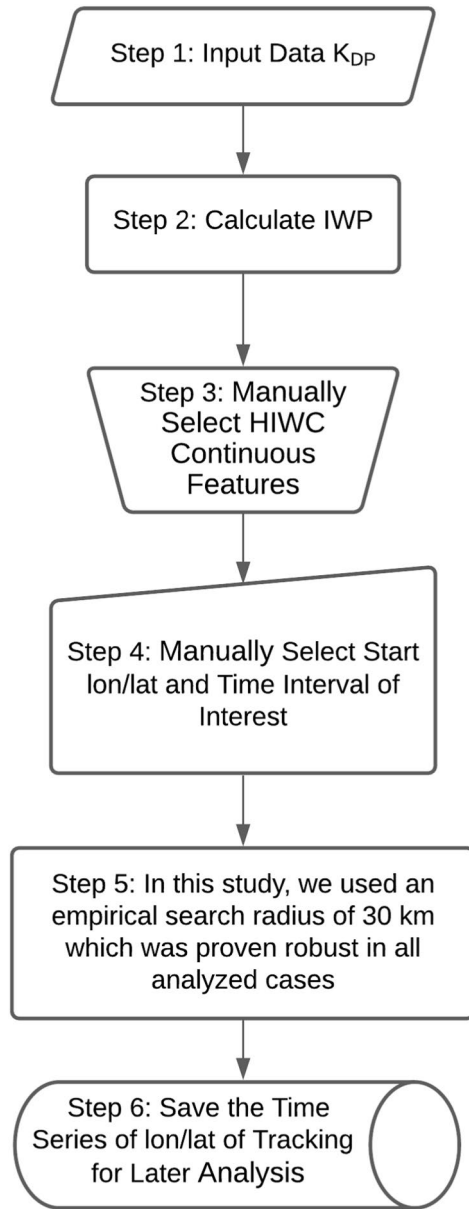


Figure 3. Flowchart of a tracking procedure for HIWC.

they are very sensitive to possible errors in the  $Z_{dr}$  measurements, particularly at lower values of  $Z_{DR}$ . For this reason, Equations 5 and 6 are utilized if  $Z_{DR} > 0.4$  dB (Carlin et al., 2021). Otherwise, IWC and  $D_m$  are estimated from Equations 7 and 8 that do not contain differential reflectivity. The inherent deficiency of these relations is that they are not immune to the variability of the particles' shapes and orientations. On the other hand, the  $D_m(K_{DP}, Z)$  estimate is not affected by the changes in the snow density or riming factor  $f_{rim}$ , whereas the relation  $D_m(K_{DP}, Z_{dp})$  is.

There are many definitions of the characteristic size of ice hydrometeors which generally have a nonspherical shape. The retrieval formulas 6 and 8 have been derived for the mean volume diameter  $D_m$  defined as the ratio of the fourth and third moments of the distribution of the *equivolume diameters*  $D_e$  of ice particles with a spheroidal shape. In the analyses of in situ measurements with the microphysical probes, the moments of the distribution of

where  $\mu$  is the shape factor of the gamma size distribution.

The errors of the estimators Equations 1–3 are specified in Ryzhkov et al. (2020). The fractional standard deviation (FSD) of the LWC estimate is about 35% if LWC varies from 0.1 to 1.0 g m<sup>-3</sup>. The FSD of the  $D_0$  estimate is about 10%. For the majority of DSDs the standard deviation of the  $\log(N_t)$  estimate is about 0.3. However, it can be larger for very high ( $\log(N_t) > 0$ ) and very low ( $\log(N_t) < -1$ ) total concentrations of raindrops.

Two recently proposed sets of polarimetric relations for determination of IWC and  $D_m$  in ice are used in our analysis. The first set of equations utilizes a combination of the specific differential phase  $K_{DP}$  and differential reflectivity  $Z_{dr}$  expressed in a linear scale ( $Z_{dr} = 10^{(0.1Z_{DR})}$ ) or reflectivity difference  $Z_{dp} = Z(1 - Z_{dr}^{-1})$  where  $Z$  is expressed in linear units (mm<sup>6</sup> m<sup>-3</sup>):

$$IWC(K_{DP}, Z_{dr}) = 4.0 \times 10^{-3} \frac{K_{DP} \lambda}{1 - Z_{dr}^{-1}}, \quad (5)$$

and

$$D_m(K_{DP}, Z_{dp}) = -0.1 + 2.0 \left( \frac{Z_{dp}}{K_{DP} \lambda} \right)^{1/2}, \quad (6)$$

In Equation 5 and 6,  $\lambda$  is the radar wavelength in mm.

Another set of relations does not utilize  $Z_{dr}$  or  $Z_{dp}$  and uses a combination of  $K_{DP}$  and  $Z$ :

$$IWC = 3.3 \times 10^{-2} (K_{DP} \lambda)^{0.67} Z^{0.33}, \quad (7)$$

and

$$D_m = 0.67 \left( \frac{Z}{K_{DP} \lambda} \right)^{1/3}, \quad (8)$$

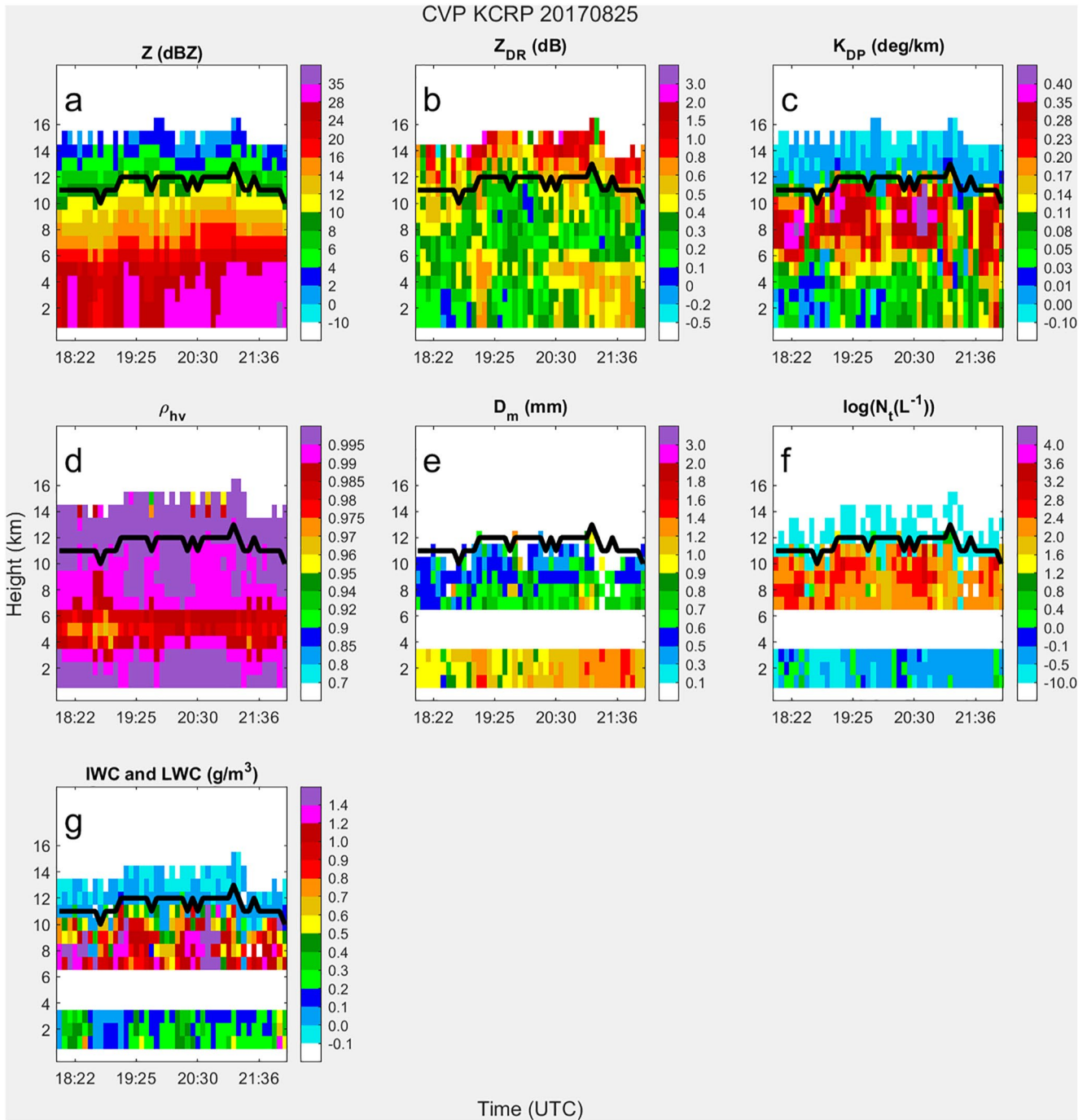
In Equation 5–8,  $Z$  is expressed in linear units. The relations (5)–(8) were derived assuming that the particles are the Rayleigh scatterers with their density inversely proportional to the equivolume diameter  $D_e$

$$\rho_s = \alpha_0 f_{rim} D_e^{-1}, \quad (9)$$

where  $\alpha_0$  is a constant and  $f_{rim}$  is the riming factor changing from 1 for unrimed ice to 5 for heavily rimed ice.

The advantage of the estimates (5) and (6) is that they are practically insensitive to the variability of the ice particles' shapes and orientations. However, they are very sensitive to possible errors in the  $Z_{dr}$  measurements, particularly at lower values of  $Z_{DR}$ . For this reason, Equations 5 and 6 are utilized if  $Z_{DR} > 0.4$  dB (Carlin et al., 2021). Otherwise, IWC and  $D_m$  are estimated from Equations 7 and 8 that do not contain differential reflectivity. The inherent deficiency of these relations is that they are not immune to the variability of the particles' shapes and orientations. On the other hand, the  $D_m(K_{DP}, Z)$  estimate is not affected by the changes in the snow density or riming factor  $f_{rim}$ , whereas the relation  $D_m(K_{DP}, Z_{dp})$  is.

There are many definitions of the characteristic size of ice hydrometeors which generally have a nonspherical shape. The retrieval formulas 6 and 8 have been derived for the mean volume diameter  $D_m$  defined as the ratio of the fourth and third moments of the distribution of the *equivolume diameters*  $D_e$  of ice particles with a spheroidal shape. In the analyses of in situ measurements with the microphysical probes, the moments of the distribution of



**Figure 4.** CVP time series between 1800 UTC to 2200 UTC 25 August 2017 near Corpus Christi, Texas (KCRP), WSR-88D radar. (a)  $Z$ , (b)  $Z_{DR}$ , (c)  $K_{DP}$ , (d)  $\rho_{hv}$ , (e)  $D_m$ , (f)  $N_t$ , (g), and IWC/LWC. Black line represents the 10 dB SNR contour and pixels over this line are not used for CFAD calculations.

*maximal particle dimensions*  $D_{max} > D_c$  are usually quantified. This circumstance has to be taken into account in the comparison of the radar retrieved characteristic sizes and the ones obtained from in situ probes.

Once IWC is determined either from Equation (5) or Equation (7), the total number concentration  $N_t$  of ice particles larger than 0.1 mm can be computed as

$$\log(N_t) = 3.39 + 2 \log(IWC) - 0.1Z(dBZ), \quad (10)$$

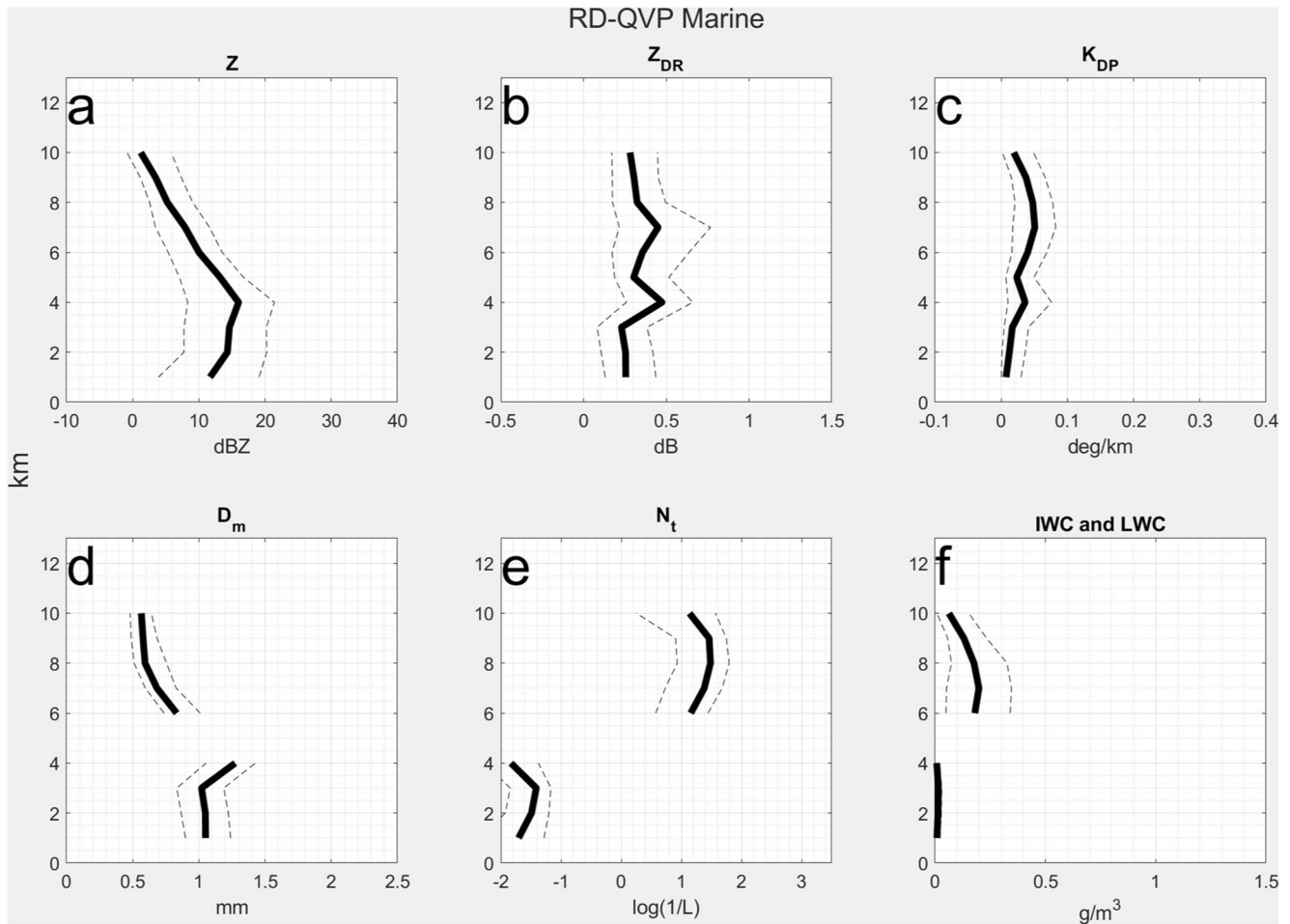
**Table 1**  
*List of Events and WSR-88D Radars Used for Analysis*

Type			
Continental MCSs	Date	UTC	NEXRAD
MCS	11 June 2018	0300–1000	KMBX
MCS	23 June 2018	0400–1100	KTLX
MCS	2 June 2018	0400–1200	KOAX
MCS	26 June 2019	0300–0800	KTWX
MCS	27 June 2019	0700–1200	KBIS
MCS	27 June 2019	1400–1900	KMPX
MCS	27 June 2019	1800–2300	KARX
MCS	30 June 2019	0900–1500	KDLH
MCS	6 June 2019	0400–0800	KDYX
MCS	15 June 2019	0500–1100	KICT
MCS	15 June 2019	0200–0700	KDDC
MCS	24 June 2019	0100–1000	KLZK
Marine MCSs			
MCS	1 February 2020	0100–2300	KBYX
MCS	7 February 2020	1000–1500	KBYX
MCS	14 May 2020	0200–0200(+1)	KBYX
MCS	25, May 2020	0400–1200	KBYX
MCS	3 June 2020	1000–1900	KBYX
MCS	4 June 2020	1000–1900	KBYX
MCS	18 June 2020	0000–0700	KBYX
MCS	22 February 2019	1800–1700(+1)	PGUA
MCS	12 September 2018	1500–0700(+1)	PHMO
MCS	23 July 2016	1700–1100(+1)	PHWA
Tropical cyclones			
MH (Harvey)	25 August 2017	1800–2200	KCRP
TS (Alberto)	28 May 2018	1400–2100	KEVX
MH (Michael)	10 October 2018	1500–2200	KEVX
TS (Imelda)	17 September 2019	1400–2400	KHGX
TS (Cindy)	21 June 2017	0000–0800	KLIX
MH (Irene)	27 August 2011	0000–2400	KMHX
MH (Dorian)	6 September 2019	0500–1100	KMHX
MH (Irma)	10 September 2017	0700–1600	KMLB, KBYX
TS (Cindy)	21 June 2017	0000–0800	KMOB
TS (Emily)	31 July 2017	0500–1100	KTBW
MH (Nate)	8 October 2017	0700–1800	KMOB, KEVX

*Note.* MH and TS labels indicate major hurricanes and tropical storms, respectively.

where  $N_i$  is in  $L^{-1}$ .

Since the retrievals (5)–(10) are based on the assumption that the ice/snow density is inversely proportional to the particle size, they are not applicable in the convective cores with strong updrafts where graupel or hail is present. Therefore, they are primarily valid in the stratiform parts of MCSs, peripheries of the tropical cyclones, and thunderstorm anvils. They also cannot be used in the melting layer (ML) filled with mixed-phase hydrometeors.



**Figure 5.** Median vertical profiles for the marine RD-QVP dataset: (a)  $Z$ , (b)  $Z_{DR}$ , (c)  $K_{DP}$ , (d)  $D_m$ , (e)  $N_t$ , and (f) IWC/LWC (solid lines). Dotted lines on the left and right hand sides of each solid line represent the corresponding 25th and 75th percentiles data.

The accuracy of the polarimetric ice retrievals is determined by the natural variability of the size distributions of ice, its shape, orientation, and density as well as the measurement errors of the polarimetric radar variables. Theoretical simulations assuming gamma size distribution with various shape factors  $\mu$  indicate that the value of FSD for IWC estimated from Equation 5 is below 20% if  $-1 < \mu < 1$ , and IWC is slightly overestimated for  $\mu < -1$  (Ryzhkov et al., 2020; Ryzhkov & Zrnica, 2019). For a given degree of riming  $f_{rim}$ , the FSD of the  $D_m$  estimate (6) is below 20%, but some adjustment of Equation 6 might be needed depending on  $f_{rim}$ . The error of the  $\log(N_t)$  estimate varies between 0.7 and 1.0 (in log units). A more detailed discussion on the accuracy of the polarimetric retrievals (5)–(10) can be found in Ryzhkov and Zrnica (2019), Ryzhkov et al. (2020), and Bukovic et al. (2018, 2020).

As mentioned earlier, one of the primary advantages of using  $K_{DP}$  is that it is proportional to the first moment of the size distribution, whereas  $Z$  is proportional to its fourth moment (if the inverse dependency of the density of snowflakes on their size is assumed) and is therefore disproportionately weighted by a few largest ice particles. Another advantage of  $K_{DP}$  is that it is not biased by noise, attenuation, and radar miscalibration. On the other hand, the magnitude of  $K_{DP}$  in dry ice and snow is relatively small, particularly at longer radar wavelengths. Aggressive spatial averaging of  $K_{DP}$  and  $Z_{DR}$  implemented in the RD-QVP and CVP methodologies helps to reduce inherent noisiness of the  $K_{DP}$  and  $Z_{DR}$  estimates and the corresponding retrieval estimates. We also avoid using the retrievals in areas where  $K_{DP} < 0.009^\circ\text{km}^{-1}$  and the signal-to-noise ratio (SNR) is less than 10 dB. In our analysis, we use  $K_{DP}$  values obtained as the output of the standard WSR-88D differential phase processing briefly described in Ryzhkov, Giangrande, and Schuur (2005) and the spatial averaging of  $K_{DP}$  was applied



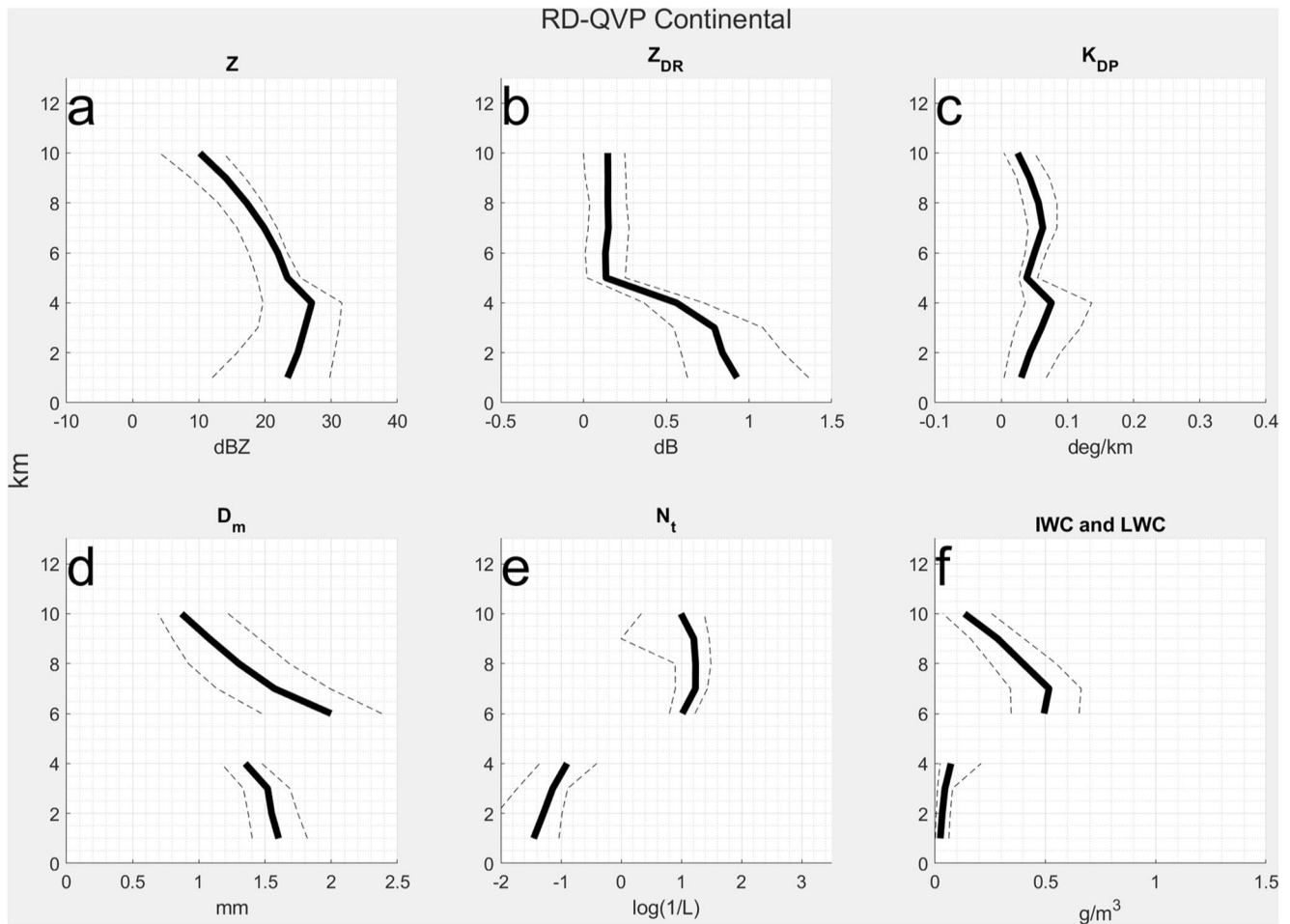


Figure 6. Same as in Figure 5, but for the RD-QVP statistics for continental MCSs.

according to the RD-QVP and CVP methodologies. Absolute calibration of differential reflectivity  $Z_{DR}$  was performed manually for each case and radar using the RD-QVP profiles of  $Z_{DR}$  and ensuring that the value of  $Z_{DR}$  is in the range of 0.1–0.2 dB in dry aggregated snow above the ML as instructed in Ryzhkov, Giangrande, Melnikov, and Schuur (2005).

The accuracy of the polarimetric retrievals in ice used in our study was evaluated experimentally using in situ aircraft measurements by Ryzhkov et al. (1998), Nguyen et al. (2019), and Murphy et al. (2020) and surface measurements by Bukovcic et al. (2018, 2020). Although the results are encouraging, we continue testing and refining the retrieval relations in ice. However, at the moment, we have enough confidence in the retrievals (5)–(10) to utilize them in our climatological study presented in this article.

Alternative statistical polarimetric retrieval methods in ice were recently suggested by Kedzuff et al. (2021) and Munchak et al. (2021) which are also designed for estimation of IWC,  $D_m$ , and  $N_t$  for each ice species and their mixtures along the radials of polarimetric radar data. Kedzuff et al. (2021) proposed the iterative stochastic ensemble Kalman filter approach and Munchak et al. (2021) used optimal estimation to solve for several parameters that describe PSD, relative contribution of pristine, aggregate, and rimed ice species, and the orientation distribution along an entire radial simultaneously. While these methodologies hold certain promises, they are very computationally intensive and their efficiency still needs to be investigated.

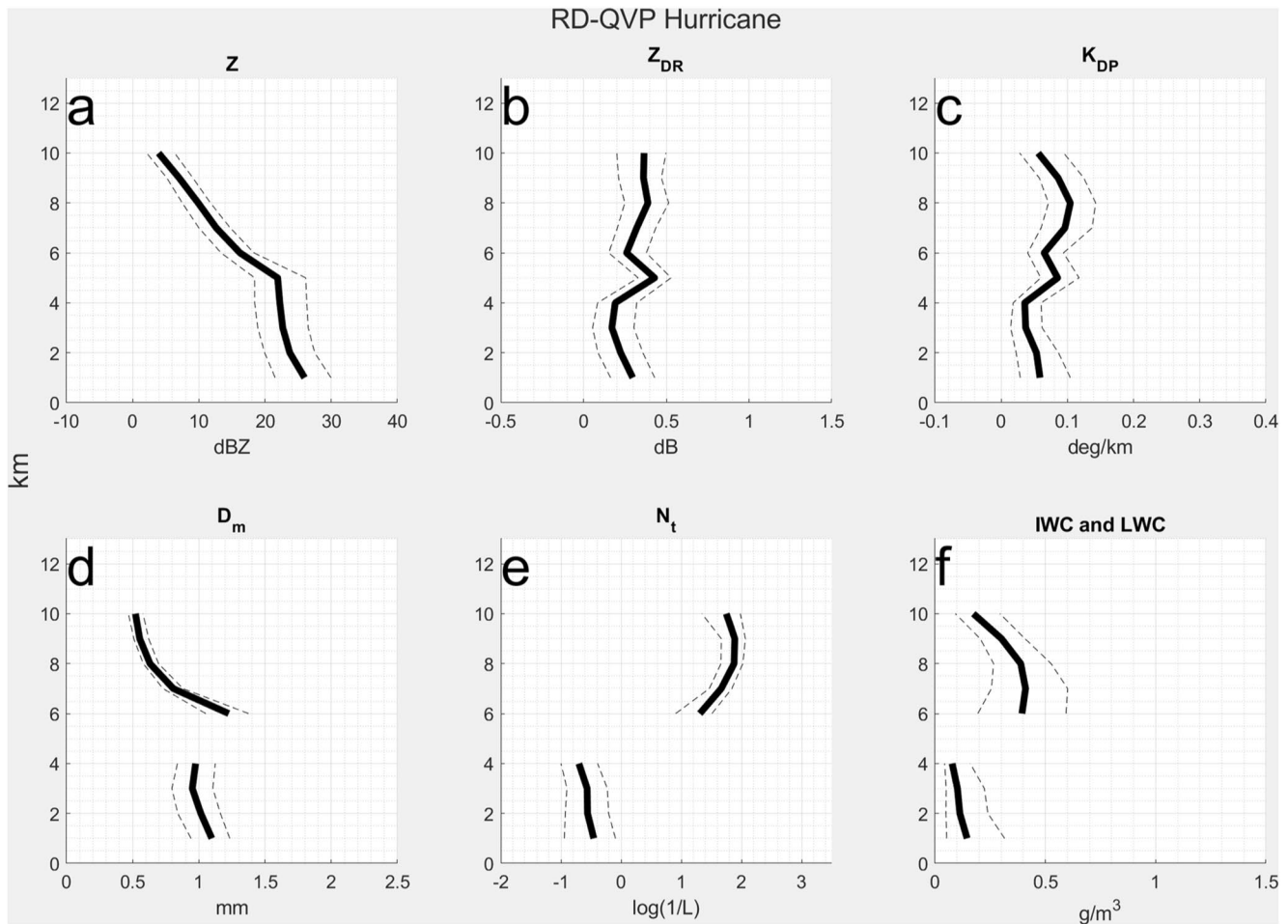


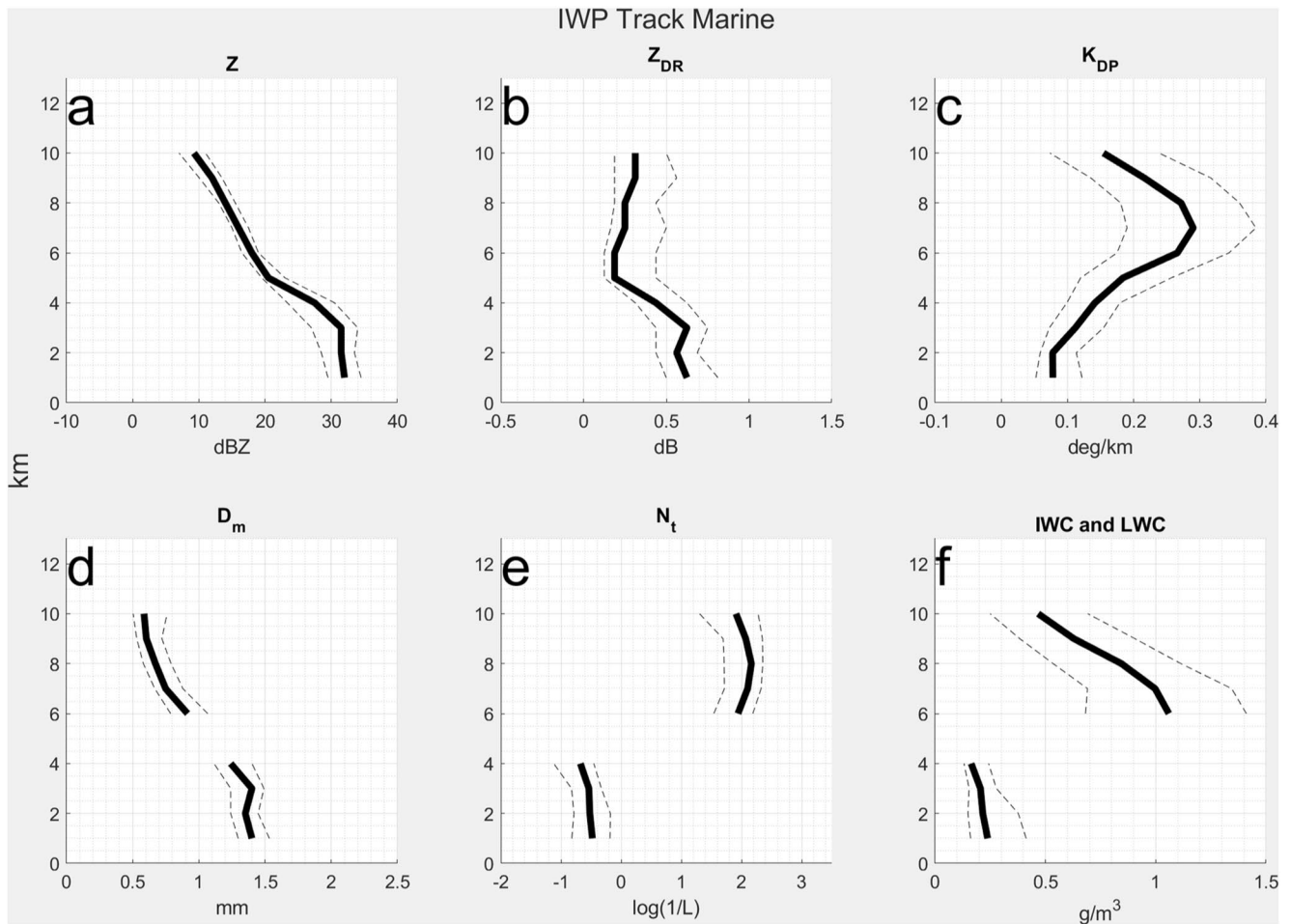
Figure 7. Same as in Figure 5 but for the hurricane RD-QVP statistics.

## 2. Methodology

In this study, we distinguish between two types of statistics of the vertical profiles of the radar and microphysical variables: the “background” and the “HIWC” statistics. The background statistic encompasses all stratiform parts of the clouds regardless of their IWC, whereas the “HIWC” statistics are built for the vertical columns in the clouds containing high IWC above the ML with ice water path (IWP; vertically integrated IWC) exceeding  $4.5 \text{ kg m}^{-2}$ . The two statistics require different methodologies for processing of the radar data. The RD-QVP technique is suitable for the background statistics approach because the data are analyzed in a 50 km—radius vertical column centered on the radar. The HIWC statistics require identification and tracking the HIWC areas within the storm which can be farther than 50 km from the radar and estimating vertical profiles in continuously moving columns containing high amount of ice. The CVP methodology is the best choice for this task.

### 2.1. RD-QVP Products

According to the original QVP methodology introduced in Kumjian et al. (2013) and Ryzhkov et al. (2016), vertical profiles of polarimetric radar variables are created by azimuthal averaging of the radar data in a full  $360^\circ$  circle at a single elevation angle usually selected between  $10^\circ$  and  $20^\circ$ . The data are presented in a height-time format which represents temporal evolution of the vertical structure of the storm with high vertical resolution. Tobin and Kumjian (2017) modified original QVP technique by suggesting the “range-defined” QVP (RD-QVP), which combines QVPs at multiple elevations using an inverse distance weighting technique. The RD-QVP technique uses radar data from the distances within 50 km from the radar at all available elevation angles.



**Figure 8.** Median vertical profiles for the marine HIWC track dataset: (a)  $Z$ , (b)  $Z_{DR}$ , (c)  $K_{DP}$ , (d)  $D_m$ , (e)  $N_t$ , and (f) IWC/LWC. Dotted lines on the left and right hand sides of each solid line represent the corresponding 25th and 75th percentiles data.

An example of the RD-QVP product for Hurricane Harvey (2017) observed by the Corpus Christi, TX (KCRP) WSR-88D radar is displayed in Figure 1. The RD-QVPs of  $Z$ ,  $Z_{DR}$ ,  $K_{DP}$ ,  $\rho_{hv}$  and LWC/IWC,  $D_m$ , and  $N_t$  are presented for the time period between 18 and 22 UTC on 25 August 2017. The RD-QVP technique captures a fine vertical structure of the storm with a clear signature of the ML in terms of  $Z_{DR}$  and  $\rho_{hv}$  between 4.5 and 5 km. Below the ML, a strong vertical gradient of  $K_{DP}$  exhibits a dominance of a classical warm rain process with rain rate increasing toward the surface as well as the raindrop size (see the  $Z_{DR}$  and  $D_m$  panels) due to a collision-coalescence process (Ryzhkov & Zrnice, 2019). In the ice part of the storm above the ML, radar reflectivity decreases with height very rapidly which is typical for tropical cyclones. Notable is a prominent increase of  $K_{DP}$  and  $Z_{DR}$  in the dendritic growth layer (DGL) centered at the  $-15^\circ\text{C}$  altitude (8 km). High  $K_{DP}$  associated with low  $Z$  in the ice part of the storm is a classical feature of the tropical cyclones indicating relatively high concentration of small-size ice particles with quite substantial IWC (Nguyen et al., 2019; Ryzhkov & Zrnice, 2019).

Commonly used IWC( $Z$ ) relations tend to underestimate IWC in the majority of tropical storms (Ryzhkov & Zrnice, 2019). A frequently utilized IWC( $Z$ ) relation of Hogan et al. (2006).

$$IWC = 0.02 \times 10^{-0.02T} Z^{0.6}, \quad (11)$$

where  $T$  is the temperature in  $^\circ\text{C}$ , yields  $IWC = 0.32 \text{ g m}^{-3}$  at the height of 8 km where  $K_{DP}$  reaches its maximum and  $Z$  is only 15 dBZ. The corresponding polarimetric estimator (5) gives the IWC value of about  $0.7 \text{ g m}^{-3}$ , that is, more than two times larger. A combination of high  $K_{DP}$  and low  $Z$  signifies smaller sized ice particles accord-

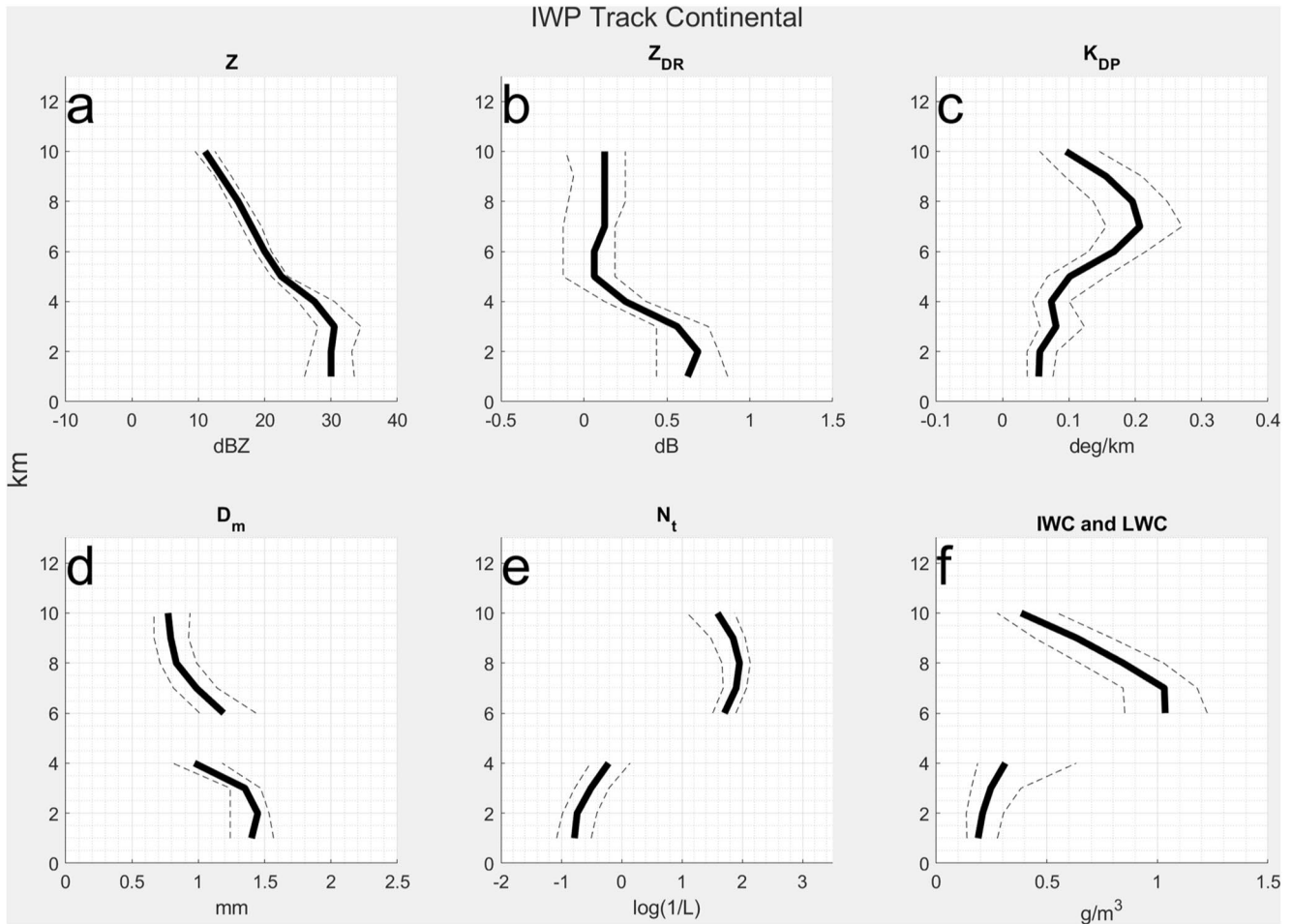


Figure 9. Same as in Figure 8, but for the continental HIWC statistics.

ing to Equation 6 or Equation 8. Indeed, the mean volume diameter  $D_m$  is only about 0.5 mm and its total number concentration reaches values over  $100 L^{-1}$  at the same height.

The layer between 4 and 6 km centered on the ML is left blank in the microphysical QVP panels because our polarimetric retrievals are not designed for mixed-phase particles. The retrievals are less reliable in areas of low signal-to-noise ratio (SNR). The contours of  $SNR = 10$  dB are overlaid in black in Figure 1. It is obvious that the retrieval estimates become erratic near the top of the storm where  $SNR < 10$  dB. Therefore, we will use only the radar data with  $SNR > 10$  dB for our quantitative analysis.

## 2.2. HIWC CVP Products

In order to identify the HIWC areas, the WSR-88D radar data are first converted into the Cartesian 3D format with a vertical resolution of 0.3 km and horizontal resolution of  $0.005^\circ$  in terms of latitude and longitude. Then a horizontal field of the IWP is generated as shown in the example illustrated in Figure 2 from the same Hurricane Harvey. In our study, we estimated IWP by integrating the vertical profile of  $K_{DP}$  starting from the altitude 6 km as

$$IWP = 3.2 \int_{H=6km} K_{DP} dh, \quad (12)$$

assuming a simplified relation

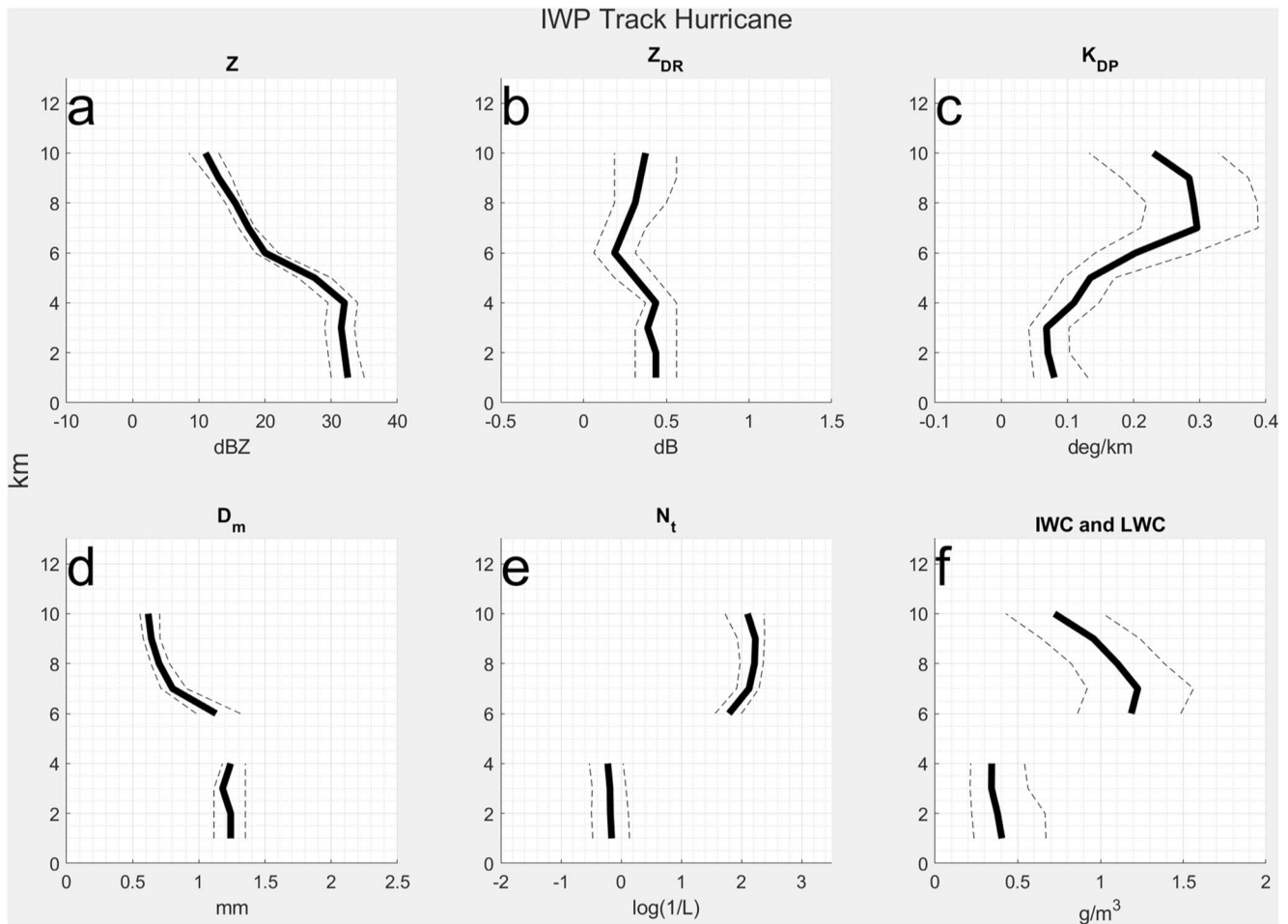


Figure 10. Same as in Figure 8, but for the hurricane HIWC statistics.

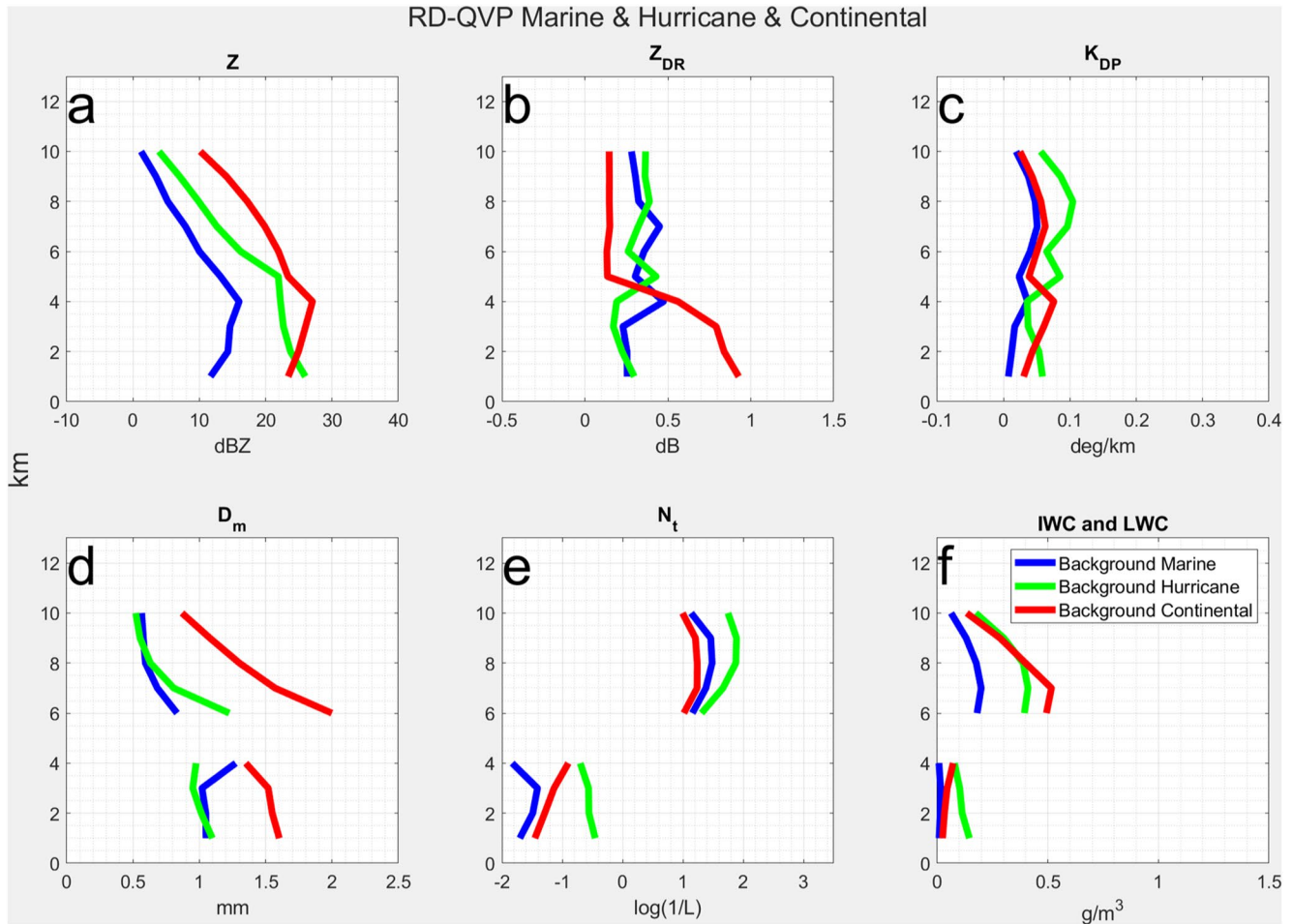
$$IWC = 3.2K_{DP}, \quad (13)$$

valid at S band (Ryzhkov et al., 1998; Ryzhkov & Zrnicek, 2019). In Equations 12 and 13, IWP is expressed in  $\text{kg m}^{-2}$  and IWC is in  $\text{g m}^{-3}$ . Equation 13 is different from the more accurate polarimetric relations 5 and 7 and we opt to use it for classification purpose only due to its simplicity (steps 1 and 2 in Figure 3 where a flowchart of the tracking method used in our study is displayed).

Because our retrievals (Equations 5–10) are not applicable in deep convective cores, we avoid estimating IWP and performing our microphysical retrievals within vertical columns where radar reflectivity  $Z$  exceeds 30 dBZ at altitudes above 6 km.

The HIWC areas in the IWP maps are identified using the IWP threshold value equal to  $4.5 \text{ kg m}^{-2}$ . We selected this threshold from the higher end of the IWP distributions in the thunderstorm anvils reported by Tian et al. (2018).

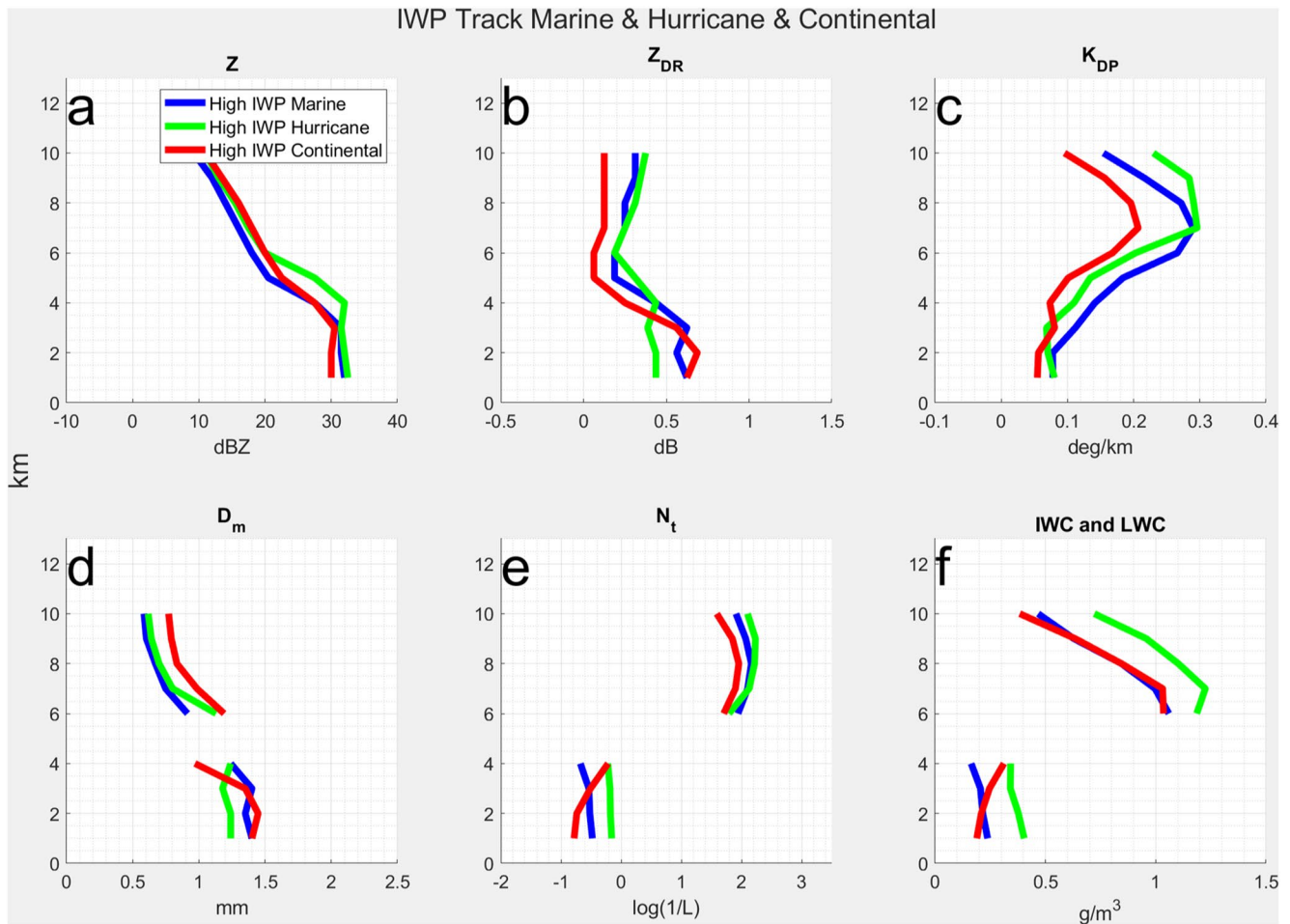
The tracking of the HIWC areas was done in a semi-subjective manner. For each examined storm, we first went through the IWP map time series and picked up continuous HIWC features as shown in the Supporting Information (Step 3 in Figure 3). Then we manually pinpointed the starting longitude and latitude for tracking. The starting and ending time steps were also subjectively selected based on the IWP map as mentioned above (Step 4 in Figure 3). The next step was to track HIWC centers between time steps, which was done by searching for the maximum IWP near the HIWC center point from the previous tracking step. In this study, we used an empirical search radius of 30 km which was proven robust in all analyzed cases (Step 5 in Figure 3). The tracking procedure runs in the Cartesian coordinates and outputs the lon/lat of HIWC centers at each time step. These locations were



**Figure 11.** Median vertical profiles for the RD-QVP dataset: (a)  $Z$ , (b)  $Z_{DR}$ , (c)  $K_{DP}$ , (d)  $D_m$ , (e)  $N_t$ , and (f) IWC/LWC. Blue, green, and red lines represent marine, tropical cyclone, and continental profiles, respectively.

used for generation of the columnar vertical profiles (CVP) of  $Z$ ,  $Z_{DR}$ ,  $K_{DP}$ , and  $\rho_{hv}$  and retrieval calculations, which will be detailed next (Step 6 in Figure 3).

Vertical profiles of the radar and microphysical variables associated with a moving HIWC vertical column were obtained using the CVP technique described by Murphy et al. (2020) and Hu et al. (2020). In our study, a radial extension of the CVP column is 20 km while its azimuthal size is  $20^\circ$ . That is, the horizontal extent of the CVP column is much smaller than the one of the radar-centered RD-QVP column which allows to better focus on the HIWC areas which are often relatively small. Both CVP and RD-QVP average data azimuthally, except CVP mean calculation utilizes 20 points ( $20^\circ$  azimuthal size with  $1^\circ$  resolution) at each vertical level in this study. Because  $K_{DP}$  in ice at S band is quite low and noisy, quite aggressive spatial averaging at any height level within the CVP column is needed. This dictates the choice of a horizontal size of the CVP columns which is sufficiently large (although smaller than the horizontal size of the RD-QVP column). An example of the HIWC CVP time series for Hurricane Harvey and the time interval between 18 and 22 UTC is shown in Figure 4. A tracking snapshot of the HIWC column is displayed in Figure 2. This column was relatively close to the eye of Hurricane Harvey when it landed near Corpus Christi. The distance between the center of a HIWC column and the KCPR WSR-88D radar varied between 93 and 108 km during this time period. It is no surprise that the vertical resolution of the CVP profiles is worse than that of the RD-QVP profiles, given that the CVP column was much farther from the radar. As a result, a signature of the ML is barely visible in the  $\rho_{hv}$  panel and is indistinguishable in the vertical cross sections of  $Z$  and  $Z_{DR}$ . Nevertheless, the CVP series displays persistently high  $K_{DP}$  at the altitudes above 6 km associated with relatively low  $Z$ , as expected. The corresponding values of IWC generally exceed



**Figure 12.** Median vertical profiles for the HIWC track dataset: (a)  $Z$ , (b)  $Z_{DR}$ , (c)  $K_{DP}$ , (d)  $D_m$ , (e)  $N_t$ , and (f) IWC/LWC. Blue, green, and red lines represent marine, tropical cyclone, and continental profiles.

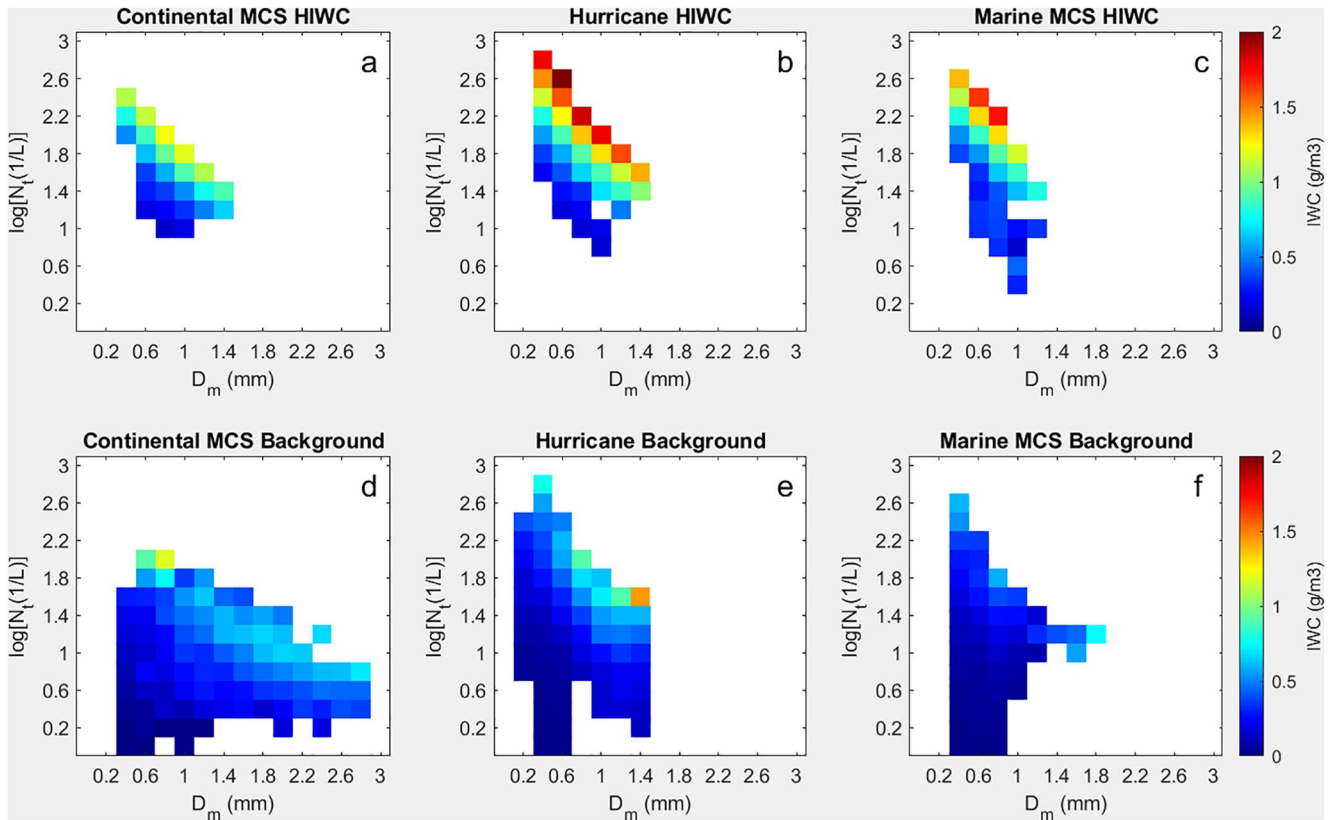
$1 \text{ g m}^{-3}$  occasionally reaching  $1.4 \text{ g m}^{-3}$ , whereas  $D_m$  remains below  $1 \text{ mm}$  and  $N_t$  is consistently higher than  $100 \text{ L}^{-1}$ .

### 3. Dataset

Three types of storm systems have been investigated in this study: continental MCSs, marine MCSs, and land-falling tropical cyclones. A list of selected storms, their dates, and the names of WSR-88D radars is shown in Table 1. All storms' paths must overlap with at least one of the WSR-88D radar sites in order to be selected. For each case in Table 1, the CVPs along the HIWC tracking paths and RD-QVPs have been processed, saved, and displayed in the same fashion as shown in Figures 1 and 4.

### 4. Results

For every case, the radar variables and retrieved microphysical parameters are stacked in a height versus time format (as shown in Figures 1 and 4 for a given storm). The vertical profiles of radar variables and microphysical parameters are combined for each of the three categories of storms and the corresponding vertical median profiles and the profiles corresponding to the 25th and 75th percentiles of the variable distribution at every height level are displayed in Figures 5–10. The microphysical differences between the three categories of weather systems



**Figure 13.** Distribution of the median values of IWC in the  $\log(N_i)$  versus  $D_m$  plane for the HIWC and background statistics for three types of weather systems ([a] and [d] Continental MCS, [b] and [e] Hurricane, [c] and [f] Marine MCS).

are exhibited in Figure 11 and 12 where the vertical profiles of  $Z$ ,  $Z_{DR}$ ,  $K_{DP}$ ,  $LWC/IWC$ ,  $D_m$ , and  $N_t$  are compared separately for the RD-QVP and HIWC CVP analyses.

#### 4.1. RD-QVPs

Vertical median profiles of radar reflectivity in Figure 11a show that  $Z$  in the ice parts of the storms is highest in the continental MCSs followed by the hurricanes. This is primarily due to the fact that the ice particles in continental MCSs are larger than those in marine MCSs and tropical cyclones. The reflectivity in the hurricanes is higher than in the continental storms only in rain next to the surface because of the strong collision/coalescence process at lower levels typical for warm rain in the tropics.

The difference in the vertical median profiles of  $Z_{DR}$  is quite dramatic with continental MCSs exhibiting the lowest values of  $Z_{DR}$  in ice above the ML and the highest values of  $Z_{DR}$  in rain below the ML (Figure 11b). Lower  $Z_{DR}$  in ice within the continental MCSs is attributed to larger size of the ice particles dominated by aggregated and possibly rimed snow which is generally characterized by lower bulk density and more spherical shape. Smaller size ice crystals with higher density and more anisotropic shape are prevalent in marine MCSs and tropical cyclones which explains higher values of  $Z_{DR}$  there. This pattern is also consistent with the highest  $K_{DP}$  in ice observed in the hurricanes (Figure 11c) because  $K_{DP}$ , being proportional to the first moment of the size distribution of ice, is mainly determined by the smallest ice particles in the size spectrum which have higher density and more nonspherical shape. Larger size snowflakes above the ML end up as larger raindrops after melting and, therefore, significantly higher values of  $Z_{DR}$  observed in the continental MCSs. Lower  $Z$  and higher  $K_{DP}$  in the ice portions of hurricanes signify smaller ice particles compared to the continental MCSs. Indeed, the mean volume diameter  $D_m$  is generally proportional to a cubic root of the ratio of  $Z$  and  $K_{DP}$  according to Equation 8. This feature is clearly illustrated by the vertical profiles of the median values of  $D_m$  in Figure 11d. In the continental storms,  $D_m$  in ice is almost two times higher than in the marine events. For a given IWC, the total number concen-



tration  $N_i$  of ice is higher in tropical storms because  $Z$  is lower—see Figure 11e. Larger  $D_m$  in ice aloft correspond to larger median values of  $D_m$  in rain for the continental MCSs, whereas a higher concentration of ice in tropical storms results in a higher concentration of raindrops below the ML. It is interesting that the median values of IWC are very comparable in the continental and tropical cases.

#### 4.2. HIWC CVPs

Similar conclusions, with a few exceptions, can be drawn from the analysis of the HIWC CVP statistics (Figure 12). As expected, the HIWC areas are characterized by much higher  $K_{DP}$  in ice with the maximal median value reaching  $0.3^\circ\text{km}^{-1}$  in the tropical cyclones and marine MCSs. The corresponding values of IWC are also about three times higher than in the “background” RD-QVP statistics. It is not surprising that the radar reflectivity in ice is significantly higher in the HIWC regions of the tropical storms compared to their background because of much larger amount of ice aloft. Note that the vertical profiles of the median values of the mean volume diameter  $D_m$  of ice particles are very similar for the RD-QVP and HIWC CVP statistics. Therefore, a three-fold increase of IWC in the HIWC areas is achieved not by the increase of the size of ice particles but by the significant jump in their number concentration  $N_i$  (Figures 12d and 12e). Median values of  $N_i$  exceed  $100\text{ L}^{-1}$  above the ML in the HIWC regions and the values of  $N_i$  higher than  $1,000\text{ L}^{-1}$  are quite common (Figure 12e). The retrieved vertical profiles of  $N_i$  in Figures 11 and 12 do not show the anticipated increase of  $N_i$  with height. This pattern is most likely caused by the loss of sensitivity of the radar to the particles less than 0.1 mm in size. In other words, although actual total concentration of ice may increase with height, a good portion of such particles becomes invisible to the radar because of their decreasing size.

It is interesting that the  $Z_{DR}$  values in ice are lower in the HIWC regions of the tropical storms compared to their “background” RD-QVP values. The high values of  $Z_{DR}$  in stratiform parts of the storms are commonly observed within the DGL centered at the altitude with temperature of about  $-15^\circ\text{C}$ . Griffin et al. (2018) showed that the highest values of  $Z_{DR}$  are observed within the DGL in the storms with lower tops just exceeding the DGL levels so that the highly anisotropic dendrites or hexagonal plates locally generated in the DGL are not masked by a bulk of more “quasi-spherical” ice with irregular shape falling from aloft. No  $Z_{DR}$  enhancement in the DGL is usually observed in the storms with high cloud tops. Hence, we believe that this is likely the reason why  $Z_{DR}$  in ice is lower in the HIWC areas commonly characterized by high cloud tops.

### 5. Discussion

An alternative way to summarize the results of our analysis illustrated in Figures 11 and 12 is to show a distribution of the median value of IWC in the  $\log(N_i) - D_m$  plane for the background and HIWC statistics and three types of weather systems (Figure 13). The median values of IWC were obtained for all  $\log(N_i) - D_m$  pairs in every  $0.2 \times 0.2$  bin in the  $\log(N_i) - D_m$  plane. Figure 13 shows that the highest median values of IWC approaching  $1.5\text{--}2\text{ g m}^{-3}$  are observed in the hurricanes and marine MCSs and these are primarily associated with the highest total number concentrations of ice  $N_i$  and smallest sizes of ice particle  $D_m$  (Figures 13b and 13c). The continental MCSs reveal quite different pattern with noticeably lower median values of IWC even for HIWC cases (Figures 13a and 13d). Some differences between the total number of  $0.2 \times 0.2$  bins in the Figures 13a–13f can be explained by the size of statistics which is the largest for the continental MCS background events.

The radar microphysical retrieval techniques in ice are still in the process of evaluation and refinement using in situ microphysical airborne and surface observations. However, we believe that Equations 5–10 used in this study is a good first attempt because they produce results consistent with occasional in situ measurements in the proximity of the polarimetric radars (e.g., Murphy et al., 2020; Nguyen et al., 2019; Ryzhkov et al., 1998) and which are in a ballpark of the majority of airborne probes’ measurements of IWC,  $D_m$ , and  $N_i$  reported in the literature (e.g., Finlon et al., 2019; Heymsfield et al., 2013, 2015, 2017; Huang et al., 2021; Leroy et al., 2017; McFarquhar et al., 2007; Stechman et al., 2020). Such measurements in the stratiform parts of the continental MCSs during the BAMEX, MC3E, and PECAN field campaigns are summarized by McFarquhar et al. (2007), Tian et al. (2016), Finlon et al. (2019), and Stechman et al. (2020). For example, Finlon et al. (2019) reported the values of IWC averaged over all altitudes at negative temperatures in ice varying between  $0.3$  and  $0.8\text{ g m}^{-3}$ , the corresponding values of the median mass-weighted diameter ( $D_{mm}$ ) from 1 to 2 mm, and  $N_i$  from 20 to

40 L<sup>-1</sup> during MC3E. Stechman et al. (2020) showed similar ranges for these variables observed in BAMEX and PECAN: 0.4–0.8 g m<sup>-3</sup> for IWC, 2.0–2.5 mm for  $D_{mm}$ , and 15–60 L<sup>-1</sup> for  $N_t$ . The in situ aircraft measurements in tropical clouds during the HAIC-HIWC experiments in Darwin, Australia, and Cayenne. French Guiana show generally higher values of IWC and  $N_t$  and lower values of  $D_{mm}$  in ice compared to the continental midlatitude MCSs. Leroy et al. (2017) reported IWC varying from 0.5 to 2.5 g m<sup>-3</sup> and  $D_{mm}$  in the range between 0.25 and 0.7 mm in the Darwin flights. Huang et al. (2021) found very similar ranges of IWC and  $D_m$  during the flights in Cayenne and noted quite high total number concentrations  $N_t$  between 100 and 200 L<sup>-1</sup>. All these numbers are consistent with the results of our polarimetric retrievals illustrated in Figure 12 and demonstrate similar differences between tropical and continental clouds.

As mentioned before, our retrieved  $D_m$  is the ratio of the fourth and third moments of the size distribution of equivolume diameters which is different from  $D_{mm}$  or median volume ( $D_{mv}$ ) size commonly estimated from in situ airborne microphysical probes which measure a maximal particle dimension. It can be easily shown that  $D_{mm} = 0.79 D_m$  and  $D_{mv} = 1.09 D_m$  for the exponential size distribution and particle aspect ratio 0.6. We again emphasize that our estimated number concentration  $N_t$  is only for particles with sizes larger than 0.1 mm.

Analysis of the underlying reasons for the microphysical differences between the three types of weather systems is beyond the scope of this article. We can only speculate that the difference in the aerosol concentrations and strengths of convective updrafts in the continental and marine systems might be responsible for their significant contrast in terms of the median size of ice particles and their number concentration. We notice that extended HIWC areas in the stratiform parts of the marine MCS or tropical cyclones with reflectivities lower than 30 dBZ are usually well connected to the convective cores which tells that a bulk of small ice might be advected from the convective updrafts where the processes of SIP take place. It is quite likely that ice splintering by raindrop freezing in the updrafts is the primary mechanism responsible for high ice concentration below the homogeneous freezing level in clouds with warm cloud base, especially in the marine convective clouds and in the tropics (Lawson et al., 2015). In the continental clouds with colder cloud bases, secondary ice is produced within the convective zone as a result of hail-snow and graupel-snow collisions. It can penetrate the stratiform area at heights of about 7–8 km, with further increases of concentration caused by sublimational breakup in decaying parts of the storm (Phillips et al., 2017). Finally, extremely large amounts of small ice crystals in cloud anvils can be a result of homogeneous freezing of small droplets forming in the course of in-cloud nucleation of ultra-small CCN in the upper parts of deep convective clouds and above the level of homogeneous freezing (Fan et al., 2018; Khain et al., 2012).

## 6. Conclusions

A climatology of the vertical profiles of polarimetric radar variables and retrieved microphysical parameters such as LWC/IWC, mean volume diameter  $D_m$ , and total number concentration  $N_t$  has been documented for three types of weather systems: continental MCSs, marine MCSs, and tropical cyclones. This climatology is built based on the analysis of the WSR-88D radar data for 13 continental, 10 marine MCSs, and 11 landfalling hurricanes using novel methodologies for processing and visualizing the radar data such as RD-QVP and CVP. Separate statistics of the vertical profiles have been examined for the high IWC (HIWC) areas in the storms and compared with their “background” environment.

An overarching conclusion of the study is that marine MCSs and tropical cyclones are characterized by smaller size ice in higher concentration compared to the continental MCSs. We believe that this is a new result because we are not aware of any systematic comparisons of the microphysical properties of ice in the tropical and continental storms performed in the previous studies. HIWC areas is primarily caused by a strong jump in a number concentration of ice particles rather than the increase of their size compared to the “background” environment. This may point to the homogeneous nucleation of excessive amounts of supercooled droplets and/or SIP as the possible origins of HIWC. We emphasize that our radar retrieval techniques are valid mainly in the stratiform parts of the storm systems where graupel and hail are usually absent. Therefore, the reported results of the microphysical retrievals are representative of the storm areas where radar reflectivity in ice does not exceed 30 dBZ.

The climatology presented in this study can be used as an observational reference for cloud models’ evaluation and optimization of their microphysical parameterization.

## Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

## Data Availability Statement

Data used here is obtained from National Centers for Environmental Information (<https://www.ncdc.noaa.gov/data-access>).

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