Statistical Analysis of Ice Microphysical Properties in Tropical Mesoscale Convective Systems Derived from Cloud Radar and In-Situ Microphysical Observations

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Abstract. This study presents a statistical analysis of the properties of ice hydrometeors in tropical mesoscale convective systems observed during four different aircraft campaigns. Among the instruments on board the aircraft, we focus on the synergy of a 94GHz cloud radar and 2 optical array probes (OAP; measuring hydrometeor sizes from 10µm to about 1cm). For two campaigns, an accurate simultaneous measurement of the ice water content is available, while for the two others, ice water content is retrieved from the synergy of the radar reflectivity measurements and hydrometeor size and morphological retrievals from OAP probes. The statistics of ice hydrometeor properties is calculated as a function of radar reflectivity factor measurement percentiles and temperature. Hence, mesoscale convective systems (MCS) microphysical properties (ice water content, visible extinction, mass-size relationship coefficients, total concentrations and second and third moment of hydrometeors size distribution) are sorted in temperature (thus altitude) zones, and subsequently each individual campaign is analysed with respect to median microphysical properties of the global dataset (merging all 4 campaign datasets). The study demonstrates that ice water content (IWC), visible extinction, total crystal concentration, and second and third moments of hydrometeors size distributions are similar in all 4 type of MCS for IWC larger than $0.1g\ m^{-3}$. Finally, two parameterizations are developed for deep convective systems. The first one concerns the calculation of the visible extinction as a function of temperature and ice water content. The second one concerns the calculation of hydrometeor size distributions as a function of ice water content and temperature that can be used in numerical weather prediction.

1 Introduction

Defining clouds and how they interact with the atmosphere is a major challenge in climate sciences and meteorology. Clouds play an important role in the evolution of the weather and climate on the Earth. They affect the dynamics and the thermodynamics of the troposphere, and impact the radiative transfer of energy in thermal and visible wavelengths by heating or cooling the atmosphere. In addition, clouds represent an important part of the hydrological cycle, due to evaporation and precipitation processes. Inversely, dynamic features such as the Madden Julian oscillation (MJO, perturbation of large scale circulation leading to an eastward propagation of organized convective activity) can also affect the development of deep convective clouds (Madden and Julian, 1994, 1971). Mesoscale Convective Systems (MCS) are complex clouds and are the result of specific synoptic conditions and mesoscale instabilities which lead to the development of cumulonimbus (Houze, 2004). The complexity of MCS is also relying on the dynamical, radiative, and precipitation characteristics which depend on the location in the evolving MCS (Houze, 2004). MCS can last several hours and can affect human societies in different ways. Indeed, MCS are often associated with hazardous weather events such as landslides, flash floods, aircraft incidents, and tornadoes, all which can cause loss of human lives.

Weather and climate models use rather simplified schemes to describe the ice hydrometeors properties. Parametrization disagreements due to larger uncertainties in the representation of ice properties in clouds (Li et al., 2007, 2005) lead to large variations in the quantification of ice cloud effects on climate evolution (Intergovernmental Panel on Climate Change Fourth Assessment Report). An accurate estimation of the spatiotemporal distribution of the Ice Water Content (IWC) is a key
5   parameter for evaluating and improving numerical weather prediction (Stephens et al., 2002). Underlying hydrometeor growth processes in MCS vary in time (growing, maturing, decaying phase) but also in space, in other words horizontally (distance from active convective zone) and vertically (as function of temperature).

A number of studies (Gayet et al., (2012); Lawson et al., (2010) and Stith et al., (2014)), demonstrate the presence of different type of ice hydrometeors in evolving MCS. In the active convective area, large super cooled droplets larger than 500μm until
10   *3mm, were observed near -4°C and rimed ice hydrometeors about the same size below -11°C. Also at -47°C large rimed particles about 2-3mm from updraft regions coexisting with small ice crystals about 100μm (pristine ice) were encountered. Near the convective zone of MCS (i.e fresh anvil) presence of pristine ice (about 100μm), aggregates of hexagonal plates (about 500μm to 1mm) and capped columns (about 500μm) has been reported (Lawson et al., 2010). In aged anvils, columns (~100μm), plates (~100μm), and small aggregates (about 200μm) are observed near -43°C while large aggregates about 2mm*
15   *and more are found at lower altitudes (-36°C). Also in the cirrus part of MCS bullet-rosettes about 500μm and less (more common for in situ cirrus (Lawson et al., 2010)) and chain-like aggregates from 100μm to about 1mm are found (aggregates of small rimed droplets caused by electric fields: Gayet et al., 2012; Stith et al., 2014).*

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With respect to ice particle density, Heymsfield et al., (2010) reported that ice particles seem to be denser near the convective part of MCS formed during the African Monsoon. Other studies have shown a variability of the mass-size relationship with
20   temperature and related altitude (Fontaine et al., 2014; Schmitt and Heymsfield, 2010), which appears to be essentially linked to the variability of ice hydrometeor shapes related to different growth regimes (vapour diffusion, riming, aggregation).

Due to above mentioned spatiotemporal variations of MCS the different mean tendencies (hydrometeor concentration, ice water content, coefficients of mass-size relationship) reported in former studies can be partly linked to the chosen observation strategy of the MCS (i.e flight track in MCS) which of course is related to particular objectives of respective field projects (i.e.
25   improvement of rain rate retrieval from satellite observations, icing condition at high altitude, comparison with ground radar observations, etc…).

Therefore the goal of this study is to investigate on the one hand the vertical variation of ice crystal properties in MCS (for example as a function of temperature) and on the other hand to study horizontal trends of ice microphysics at constant temperature levels. The latter will be accomplished by a composite analyses of microphysical properties and simultaneously
30   measured radar reflectivity factor (Z). *Investigations on the impact of vertical velocity has been performed asides, however no significant tendencies were found to allow us to present our results as function of vertical velocity.* A frequency distribution of the profiles of the radar reflectivity factor throughout the MCS as a function of temperature allows to divide the microphysical in situ measurements into eight zones. For these height reflectivity zones microphysical properties are analysed and compared between the eight zones, but also intercompared between different locations and associated measurement
35   campaigns where MCS were observed. Direct applications of this study are for example to improve retrievals of cloud properties from radar observations and also parameterization of ice properties in weather and climate models. Moreover, it can help identifying zones in MCS where numerical weather predictions fails in representing ice microphysics.

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Our statistical analysis is performed on cloud radar Doppler measurement and in-situ measurement. Cloud radar measurements include more than one million of data points of radar reflectivity factors and retrieved vertical velocities
40   *spanning from 170K to 273.15K (Temperature profiles from RASTA are calculating using re-analysis of ECMWF). And in-situ measurements include 55844 data points of 5 s duration in the temperature range from 215K to 273.15K.* The following second section describes the utilized datasets and their derived parameters used in this study. *The third section presents the analysis of radar reflectivity factors (Z) which provides the ranges of Z to perform the intercomparison between the four types*

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of MCS. Moreover, for each range of Z a statistical analysis of vertical velocity is presented to bind the vertical dynamic of MCS and ice microphysical properties. The section 4 present the methodology of intercomparison used in this study. And section 5, present the inter-comparison of the microphysical parameters as function of Z and T. The end of this section is dedicated to present shortly the results of the investigations performed about the impact of vertical velocity. The sixth section, provide the parameterization of visible extinction and the parameterization of ice hydrometeors distributions. The last section adds the discussion and conclusion.

Commenté [EF4]: R1#2

2 Data description

This study uses a data set where MCSs were observed in four different locations in the tropics and related to two different projects:

1. *Megha-Tropiques in Niamey, during July and August 2010: observation of continental MCS formed over the region of Niamey (Niger) during the West African Monsoon (Drigeard et al., 2015; Fontaine et al., 2014; Roca et al., 2015). These MCS developed over the continent. 7665 points of 5 seconds.*

2. *Megha-Tropiques in Maldives, during November and December 2011: observation of oceanic MCS developed over the southern part of the Maldives and related to the ITCZ (Inter Tropical Convergence Zone) in the Indian Ocean. (Fontaine et al., 2014; Martini et al., 2015; Roca et al., 2015). It includes MCS developed during the wet phase of MJO and two event with isolated convective systems developed during the dry phase of MJO. 3347 points of 5 seconds.*

3. *HAIC-HIWC in Darwin, from January to March 2014: observations of MCS formed over Darwin and the North-East cost of Australia during the North Australian Monsoon (Leroy et al., 2016; Protat et al., 2016; Strapp et al. 2016; Leroy et al. 2017, Fontaine et al. 2017). During this campaigns, MCS developed over the land, the ocean, and near the cost. 23265 points of 5 seconds.*

4. *HAIC-HIWC in Cayenne during May 2015: observations of MCS developed over the French Guyana during the peak of its raining season (Yost et al., 2018). Same as for Darwin, MCS developed over the land, the ocean, and near the cost. 21567 points of 5 seconds.*

Note that observations were performed in mature MCS. All four measurement campaigns were conducted with the French research aircraft Falcon-20 operated by SAFIRE (Service des Avions Francais Instrumentés pour la Recherche en Environnement). On board the Falcon 20 were mounted two optical array probes (OAP): the 2D-S (2D stereographic probe; Lawson et al., 2006) and PIP (Precipitation Imaging Probe; Baumgardner et al., 2011), the cloud radar RASTA operating at 94GHz (Protat et al., 2016; Delanoë et al., 2014). In addition, bulk IWC measurements *performed with the isokinetic evaporator probe (hereafter IKP-2 probe;* Strapp et al. 2016; Davison et al. 2010) were available for the HAIC-HIWC flight campaigns (Darwin and Cayenne).

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Commenté [EF6]: R2#8

Both OAP probes record black and white images of hydrometeors with a resolution of 10μm and 100μm (2D-S and PIP, respectively). They are used to derived the size of hydrometeors (Dmax [cm] in this study), their projected surface (S [cm2]), their concentrations as a function of their size (N(Dmax) [#/L/μm]). The sizes of hydrometeors span from 10 μm to 1.28 cm with Dmax calculated as a function of the projected surface of hydrometeors (taking the maximum of radius passing through its barycentre; see Figure 1 in Leroy et al., 2016).

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During both HAIC-HIWC campaigns, the IKP-2 probe was used to measure total condensed water, composed exclusively of ice water content (IWC [g m-3]) and water vapour, then IWC were deduced using in-situ measurement of relative humidity. However, IWCs< 0.1g m-3 are not considered in this study, due to IKP-2 uncertainties particularly important for low IWC measurements (see Strapp et al. 2016a). For both Megha-Tropiques campaigns, IWC was retrieved using simulations of the reflectivity factor Z, thereby using the approximation of ice oblate spheroids (Fontaine et al., 2017; Fontaine et al., 2014).

Results about accuracy of IWC retrieved from this method with regards to IKP-2 measurement are discussed in Fontaine et al., (2017).

The 94GHz RASTA radar measures *Z* and Doppler velocity *Vd* below and above the aircraft. RASTA has 6 antennas that allow measuring three non-collinear Doppler velocities, from which the 3 wind components (including the vertical air velocity) have been reconstructed (using the Protat and Zawadzki 1999 3D wind retrieval technique modified for the aircraft geometry). *Detailed description of data processing is documented in Leroy et al. (2016 and 2017), Protat et al. (2016), Strapp et al. (2016b), and Davison et al. (2016). These references give a processing description for both datasets of the HAIC-HIWC project. But, Megha-Tropiques datasets (Fontaine et al. (2014)) were reprocessed in order to undergo exactly the same version of processing tools for comparison reasons in this study.*

Moreover, investigations have been performed to detect supercooled water using Rosemount icing detector (Baumgardner and Rodi 1989; Claffey et al. 1995; Cober et al. 2001) and Cloud Droplet Probe measurement. Few cases of super cooled water were detected and remove from the dataset (Leroy et al., 2016). Hence, the dataset used in this study is using exclusively data collected where only ice particles were measured. Also, retrieval of IWC for the Megha-Tropiques project were not performed in mixed phase conditions (more details in Fontaine et al., (2014) and (2017)).

3 Radar observations

3.1 Radar reflectivity factors

In this section distributions of radar reflectivity factors *Z* from nadir and zenith profiles are investigated for the 4 datasets. Figure 1 shows percentiles of *Z* as a function of *T* measured with RASTA during the 4 airborne campaigns. The lines are colour coded as a function of the calculated percentiles (blue =1th, light blue = 10th, cyan =30th, green=50th, yellow=70th, orange=90th, and red=99th percentile). *The percentiles of Z are calculated for a merged dataset that include 11 flights for MT over Niamey, 11 flights for MT over Maldives, 19 flights for HAIC-HIWC over Darwin and 17 flights for HAIC-HIWC over Cayenne. Percentiles are not calculated as function of the number of profiles but by temperature ranges of 5K where only points with Z larger than -30dBZ are taken into account. Figure 1 shows that distributions of Z are not totally similar for all 4 airborne campaigns. MCS can expend over hundreds or thousands square kilometres, where size and repartition of their convective and stratiform areas can vary from one MCS to another. So the same sampling strategy in two different MCS would provide two different mean or median profiles of ice microphysics properties as function of T. But two different sampling strategy in the same MCS would have the same results. The idea of this study is to compare the properties of ice hydrometeors for different tropical MCS locations, thereby rendering comparable different MCS systems (as a function of temperature), through the analysis of the frequency distribution of profiles of Z dividing all MCS into eight zones. This strategy aims to reduce the impact of the different flight patterns and objectives for sampling MCS during each airborne campaigns used in this study.*

Note that Z at 94 GHz is linked to the ice water content (Fontaine et al., 2014; Protat et al., 2016), but also to the size distribution of ice hydrometeors, respective crystal sizes, and mean diameter (Delanoë et al., 2014).

Our motivation to choose the limits of Z ranges on what the statistic of ice hydrometeors properties holds in two facts. First, Figure 1 shows that the variability of Z at a given T is large and this variability of Z vary along the altitude. We can observe in Figure 1 that Z extend from about -20dBZ to 18 dBZ at 260K while it spread out from -10dBZ to 10 dBZ at 200K. So, this has to be considered if we want to sort our dataset as function of T and Z. So the limit of the Z range cannot be the same for each altitude has meeting ice hydrometeors linked to 15 dBZ or linked to -20dBZ at 200K is quiet impossible. The second fact holds on result on a former study. Indeed, Cetrone and Houze, (2009) used the profiling radar of TRMM satellite ((Tropical Rainfall Measuring Mission; Huffman et al., 2007) to demonstrate with frequency distributions of radar reflectivity Z as a function of height that higher Z occur more often in convective echoes of MCS (in West African Monsoon, Maritime Continent

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and Bay of Bengal) than in their stratiform echoes. This former study was performed with the 13GHz radar profiler on board TRMM satellite, which is more sensitive to the precipitating particles (large drops and large ice crystals). The radar used in our study is more sensitive to smaller size of hydrometeors, then it is more adapted to sort the properties of ice crystals presented in our study. Hence, this study presents ice microphysical properties in MCS as a function of temperature layers and also as a function of zones of reflectivity Z. In order to fix the limits of a limited number of Z levels, this study takes the percentiles of all merged campaigns datasets shown by the solid lines (all data) in Figure 1. This defines Z ranges as a function of height. Hereafter, these ranges will be called MCS reflectivity zones and numbered 1 to 8:

- *MCS reflectivity zone 1: $Z < Z^{1th}$*
- *MCS reflectivity zone 2 : $Z \in [Z(T)^{1th} ; Z(T)^{10th}[$*
- *MCS reflectivity zone 3 : $Z \in [Z(T)^{10th}; Z(T)^{30th}[$*
- *MCS reflectivity zone 4 : $Z \in [Z(T)^{30th}; Z(T)^{50th}[$*
- *MCS reflectivity zone 5 : $Z \in [Z(T)^{50th}; Z(T)^{70th}[$*
- *MCS reflectivity zone 6 : $Z \in [Z(T)^{70th}; Z(T)^{90th}[$*
- *MCS reflectivity zone 7 : $Z \in [Z(T)^{90th} ; Z(T)^{99th}[$*
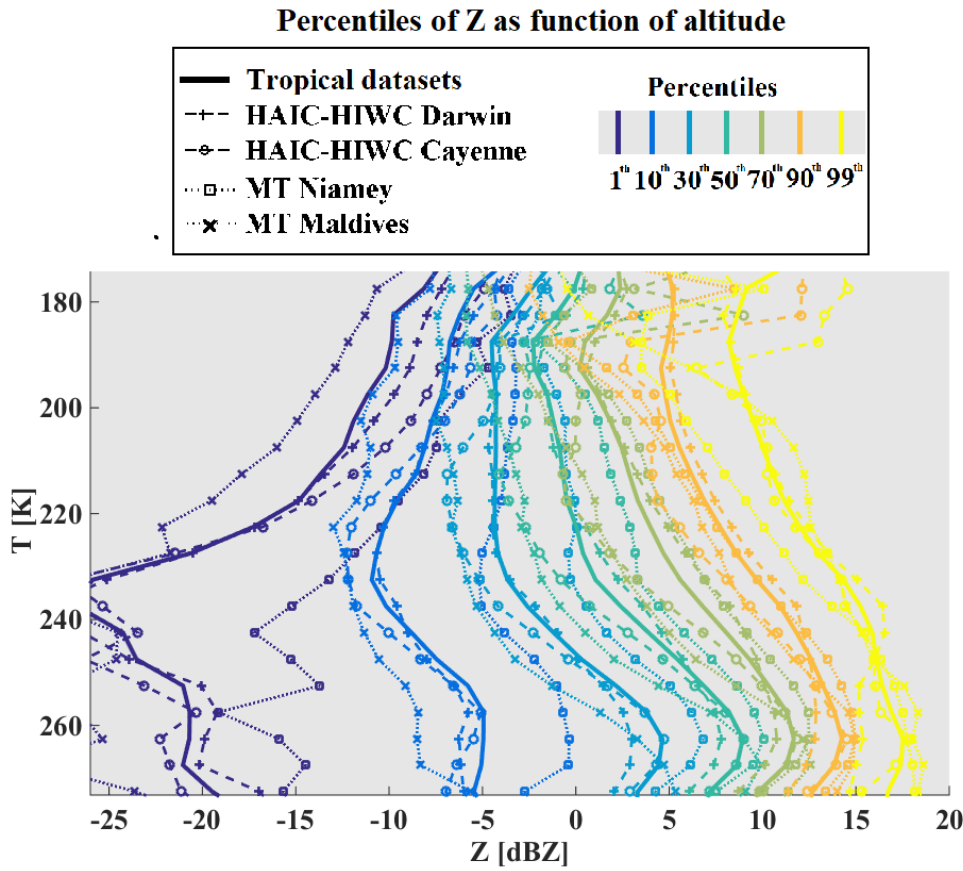- *MCS reflectivity zone 8 : $Z \geq Z(T)^{99th}]$*

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Figure 1: Median reflectivity factor *Z* and percentiles of radar reflectivity factors in dBZ on *x*-axis, as a function of temperature on *y*-axis.

Figure 2 shows an example of the method to store data as a function of *T* and MCS reflectivity zones. In Figure 2(a), we can

5   see original processed *Z* profiles for the flight 13 of HAIC-HIWC of the Darwin experiment. In Figure 2(b), eight colours

representing the above defined MCS reflectivity zones. This method is applied for all datasets thereby using all radar

reflectivity profiles (*Z* from Nadir and Zenith direction).
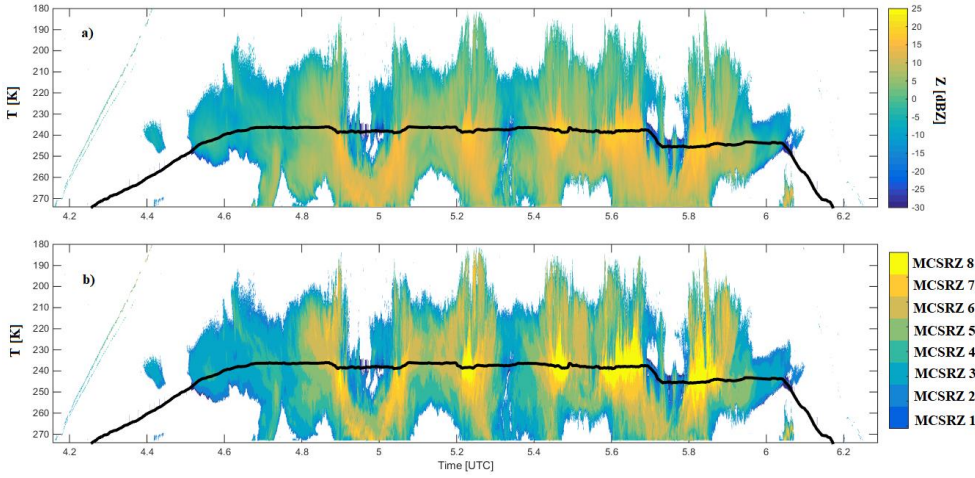
Figure 2: a) Time series of cloud radar profiles of flight 13 of HAI-HIWC at Darwin. Z color coded in dBZ and plotted as a function of the temperature (y-axis). b) Similar to a) with Z classified according to altitude dependent Z percentile ranges.

3.2 Retrieved vertical velocity in MCS reflectivity zones

5   *This section investigates links between retrieved vertical velocity and MCS reflectivity zones. We assume that Vz (V_d) = w_{ret} + V_t, where V_t is the terminal velocity of hydrometeors (Delanoë et al., 2007, 2014) and w_{ret} the vertical wind speed. In a first order, our study investigates variability of bulk microphysical properties of the icy part of MCS as function of temperature range and Z range (i.e. MCS reflectivity zones). As no clear tendencies have been found as function of vertical velocities, we decide to investigate the probability to observe significant vertical movement in each range of Z (or MCS reflectivity zones).*

10   *In other words, we investigate if there is any relationship between MCS reflectivity zones and vertical dynamic of MCS. We assume that convective part of MCS are associated with pronounced updraft and downdraft and that stratiform part of MCS have non-pronounced vertical velocity ($w\approx$0m.s-1) (see Figure 16 from Houze 2004).*

Figure 3 shows median updraft (w_{ret}>0) and downdraft (w_{ret}<0) in each MCS reflectivity zones (MCSRZ 2 to MCSRZ 8 from the top line to the bottom line respectively) and for each airborne campaign (Cayenne, Darwin, Maldives Island and Niamey,

15   *from left column to right column respectively). Black lines represent median updraft and downdraft for each respective airborne campaigns, while grey lines are median (solid line), 25th and 75th percentiles (dashed lines) and 10th and 90th percentiles (dotted lines) for the merged dataset. Black lines and grey lines are calculated using RASTA vertical profiles. The red stars are median downdraft and updraft when we use only vertical velocity measured by the aircraft (w; in-situ measurement).*

20   *We can observe a symmetry between updraft and downdraft in all MCS reflectivity zones for each campaigns, meaning that at a given altitude, absolute magnitude of downdraft is about the magnitude of updraft for median, 25th, 75th,10th and 90th calculated percentiles. For RASTA measurement, we can see that median updraft (w_{ret}>0m.s^{-1}) and median downdraft (w_{ret}<0m.s^{-1}) for each airborne campaigns agree well with median updraft and downdraft for the merged dataset in all MCS reflectivity zones. Except for Maldives observations where median w_{ret} are smaller for T < 255K. Also, median in-situ w tend*

25   *to be a bit smaller than median w_{ret}, except for updraft in Maldives above the bright band; $w\approx$2.5m.s^{-1} versus wret $\approx$1m.s^{-1}.*
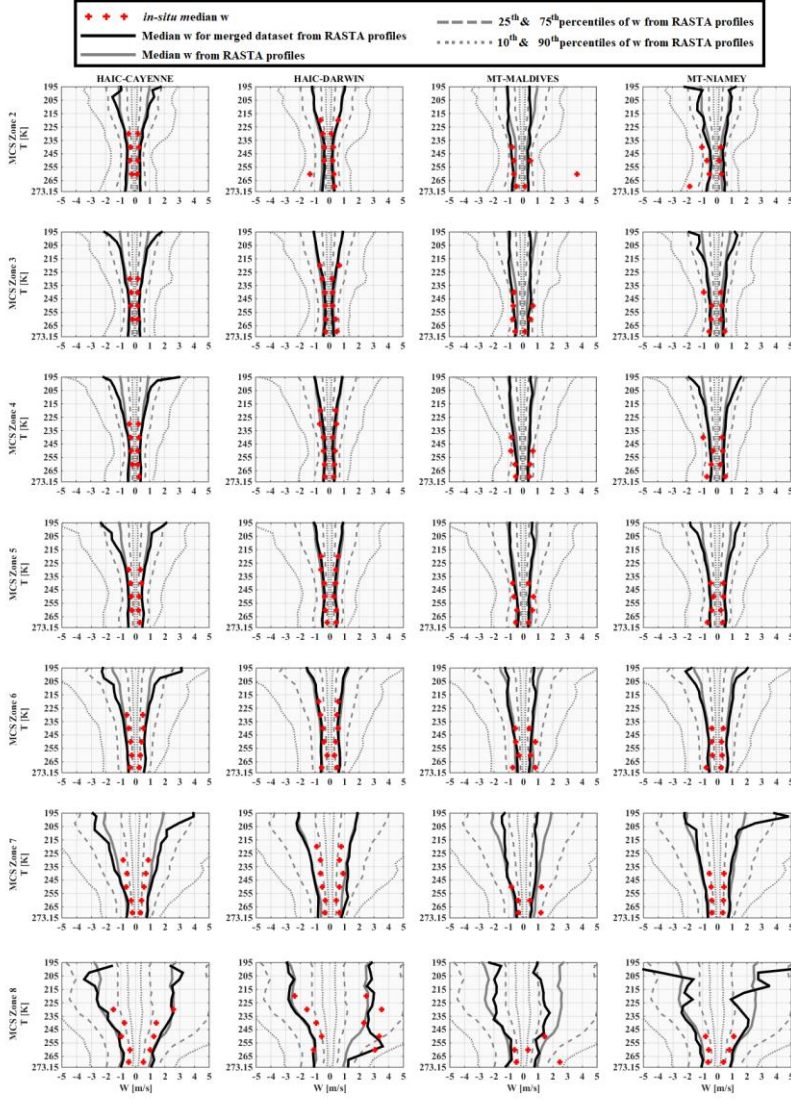
Figure 3: from the top line to the bottom line vertical velocities for MCS reflectivity zone 2 to MCS reflectivity zone 8.

In general the updraft and downdraft wind speeds increase with altitude and MCS reflectivity zones, where magnitudes of vertical velocity (negative and positive) are highest for MCS reflectivity zones 8. For all 4 datasets vertical wind speeds of MCS reflectivity zones 2-6 are smaller than $1m.s^{-1}$.

To complete our study on vertical dynamic that could exist in each MCS reflectivity zones, we study the probability to observe vertical movement. We use a threshold for vertical velocity to distinguish between discernible vertical movement and nearly not.

We take roughly a value of 1m/s to be the threshold to detect vertical movement, such -1m/s < w < 1m/s there is no noticeable vertical movement neither upward nor downward. The decision of taking a threshold of 1m/s for updraft and downdraft, is

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motivated by the fact that we have to take into account the measurement uncertainty (less than 0.25-0.5m.s-1). Moreover, knowing that variance of vertical turbulences are about 1.5 m^2/s^2 (Large Eddy Simulations at 50 m resolution; personal communication with Dr. R. Didier). The fact that median wret for the merged dataset in MCS reflectivity zones 2 to 6 are smaller than 1m.s-1 consolidate our decision to take a threshold of 1m.s^{-1}.

5   *Then, knowing T and Z, a probability to observe $| w_{ret} | \geq 1m\ s^{-1}$ is calculated as a function of MCS reflectivity zones and temperature. Colored solid lines in Figure 4 are probabilities calculated from RASTA measurement and dashed lines with stars are probabilities calculated with vertical velocity measured at the aircraft level (in-situ measurement). Both type of probabilities are different in each MCS zones and probabilities made with in-situ measurement are smaller than these calculated with RASTA retrievals; except in MCS reflectivity zones 8 in Darwin where they are similar. Hence, we know from*

10   *the point of view of vertical velocity that the in-situ dataset is not representative to the observations from RASTA retrievals: different probability to observe vertical velocity with magnitude larger than 1m/s (updraft and downdraft).*
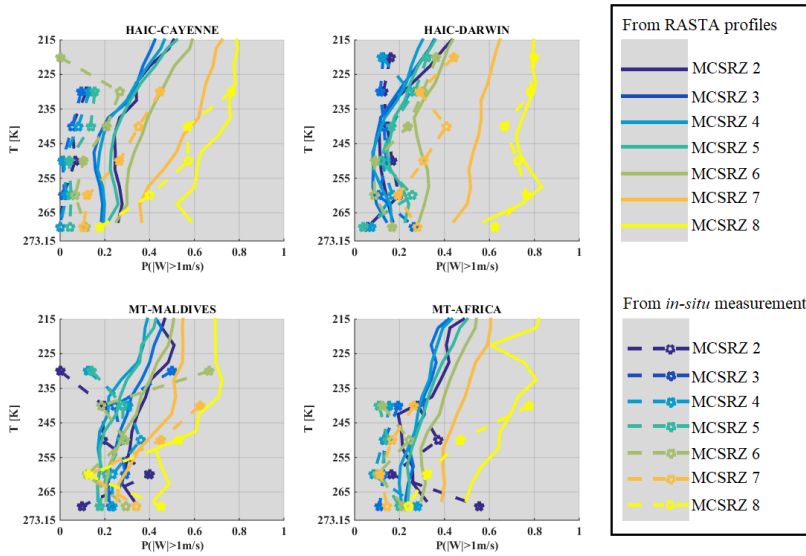

Figure 4: Probability to observe vertical velocity with absolute magnitude larger than 1m/s in each MCS reflectivity zone (MCSRZ; color scale) for measurement from the radar Doppler RASTA in solid lines and in dashed lines with stars marker

15 *for in-situ measurement.*

   In Figure 4 we show that probabilities to observe $| w_{ret} | \geq 1m\ s^{-1}$ are highest for MCS reflectivity zones 8 then 7 and 6, meaning that these MCS reflectivity zones tend to be more impacted by vertical movement (convective areas of MCS), than it is the case for other MCS reflectivity zones. Also, these probabilities generally increase with altitude for all airborne campaigns. Which meet the conclusions from Figure 3. Generally, in MCS reflectivity zones 5, 4, 3, and 2, the probabilities

20 *$P(|w_{ret} \geq 1|)$ as a function of T are close to each other with a decreasing trend as reflectivity decreases, except for the Maldives campaign. Statistically, MCS reflectivity zones 8 and 7 represent for all 4 datasets the most convective part of observed MCS and the lower reflectivity zones the stratiform part with significantly lower vertical wind speeds.*

   As a conclusion, at a constant altitude largest Z tend to be related with largest probabilities to observe vertical movement (downward or upward). In other words, MCS reflectivity zones 7 and 8 are good candidates to represent observations in the

25 *convective area of MCS or closer to the most convective part of MCS.*

Commenté [EF15]: R1#3

4 Method of intercomparison

This study compares and discusses a series of ice cloud properties, such as IWC, visible extinction, α and β coefficients of the dynamically retrieved m(D) power law, large crystal proxy of PSDs, crystal number concentrations N, PSD 2nd and 3rd moments (M_2 and M_3, respectively), and the ratio of IWC/M_2. The above mentioned ice hydrometeor properties in all 4 MCS locations will be investigated as a function of T and MCS reflectivity zones (range of Z given by percentiles of Z as a function of T) which have been introduced in section 3. In the subsequent section 5 a series of figures presenting results for above mentioned ice cloud properties (parameter X) will be presented in a uniform format. In all these Figures (5, 7, 9, 11, 13, 15, 17, 21, 23, 25) we show the median values of X, averaging MCS data from the 4 merged dataset (with 25th and 75th percentiles represented by whiskers), as a function of T and MCS reflectivity zones. The grey band shows 25th and 75th percentiles of the parameter for the entire merged dataset thereby merging data from all MCS reflectivity zones. 25th, median, and 75th percentiles of all parameters presented in the figures for the merged dataset are given in Annexe C, in order to allow comparison with other datasets and evaluation of numerical weather prediction models. If the range of variability of this median of parameter X in MCS reflectivity zone i defined by its 25th and 75th percentiles, does not overlap with corresponding ranges of variability of X defined by the 25th and 75th percentiles of MCS reflectivity zones i-1 and i+1, respectively, this makes the median (4 tropical campaigns) of X a candidate for X parametrization as a function of MCS reflectivity zone and T.

Then, in all these Figures (6, 8, 10, 12, 14, 16, 18, 22, 24, 26) we calculate the median relative difference in percent (hereafter MRD-X) for all 4 individual MCS datasets (Cayenne (a), Darwin (b) , Maldives (c), and Niamey (d)) with respect to the median of X as a function of MCS reflectivity zone and T.

In order to take into account the uncertainties in all type of measurements, uncertainties (hereafter noted U(X)/X) represented by grey bands on Figure showing MRD-X) for each parameter X were taken from Baumgardner et al. (2017). When the MRD-X is larger than $U(X)/X$, this means that there is a significant difference between the median of the studied parameter for the tropical dataset and the respective X of the selected individual MCS dataset. For the case that MRD-X is smaller than or equal to $U(X)/X$, the median of X of the tropical dataset, under the condition that the median (4 tropical campaigns) of X is distinguishable between neighboring MCS reflectivity zones, can be utilized for the respective type of MCS. Hence, if the latter case is true for all 4 MCS locations, then the median (4 tropical campaigns) of X is suitable to represent all 4 types (=location) of observed MCS.

Note that in all figures (Figures 5, 6, 8, 9, 10, 11, 12, 13, 14, 15 and 16) temperature of in-situ observations will be on the y axis and the color coded MCS reflectivity zones correspond to RASTA reflectivity statistics as a function of temperature. Measured/calculated parameters X are sorted into MCS reflectivity zones according to Z derived at flight level simultaneously to measured/calculated X parameter.

The comparison of ice hydrometeors' properties of the 4 MCS locations investigated in this study, will mainly focus on the question, if MRD-X (for individual MCS reflectivity zones) is larger or smaller than $U(X)/X$, also depending on MCS locations.

For each parameters presented in this study, either for the merged dataset or the campaigns individually (for calculation of MRD-X), the calculation are performed with the same conditions. The samples in each conditions (T bins and Z bins; Z bins vary as function of altitude, i.e. MCS reflectivity zones) have the same size for all parameters. Indeed, data points are selected if they meet the temperature and radar reflectivity criteria, but also the total concentration has to be positive (for Dmax >50μm); mixed phased conditions being excluded. So, the size of the samples (i.e. number of data points in each ranges of T and of Z) for NT, NT$_{50}$, NT$_{500}$, IWC, visible extinction, mass-size relationship coefficient, and max(D_{max}) are equal.

Commenté [EF16]: R2#11

Commenté [EF17]: R1#14

5.1 Ice water content

This section discuss about IWC measured during HAIC-HIWC project and the IWC retrieved for the Megha-Tropiques project.
IWC from the four dataset were merged to calculate the main statistic (merged dataset). Figure 5 shows median IWC for the
5　*merged dataset as a function of T and as function of MCS reflectivity zones (colored lines). Solely, the graphical representation*

is limited to medians of IWC for MCS reflectivity zones 4 to 8. Indeed, IWC in MCS reflectivity zones 2 and 3 are linked to
IWC smaller than 0.1 g m^{-3}, where IWC data are subject to less confidence. Globally, 30% of the data observed in 4 tropical
MCS have an IWC lower than 0.1g m^{-3}, and the lower limit of MCS reflectivity zone 4 is defined with the 30th percentiles of
Z. The figure reveals an IWC increases with increasing MCS reflectivity zone for a given range of temperature. IWC median
10　*values differ clearly as a function of the MCS reflectivity zone, and this for the entire range of temperatures, with only a few*
exceptions above the freezing level (T $\in$ [265 K; 273 K[), between MCS reflectivity zones 4 and 5, and MCS reflectivity zones
7 and 8, respectively, with small overlap in IWC ranges. In MCS reflectivity zones 4 to 7, median IWC increase with increasing
T between 215 K and 260 K (where IWC has its maximum) and then slightly decrease as T further increases towards 273K. In
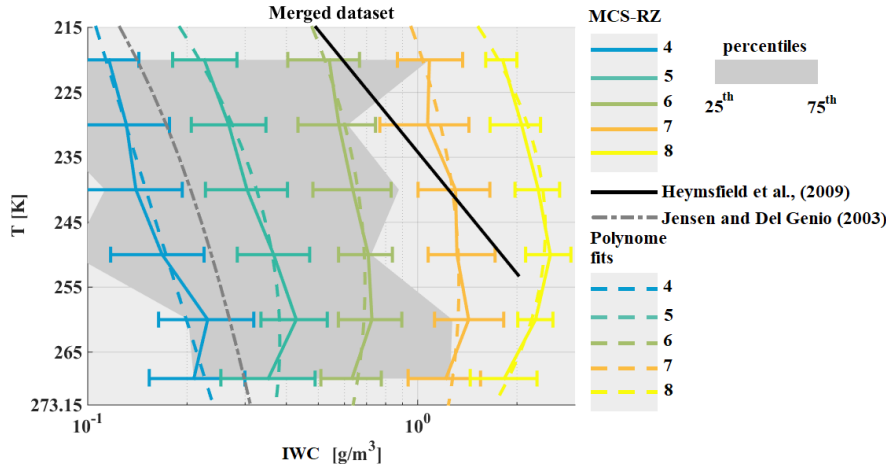*MCS reflectivity zone 8 IWC behaves rather similar with a maximum IWC already reached at 250 K.*

15
Figure 5: Median of IWC in [g/m^3] on x-axis, as a function of temperature in [K] on y-axis for different MCS reflectivity
zones. Results for the merged dataset including both MT and both HAIC-HIWC datasets. The grey band represents 25th
and 75th percentiles of merged dataset. Extremity of error bar show 25th and 75th percentiles of IWC in each MCS-RZ.

Figure 6 shows MRD-IWC for the four different campaigns. It is necessary that we recall that median IWC as function of T
20　*and MCS reflectivity zones are calculated using a merged dataset where there are IWC from direct measurement and retrieved*
IWC from Z and PSD (Fontaine et al., 2017). Then, there is two different uncertainties to consider to evaluate the MRD-IWC
in each campaigns. Firstly, for Darwin and Cayenne campaigns the IWC were measured with IKP-2 probe (direct
measurement) with an uncertainty on measured IWC increasing with temperature (~5% at 220K and ~20% at 273.15 K;
Strapp et al., 2016). Secondly, for Niamey and Maldives IWC were retrieved using the method described by Fontaine et al.,
25　*(2017) (indirect measurement) with an uncertainty with regards to the IKP estimated by about ±32%. Hence, in Figure 6-a)*
and Figure 6-b) the grey band area show the uncertainty of the IKP-2 probe that was used for Cayenne and Darwin campaigns.
While in Figure 6-c) and Figure 6-d) the grey band area describe the uncertainty on the retrieval method for IWC that was
used for datasets of Niamey and Maldives.

Note that confidence in direct bulk IWC measurements from the IKP-2 is significantly higher than in indirect IWC calculations from the retrieval method (Fontaine et al., 2017).
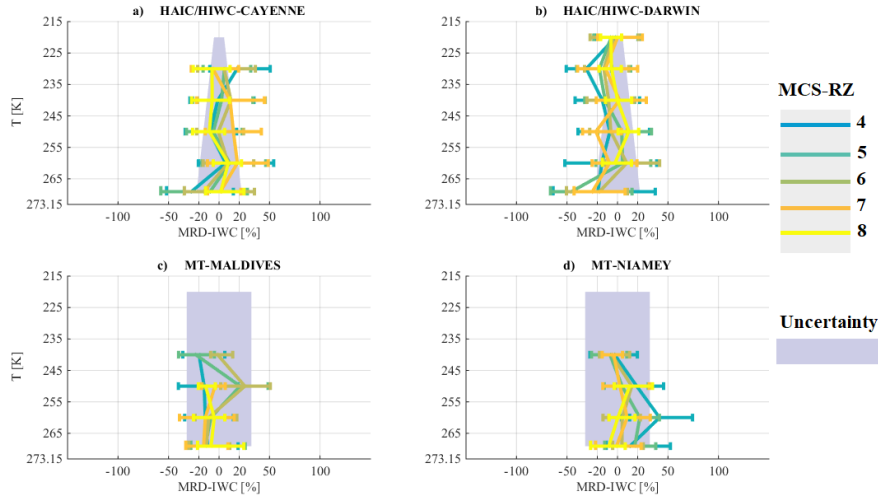
Figure 6: Median relative difference (MRD) of IWC during a) HAIC-HIWC in Cayenne, b) HAIC-HIWC in Darwin, c) Megha-Tropiques Maldives Islands and d) Megha-Tropiques in Niamey, with respect to median of IWC for the Tropical dataset on x-axis as a function of temperature in [K] on y-axis. The grey bands represent the uncertainties of the IWC measurement in b) and c), and the median deviation between measurement and the IWC retrieval method (Fontaine et al. 2016) in d) and e). Lines are colored as a function of the MCS reflectivity zones where in-situ measurement were performed, dashed colored lines are corresponding to the polynomial fit. Extremity of error bar show 25th and 75th percentiles of IWC relative error in each MCS reflectivity zone.

In addition, Figure 6(a), (b), (c), and (d) show MRD-IWC for all MCS reflectivity zones as a function of T. For all 4 tropical MCS, MRD-IWC in MCS reflectivity zones 4 to 8 are distributed around 0 and are in general less than 30-40% (25th to 75th percentiles). Measured IWC in MCS reflectivity zone 8 are in particular good agreement with the median IWC for all 4 tropical datasets, except maybe for high altitude MT-Niamey data. Uncertainty U(IWC)/IWC for IKP-2 measurements (Darwin and Cayenne) especially at high altitude (about 5%) is smaller than the expected deviation MRD-IWC. For mid and lower altitudes, MRD-IWC for Darwin and Cayenne particularly for zones 5 and 8 are of the order of corresponding U(IWC)/IWC. Concerning, MCS over Niamey and the Maldives Island, MRD-IWC (25th to 75th percentiles) in general do not exceed corresponding U(IWC)/IWC.

For comparison purposes with former studies, two IWC-T relationships from literature are added in Figure 5(a). Jensen and Del Genio (2003) suggested an IWC-T relationship in order to account for the limited sensitivity of the precipitation radar aboard the TRMM satellite, not allowing for small ice crystals at the top of convective clouds' anvils to be observed. They used radar reflectivity factors of a 35GHz radar based on Manus Island (North-East of Australia; 2.058°S, 147.425°E), thereby calculating IWC from an IWC-Z relationship (IWC=0.5*(0.5.$Z^{0.36}$); Jensen et al., 2002). The resulting IWC-T relationship given by Jensen and Del Genio (2003) is reported by a dashed-dotted grey line, which fits between 75th percentiles of merged median IWC of MCS reflectivity zone 4 and 25th percentile of MCS reflectivity zones 5. We recall that IWC, as a function of T, in MCS reflectivity zones 4 and 5 are related to Z between 30th-50th and 50th-70th percentiles, respectively. We may notice that the IWC-T relationship from Jensen and Del Genio (2003) is different and smaller than the median IWC (4 tropical campaigns). Hence, IWC-T relationship from Jensen and Del Genio (2003) is more adapted to stratiform part of MCS where convective movement occurs less often.

Moreover, Heymsfield et al., (2009) established an IWC-T relationship based on 7 fields campaigns (black line in Figure 5. They focused their study on maritime updrafts in tropical atmosphere for a temperature range T $\in$ [213.15K; 253.15K]. Their

suggested IWC tend to be in the range of IWC of MCS reflectivity zones 6- 8 with IWC increasing with T. We already showed in section 3.2 that MCS reflectivity zones 7 and 8 have higher probabilities to be convective (updraft regions with higher magnitudes of vertical velocity), as compared to other MCS reflectivity zones. Therefore, Heymsfield et al., (2009) IWC parametrizations for maritime updrafts are not inconsistent with data from this study.

5   *Overall, this section demonstrates that variation of IWC with the temperature is similar in all type of MCSs for corresponding ranges of radar reflectivity factors. Hence, we assume that IWC-Z-T relationships developed in Protat et al., (2016) is usable for all types of MCS in the Tropics, at least for IWC larger than 0.1g m⁻³.*

5.2 Visible extinction

Figure 7 shows visible extinction coefficients (σ) calculated from OAP 2D images (approximation of large particles; Van de
10   *Hulst, 1981):*

$$\sigma = 2 \cdot \sum_{15\mu m}^{12845\mu m} N(D_{max}) \cdot S(D_{max}) \cdot \Delta D_{max} \qquad [m^{-1}] \qquad (1)$$

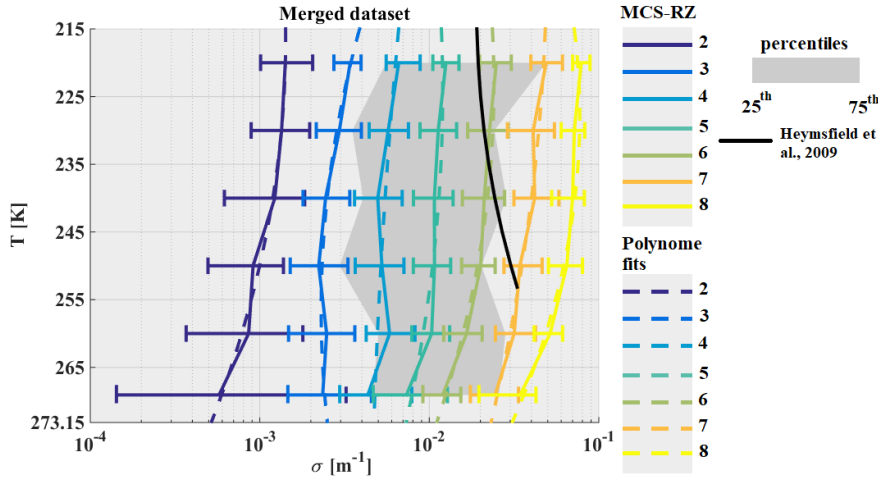**Figure 7: Same as Figure 5 but for visible extinction σ given on x-axis in m⁻¹.**

In Figure 7, median σ (4 tropical campaigns) increase with MCS reflectivity zone as expected, and also increase with altitude
15   *(decrease with T), with larger gradients for T ∈ [245; 273.15] than for T ∈ [215K; 245K].*

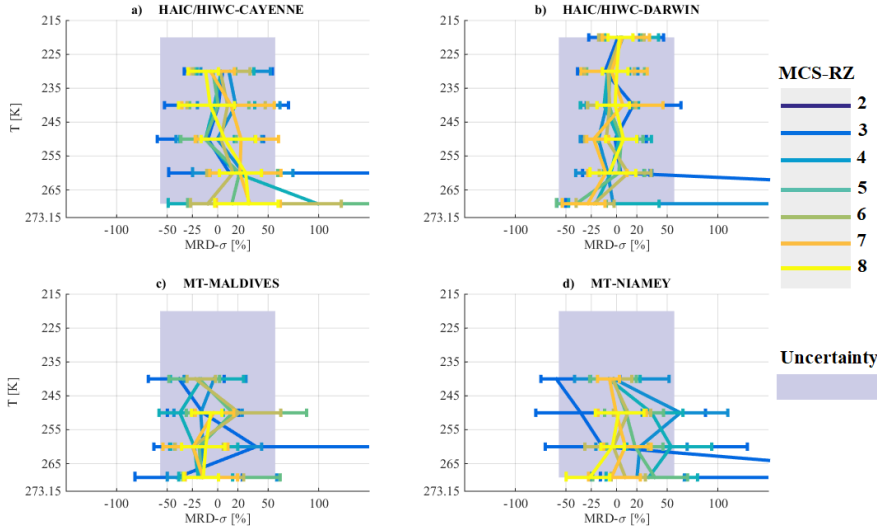*Figure 8: Same as Figure 6 but for visible extinction MRD-σ.*

The uncertainty (U(σ)/σ) (grey band in Figure 8(a) to Figure 8(d)) is calculated as follows:

$$\frac{U(\sigma)}{\sigma} = \sqrt{2 \cdot \frac{U(D)^2}{D} + \frac{U(N)^2}{N}} = \pm 57\% \qquad (2)$$

With $\frac{U(D)}{D} = \pm 20\%$, taking into account the uncertainty in the calculation of the size of hydrometeors and $\frac{U(N)}{N} = \pm 50\%$ for the uncertainty on the calculation of the concentration of hydrometeors from optical array probes (Baumgardner et al., 2017). Above uncertainties are those for particles larger than 100 μm. Note, that if we took uncertainties for particles smaller than 100μm (with (U(D))/D=±50% and (U(N))/N=±100%) the uncertainty on the calculation of σ would increase to ± 122%. The reason why we do not take into account uncertainty of smaller particle is due to that these particles contribute little to the visible extinction (2% in the range [235K; 273.15] and 10% in the range [215K; 225K].

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For all 4 types of tropical MCS, MRD-σ shown in Figure 8(a), 8(b), 8(c), and Figure 8(d) are in general smaller or equal to $\pm \frac{U(\sigma)}{\sigma}$. Hence, visible extinction in tropical MCS tend to be similar for all types of MCS observed in the same range of T and MCS reflectivity zone. Also MRD-σ trends are very comparable to above discussed MRD-IWC trends.

Furthermore, a σ–T relationship from Heymsfield et al. (2009) (black line) is added in Figure 7, which is calculated, as a function of T, as the sum of the total area of particles larger than 50μm plus the total area of particles smaller than 50 μm multiplied with a factor of 2 in order to satisfy Eq. (1) and to compare with results of this study. We conclude that σ–T estimation presented in Heymsfield et al. (2009) for maritime convective clouds is rather comparable to median σ calculations (merged dataset) in MCS reflectivity zones 6 to 7 corresponding to higher reflectivity zones, and thus statistically to zones with some remaining convective strength.

5.3 Concentration of ice hydrometeors

Subsequently are presented observed total concentrations for the merged datasets integrating particle sizes beyond 55μm ($N_T(D_{max} > 55\mu m)$; hereafter $N_{T,55}$):

$$N_T(D_{max} > 50\mu m) = \sum_{Dmax=55}^{Dmax=12845} N(D_{max}) \cdot \Delta D_{max} \qquad [L^{-1}] \qquad (3)$$

14

Median of $N_{T,55}$ as a function of T and MCS reflectivity zones are shown in Figure 9 as well as MRD-$N_{T,55}$ for the 4 tropical MCS locations in Figure 10 (a), 10(b), 10(c), and 10(d). We observe an increase of median $N_{T,55}$ with altitude for all MCS reflectivity zones. Also $N_{T,55}$ increases with MCS reflectivity zones for a given T, with highest $N_{T,55}$ in MCS reflectivity zone 8. The range of variability for $N_{T,55}$ reveals significant overlap of 25th and 75th percentiles of neighboring MCS reflectivity zones.
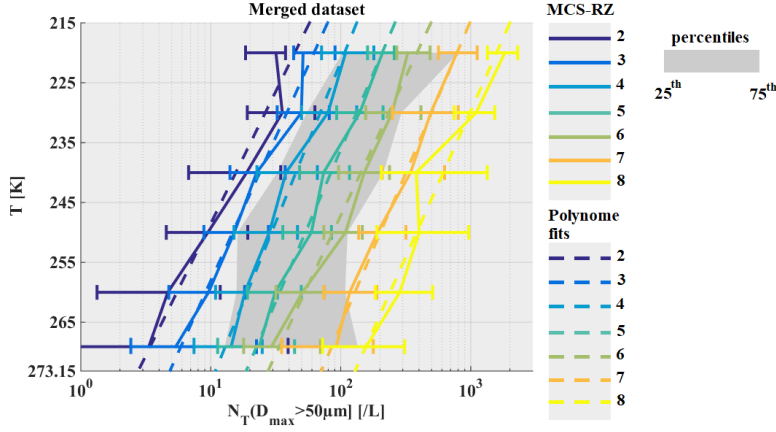

5

Figure 9: Same as Figure 5, but for total concentrations integrated beyond $D_{max}=55\mu m$ in $[L^{-1}]$.

Figure 10 show MRD-NT55 where measurement uncertainty on concentrations are assumed ±100% (Baumgardner et al., 2017). MRD- $N_{T,55}$ in 4 different tropical MCS locations, particularly for higher MCS reflectivity zones are of the order and even larger (75th percentile MRD-$N_{T,55}$) than the measurement uncertainty. Even if the limit of concentrations of ice

10 *hydrometeors are not well defined between neighboring MCS reflectivity zones (Figure 9). These concentrations tend to be similar for a given range of T and Z for the four different MCS locations.*

A similar investigation is performed for total concentrations integrating beyond 15 μm (NT). Since major conclusion are similar to these given for NT55, figures for NT are shown in Appendices A. Globally, median of $N_{T,55}$ for the tropical dataset are smaller by about one order of magnitude with respect to the median of N_T for the same MCS reflectivity zone. And NT over

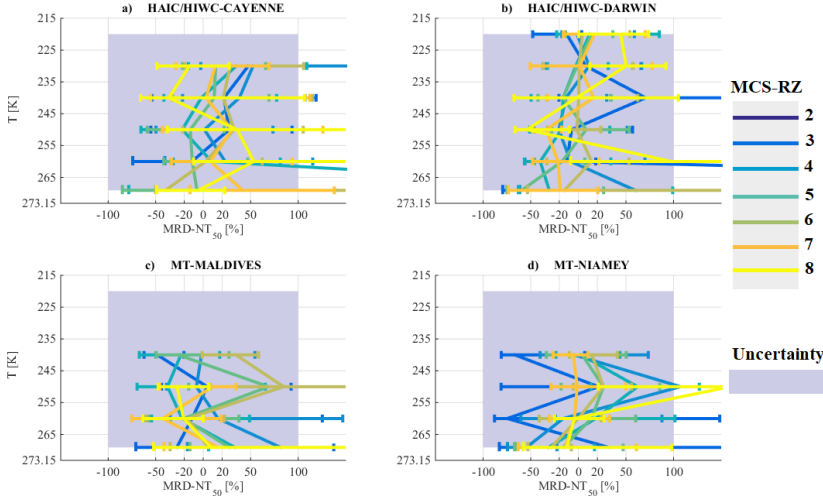15 *Maldives tend to be larger than median NT for the merged dataset.*

15

Figure 10: Same as Figure 6, but for MRD-NT₅₀.

Finally, Figure 11 shows concentrations of hydrometeors when number PSD are integrated only beyond 500µm (hereafter $N_{T,500}$; eq. (4)), where the uncertainty on their measurement is estimated as about ±50% for hydrometeors larger than 100µm (Baumgardner et al., 2017).

$$N_T(D_{max} > 500\mu m) = \sum_{Dmax=505}^{Dmax=12845} N(D_{max}) \cdot \Delta D_{max} \qquad [L^{-1}] \tag{4}$$
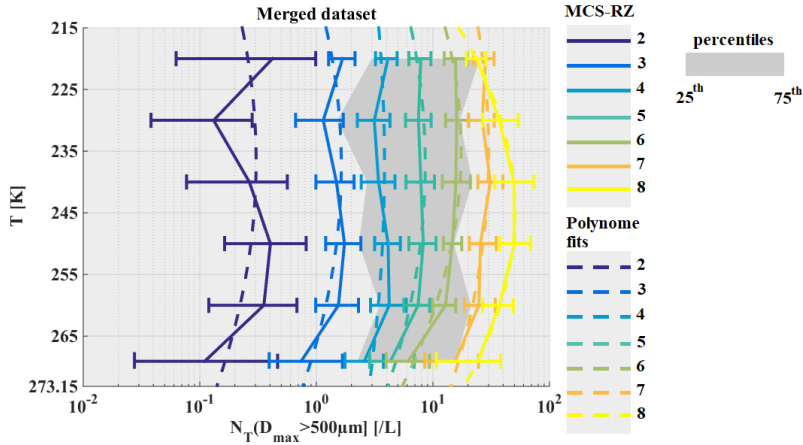
Figure 11: Same as Figure 5, but for concentrations of hydrometeors integrated beyond D_{max} =500µm in [L^{-1}].

In Figure 11 median $N_{T,500}$ are presented as a function of T and MCS reflectivity zone. The curves of median $N_{T,500}$ are different from curves of median N_T and $N_{T,55}$. Indeed, particularly for higher MCS reflectivity zones and in lower altitude levels (T ∈ [250K; 273.15K]), $N_{T,500}$ tends to increase with altitude, reaches a maximum value around T ∈ [235K; 250K], and then rather decreases for T ∈ [215K; 235K]. The range of variability for $N_{T,500}$ reveals a rather small overlap, if any, of 25th and 75th percentiles of neighboring MCS reflectivity zones 8, 7, and may be 6, mainly at coldest T ∈ [215K; 225K]. No overlap for

16

MCS reflectivity zones 2-5 and concentration of ice hydrometeors beyond 500µm are rather constant from 215K to 265K for observations in MCS reflectivity zones 3 to 5.
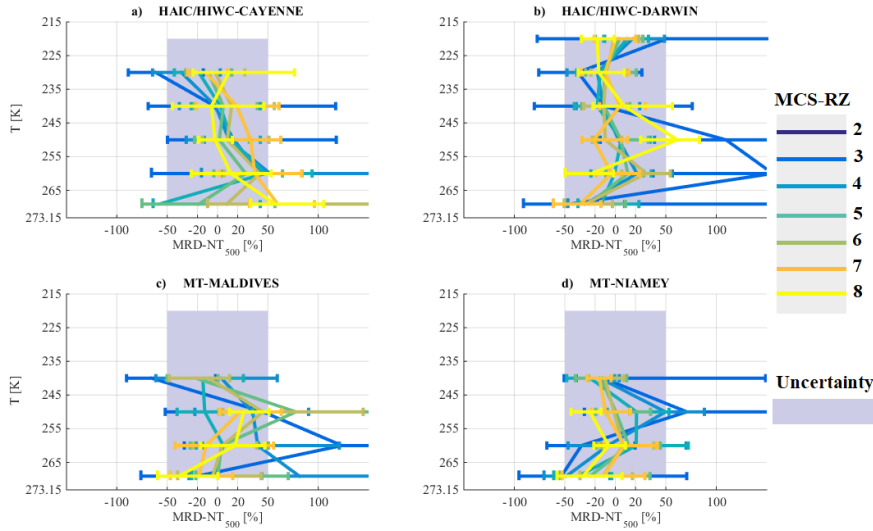

Figure 12: Same as Figure 6, but for MRD-NT$_{500}$.

5 *Figure 12 (a), 12(b), 12(c), and 12(d) reveal that MRD-N$_{T,500}$ in higher MCS reflectivity zones are considerably smaller or roughly equal to the measurement uncertainty for large hydrometeors. Some smaller exceptions are noticeable where MRD-N$_{T,500}$ are larger than the measurement uncertainty for very low altitudes at T $\in$ [265K; 273.15K[, namely Cayenne in MCS reflectivity zones 7 and 8, and Darwin in MCS reflectivity zone 8. Note, that in general MRD-N$_{T, 500}$ have smaller 75th percentiles (from Figure 10 (b), 10(c), 10(d), and 10(e)) compared to respective MRD-N$_{T,55}$ and MRD-N$_T$, showing that*

10 *variability in each MCS reflectivity zone for hydrometeors larger than 500µm is smaller than the variability of concentrations which include smaller (N$_{T,55}$) and smallest (N$_T$) hydrometeors. This finding is clearly related to the uncertainty estimation given by (Baumgardner et al., 2017)) that small hydrometeors (D$_{max}$< 100µm) have a larger estimated uncertainty of 100% (due to shattering, very small sample volume), compared to the uncertainty of only 50% for larger hydrometeors (D$_{max}$>100µm). Hence, it is not surprising that variability around a median value is larger for N$_T$ and N$_{T,55}$ than for N$_{T,500}$. It*

15 *is important to resume here that not just MRD-N$_{T,500}$ is smaller than the uncertainty of 50%, but also that MRD-N$_{T,500}$ is tremendously smaller than MRD-N$_{T,55}$ and MRD-N$_T$. Even though we have to keep in mind that we'll never have sufficient statistics in flight data, due to sampling bias of flight trajectories and variability of microphysics from one system to another. Indeed, Leroy et al., (2017) demonstrated that median mass diameter MMD$_{eq}$ generally decrease with T and increasing IWC for the dataset of HAIC-HIWC over Darwin. However, for two flights performed in the same MCS, Leroy et al., (2017) showed*

20 *that high IWC were linked to large MMD$_{eq}$, where MMD$_{eq}$ tends to increase with IWC. This demonstrates that comparable high IWC can be observed for two different microphysical conditions (short-lived typical oceanic MCS versus long lasting tropical storm in one and the same dataset).*

We observe that total concentrations starting from 15µm can be different between MCS locations as a function of T and Z, especially in oceanic MCS over Maldives Islands in the more stratiform part of these MCSs where measured concentrations

25 *can reach 10 times the median concentrations observed globally for merged tropical dataset. Also MCS over Niamey show*   **Commenté [EF22]:** R2#14

larger concentrations near the convective part of MCS. However, concentrations of ice hydrometeors beyond 55µm tend to be more similar as function of T and Z, even if the limits between each MCS reflectivity zones are not well defined.

Between 4 MCS locations, differences of aerosol loads and available ice nuclei might exist. Despite those possible differences, ice crystal formation mechanisms may be primarily controlled by dynamics, thermodynamics and particularly by secondary ice production rather than primary nucleation; (Field et al., 2016; Phillips et al., 2018; Yano and Phillips, 2011) that regulate the concentrations of hydrometeors beyond ~55µm making these concentrations quiet rather similar for different MCS locations.

5.4 Coefficients of mass-size relationship

The relationship between mass and size of ice crystals is complex. Usually in field experiments the mass of individual crystals is not measured, instead bulk IWC is measured which is the integrated mass of an ice crystal population per sample volume to be linked to PSDs of ice hydrometeors. Yet IWC is not always measured or with low accuracy. Due to the complex shape of ice hydrometeors, various assumptions allow to estimate the mass of ice crystals for a given size. Indeed, many habits of ice crystals can be observed in clouds, primarily as a function of temperature and ice saturation (Magono and Lee, 1966; Pruppacher et al., 1998). Also hydrometeors of different habits can be observed at the same time (Bailey and Hallett, 2009). Locatelli and Hobbs (1974) and Mitchell (1996) suggested mass-size relationships represented as power laws with $m = \alpha \cdot D^\beta$ for different precipitating crystal habits. Coefficients α and β vary as a function of the ice crystals habit. Further studies performed calculations of mean mass-size relationships (also using power law approximations) retrieved from simultaneous measurements of particle images combined with bulk ice water content measurements (Brown and Francis, 1995; Cotton et al., 2013; Heymsfield et al., 2010). Schmitt and Heymsfield (2010), Fontaine et al (2014), Leroy et al. (2016) showed that mass-size relationship coefficients α and β vary as a function of temperature. In the latter studies, coefficient β is calculated from OAP images, and then α is retrieved either also from processed images or constrained with integral measured IWC or radar reflectivity factor Z. Recently, Coutris et al (2017) retrieved masses of hydrometeors by an inverse method using direct measurement of PSD and IWC. In this latter study, the mass of ice crystals is retrieved without any assumption on the type of function linking mass and size of ice hydrometeors.

This study uses the power law assumption to constrain the mass of ice hydrometeors. Thereby, the β exponent of the mass-size power law relationship is calculated (eq. 7) as presented in Leroy et al (2016) for hydrometeors defined by D_{max} dimension:

$$\beta = 1.71 \cdot f_s - 0.62 \cdot f_p \tag{5}$$

Here f_p is the exponent of the perimeter-size power law relationship (Duroure et al. 1994) with $P(D_{max}) = e_p \cdot D_{max}^{f_p} \ [cm]$ and f_s is the exponent of the 2D image area-size relationship (Mitchell, 1996) with $S(D_{max}) = e_s \cdot D_{max}^{f_s} \ [cm^2]$. These two relationships are calculated using Images from 2D-S and PIP. Hence, β is a proxy parameter that describe the global (all over the size range of hydrometeors from 50µm to 1.2cm) variability of the shape of the recorded hydrometeors during the sampling process (Leroy et al., 2016; Fontaine et al., 2014). Figure 13 shows the variability of β as a function of temperature and MCS reflectivity zones for the merged dataset. For a given MCS reflectivity zone, β increases with increasing temperature. Also for a given temperature, β increases with MCS reflectivity zone, although MCS reflectivity zones 4, 5, 6, 7, and 8 share a range of common values for β, making it more uncertain to predict with a good accuracy using a parametrization as function of IWC and T.

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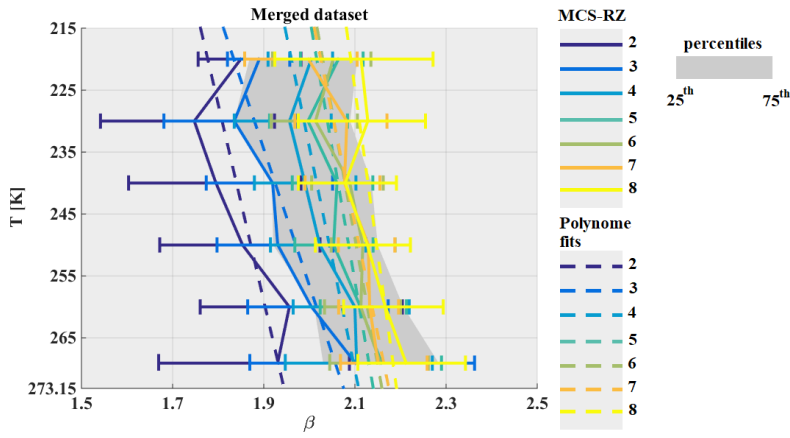
Figure 13: As Figure 5, but for exponent β of mass-size relationships for used ice hydrometeor size definition D_{max}.
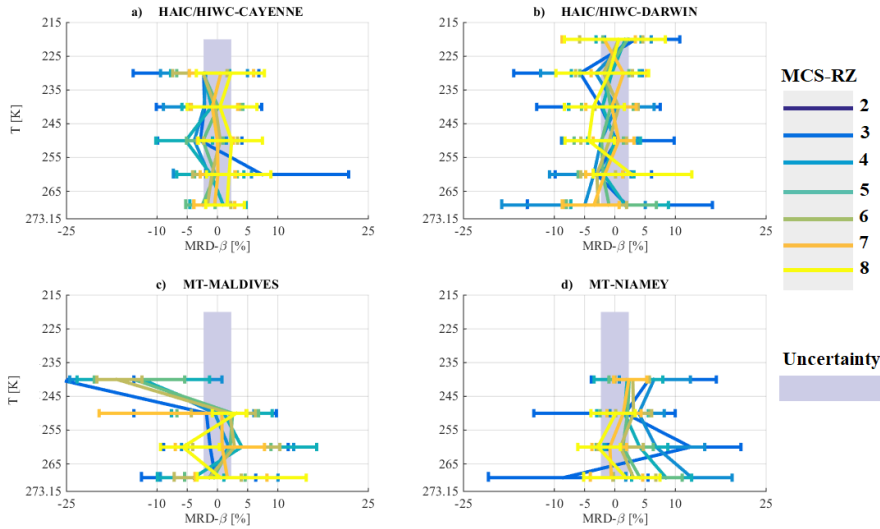
Figure 14: As Figure 6, but for exponent MRD-β.

In order to estimate the uncertainty on the calculation of β (grey band in Figure 14 (a), (b), (c), and (d), results from (Leroy et al., 2016) have been utilized, with U(β)/β=±2.3%. However, if we have calculated the uncertainty on retrieved β from the uncertainty on the measurement of the size and concentration of hydrometeors from OAP images, the uncertainty would have been by about 44%. In general, MRD-β in MCS reflectivity zones 8 and 7 tend to be in the range of U(β)/β assuming that β are similar for all observed MCS in the four campaigns for the conditions described by MCS reflectivity zones 7 and 8.

However, in MCS reflectivity zones 2 to 6 MRD-β are more scattered around U(β)/β with sometimes larger MRD-β than uncertainty of β. Especially for MCS over Maldives and Niamey. Over Maldives at higher altitudes β tend to be smaller compared to the median β calculated for the merged dataset. While, MCS over Niamey tend to have β larger than median β calculated for the merged dataset.

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Overall, the predictability of β coefficients as a function of T and MCS reflectivity zone remains challenging. We are aware of the fact that the power-law approximation has certain limits, trying to impose one single β to an entire crystal population composed of smaller (dominated by pristine ice) and larger crystals (more aggregation, also riming).

5 ***Figure 35: Same as Figure 5, but for α of mass-size relationships for used ice hydrometeor size definition D_{max}.***

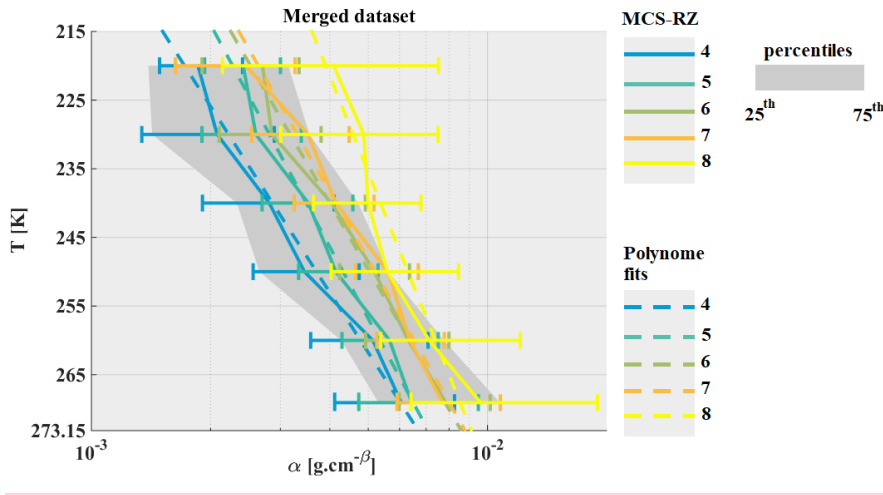*For HAIC-HIWC data, coefficients α are retrieved, while matching measured IWC from IKP-2 with calculated IWC thereby integrating PSD times m(D) power law relationship. For Maldives and Niamey datasets, coefficients α are retrieved from T-matrix simulations of the reflectivity factor (Fontaine et al., 2017).*

For both situation, α calculation is solely constrained by the fact that the mass of ice crystals remains smaller or equal than
10 *the mass of an ice sphere with the same diameter D_{max}:*

$$\alpha = \frac{IWC}{\sum_{15}^{12845} N(D_{max}) \cdot D_{max}^{\beta} \cdot \Delta D_{max}} \quad | \quad \alpha \cdot D_{max}^{\beta} \leq 0.917 \cdot \frac{\pi}{6} \cdot D_{max}^{3} \qquad [g\ cm^{-\beta}]. \tag{6}$$

For the uncertainty calculation of α we take the maximum value of β which is 3:

$$\frac{U(\alpha)}{\alpha} = \sqrt{\left(\frac{U(IWC)}{IWC}\right)^2 + 3 \cdot \left(\frac{U(D)}{D}\right)^2 \left(\frac{U(N)}{N}\right)^2} \tag{7}$$

Figure 15 shows median α coefficients as a function of T and MCS reflectivity zone. As has been already stated in previous
15 *studies, α is strongly linked to the variability of β (Fontaine et al., 2014; Heymsfield et al., 2010). Figure 15 compared to Figure 13 confirms that results for α have similar trends as those discussed for β. α vary from 5.10^{-4} (in MCS reflectivity zone 2) to $\approx 2.10^{-2}$ (in MCS reflectivity zone 8). In general, α increases as a function of T for a given MCS reflectivity zone and also increases as a function of MCS reflectivity zone (and associated IWC) for a given T level. As already stated for the median exponent β in Figure 13, median α in MCS reflectivity zones 4, 5, 6, 7 and 8 are more or less overlapping. ~~Median α in MCS~~*
20 *~~reflectivity zones 2 and 3 are shown for completeness reasons, however with less confidence as they are related to IWC generally smaller than 0.1g m⁻³.~~*
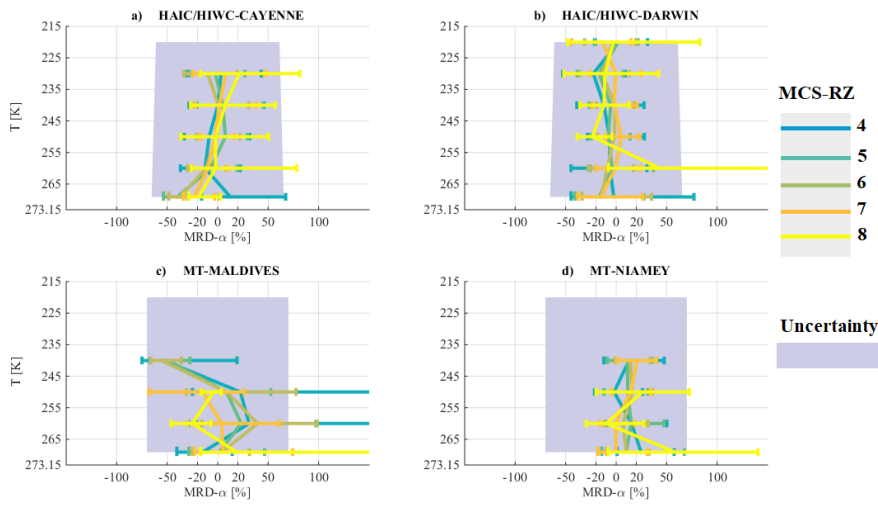
Figure 16: As Figure 6, but for exponent MRD-α.

From Figure 16(a) and Figure 16(b) we can note that even with a good accuracy of the measured IWC (from IKP-2; U(IWC)/IWC ≈ ±5% for the typical IWC values observed in HAIC-HIWC at 210K), the uncertainty of α, is rather large which is mainly due to uncertainties in OAP size and concentration measurements. Taking into account the large uncertainty on the retrieved α, we find that MRD-α for all 4 tropical datasets for MCS reflectivity zones 4, 5, 6, 7, and 8 are smaller than U(α)/α. For data from Niamey (Figure 16 (d)), α tend to be larger than median α for the tropical dataset (MRD-α not centered on 0, but shifted to positive values).

In previous sections, this study documented similar IWC values and visible extinction coefficients for a given range of Z and T and a clear increase of IWC and visible extinction coefficient from MCS reflectivity zones 4 to 8. The increase of α and β with MCS reflectivity zones is not as much clearly visible, whereas at least α seems to increase with temperature in different MCS reflectivity zones). And we cannot ignore that α and β tend to be larger in MCS reflectivity zone 8 than in MCS reflectivity zone 4, especially at higher altitude. But, the increase of IWC and visible extinction with MCS reflectivity zone Z is not linked to an increase of the mass-size coefficients. This conclusion takes into account the variability of the mass-size coefficients shown by 25 and 75 percentiles. Moreover, ice hydrometeors habits describe with β in MCS reflectivity zone 4, 5 and 6 are different in MCS over Maldives and MCS over Niamey compared to MCS over Darwin and Cayenne (smaller β over Maldives and larger β over Niamey).

As visible extinction (hence projected surface) and IWC are similar for the same range of T and Z in all types of MCS, but the shapes of crystals might be different from one to another MCS location. Our assumptions is that the ratio of projected surface vs IWC is similar. In other words the density of ice per surface unity (or by pixels of projected surface) is similar as function of T and Z in all types of MCS even if there might be a possibility that the habit or the shape can be different (pure oceanic MCS vs pure continental MCS). Note that these assumptions are established for IWC larger than 0.1g.m⁻³.

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5.5 Largest ice hydrometeors

Figure 17 investigates the variability of the size of the largest ice hydrometeors in the PSD (hereafter max(D_max) as defined in Fontaine et al (2017)). Figure 17 reveals globally for all MCS reflectivity zones that the median of max(D_max) increases with T, with larger hydrometeors at cloud base compared to cloud top, particularly in the stratiform cloud part, where PSD are mainly impacted by a combination of aggregation and sedimentation. At higher levels for T ∈ [215K; 245K[largest median

of max(D_{max}) are observed in the most convective MCS reflectivity zone 8, followed by zones 7, 6, and 5, where sedimentation becomes more and more active. Below the 250K level, largest max(D_{max}) can be observed in MCS reflectivity zones 6 and 7 (still significant sedimentation source from above), followed by 5 (increasing depletion of large crystals) and 8 (more convective or at least transition zone from convective to stratiform cloud part). Smallest max(D_{max}) are observed in MCS

5 *reflectivity zones 2 and 3.*
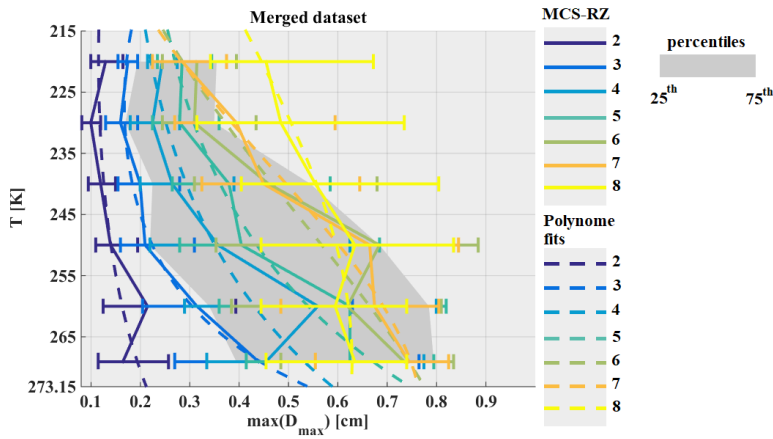
Figure 17: As Figure 5, but for maximum size of hydrometeors max(D_{max}) in PSD in [cm].

MRD-max(D_{max}) shown in Figure 18(a), 18(b), 18(c), and 18(d) are a bit larger than the measurement uncertainty estimated with ±20% ((Baumgardner et al., 2017). Cayenne, Darwin, and Niamey data are centered around the median max(D_{max}) of

10 *the 4 tropical datasets in MCS reflectivity zone 8 for all type of MCSs, in MCSs reflectivity zone 7 in MCS over Darwin, Cayenne and Niamey. MCSs over Cayenne et Darwin tend to have similar max(D_{max}) in other MCS reflectivity zones. Maldives dataset shows mainly negative MRD-max(D_{max}) values, indicating that max(D_{max}) for the Maldives Island data are generally smaller than those of the other three tropical datasets. Also MCS over Niamey show larger max(D_{max}) in MCS reflectivity zones 2 to 4, illustrating that snow aggregates can reach larger sizes during the West African monsoon than in other MCS*

15 *locations. It confirms conclusions from Frey et al., (2011) and Cetrone and Houze (2009), who suggest that there are larger ice hydrometeors in MCS over continent than MCS over maritime regions.*

Commenté [EF25]: R2#5

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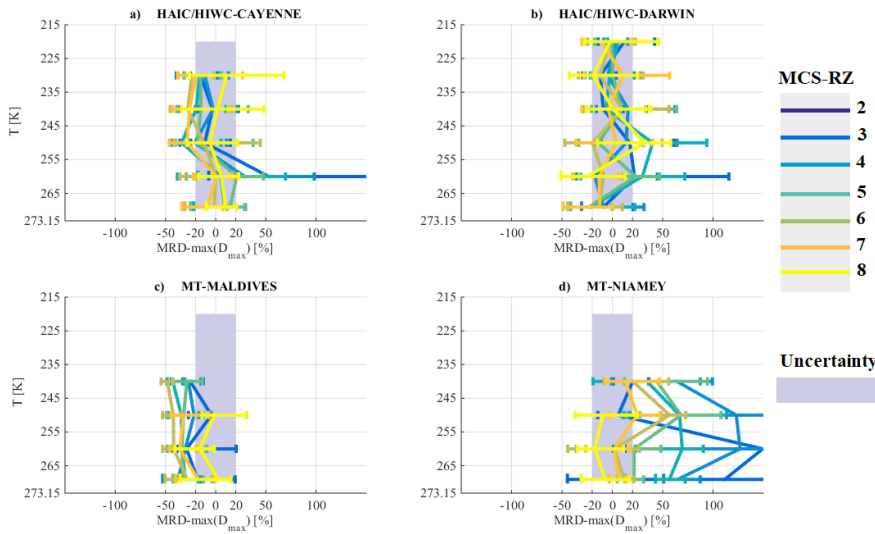
Figure 18: As Figure 6, but for maximum size of hydrometeors max(D_{max})

In this section, it is shown that in the stratiform part of MCS, largest hydrometeors are larger in MCSs over Niamey than in other types of MCS, and tend to be smaller in MCS over Maldives Islands. Mainly, large crystals (Dmax > 1mm) are

5   *agglomerates of pristine ice crystals, for which the growth process is leaded by aggregations (by sedimentation) instead of vapour diffusion. Some large pristine ice (large dendrites) were found in the dataset (especially over Maldives see Figure 1 in Fontaine et al., 2014) but usually their size do not exceed 3 to 4 mm. Hence, aggregation efficiency is different from one MCS type of MCS to another, this could explain the differences of mass-size coefficient β, as it is calculated on the slope in a log-log scale of mean perimeter and mean surface as a function of median diameter in each size bin. Because, large hydrometeors*

10   *have a non-negligible impact on the slope (i.e. fp and fs, see Eq. (5)).*

5.6 note on the impact of vertical movement on ice microphysic

This section discussed about the investigation performed about the impact of vertical velocity on the ice microphysical parameters presented earlier in this section 5. We separated the merged dataset in three sub-datasets such: i) w <-1m/s , (ii) -1m/s < w < 1m/s and (iii) w>1m/s. Then, median relative difference for the three conditions and for each parameters

15   *presented in this section 5 were calculated and compared to the median relative difference when no distinction is performed as function of vertical velocity. Firstly, we noticed that MRD-X for the merged dataset and MRD-X for the second condition (i.e. 1m/s < w < 1m/s) are similar (MRD-X: X being used to replace IWC, σ, NT, NT_{50}, NT_{500}, β, α, max(Dmax)). Secondly, differences of MRD-X in updraft and in downdraft with regards to MRD-X for merged dataset and no vertical movement are visible. But most of the times these differences are not enough pronounced compared to measurement uncertainties (U(X)/X).*

20   *Appendices B shows the Figures that shows when updraft have an impact on ice microphysic parameters for a given range of temperature and MCS reflectivity zones. So, Figure B1 shows MRD-IWC, Figure B2 shows MRD-NT and Figure B3 shows MRD-NT50. For the others parameters impact of updraft are uncommon.*

It appears that updraft tends to impact mainly concentrations of small hydrometeors and IWC for some type of MCS and some MCS reflectivity zones. So for NT (Figure B2), we observe larger NT for updraft in MCS observed over Cayenne, Maldives

25   *and Niamey. For Cayenne, it appears in MCS reflectivity zone 5 and 6 for temperatures between 245K and 265 K with NT 2 to 3 times larger than NT for merged dataset. For MCS over Maldives, median NT are 5 times to 20 times larger than NT when there is no noticeable vertical movement in MCS reflectivity zones 6, 7 and 8. Finally for MCS over Niamey, we observe larger NT in updraft than NT for the merged dataset in MCS reflectivity zones 6 for T around 240 K and in MCS reflectivity*

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zones 8 above the bright band. We have similar conclusions for NT_{50} (Figure B3), except that ratios between NT_{50} in updraft and NT_{50} when no updraft is smaller than the ratio between NT in updraft and NT when no updraft.

IWC are impacted by updraft, only for MCS over Cayenne, in MCS reflectivity zone 4, 5, 6 and 7. IWC in updraft tend to be larger about +50% than IWC when no updraft, except in MCS reflectivity zones where IWC are about 2 times larger in updraft than IWC when no updraft.

This investigation on the impact of updraft and downdraft on ice microphysics, shows that updraft may have an impact on concentrations of small hydrometeors and IWC. However, updraft does not impact all type of MCS in the same way. So, there will need to perform deeper investigations on updraft impact.

Despites some noticeable impact of updraft on ice microphysic for our dataset, there is no significant (recurrence trough all types of MCS or as function of T or Z) results to assess them for the merged dataset. So, the parameterization provided in the next section are not functions of vertical velocity.

> **Commenté [EF27]:** R1#4

6. Parameterizations as function of IWC and T

> **Commenté [EF28]:** R2#4

6.1 visible extinction

Since we concluded from Figure 7 and Figure 8 that visible extinction σ and IWC in tropical MCS tend to be similar for all MCS locations in the same range of T and for corresponding MCS reflectivity zones 4 to 8. Moreover Figure 19 shows that there is a linear relationship between $\log(\sigma)$ and $\log(IWC)$. Moreover it seems that $\log(\sigma)$ decrease with temperature increasing at constant $\log(IWC)$. Then, we performed a surface fitting using input coefficients $\log(IWC)$ and T to fit $\log(sigma)$ to deduce a parametrization of σ (Eq. (8)) as a function of IWC and T for deep convective cloud data (merged dataset) of this study limiting data to IWC > 0.1g m^{-3}:

$$\sigma = exp(-0.0194587 \cdot T + 0.9134019 \cdot ln(IWC) + 1.2423609) \qquad [m^{-1}] \qquad (8)$$

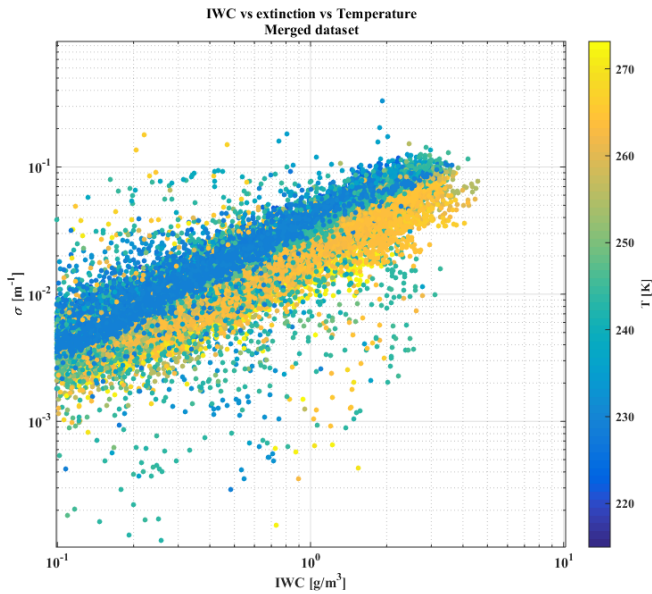***Figure 19: visible extinction in [m-1] on y-axis as function of IWC in [kg.m^{-3}] on x axis and as function of T in [K] with color scale. Scatter plot using the merged dataset (4 campaigns).***

> **Commenté [EF29]:** R2#12

24

An evaluation of this parametrization is presented in Figure 20, where black lines in Figure 20-a) to Figure 20-d) represent median relative errors of σ (with 25th and 75th percentiles represented by whiskers) for the merged dataset predicted with Eq. (8) with respect to retrieved σ from OAP images from Eq. (2). In addition, median relative errors of σ for individual MCS datasets over Darwin, Cayenne, Maldives Islands, and Niamey with respect to σ calculations (Eq. (8)) are shown in Figure 20(a), Figure 20(b), Figure 20 (c), and Figure 20(d), respectively. The uncertainty $\pm \frac{U(\sigma)}{\sigma}$ is given with the grey band. All relative errors (25th - 75th percentiles) tend to be smaller than $\pm \frac{U(\sigma)}{\sigma}$, with median relative errors that are smaller than ±25% of σ uncertainty calculated from Eq. (2). In general, Eq. (8) seems to produce smallest relative errors of σ for Niamey and Darwin datasets (especially for IWC<2g m^{-3}).
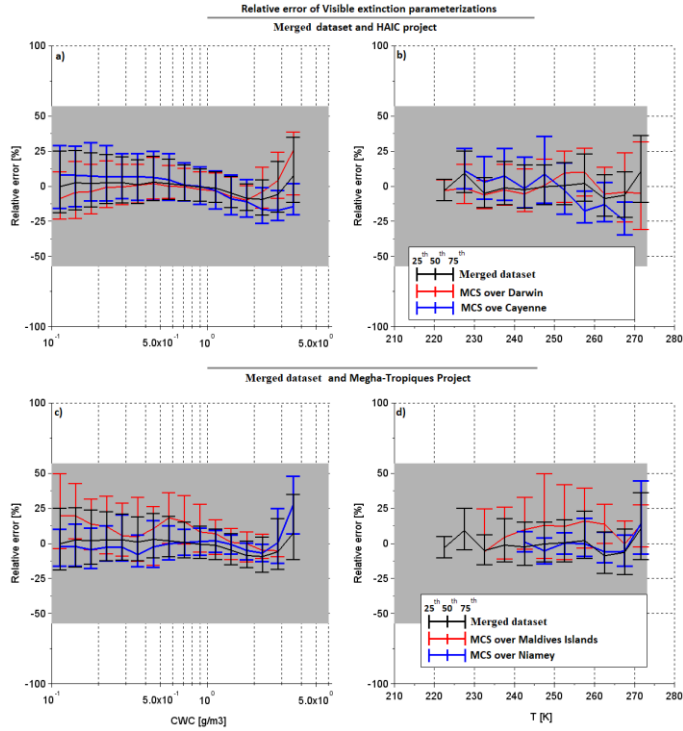
Figure 20: Relative errors of predicted visible extinction Eq. (3) with respect to measured visible extinction for a), b), c), and d. Relative errors as a function of IWC in a) and c) and as a function of T in b) and d). Black lines in 4 sub figures represent the relative errors when calculated for the entire tropical dataset. In a) and b) red lines show median relative error for MCS over Darwin, and blue line for MCS over Cayenne. In c) and d) red line represent median relative errors for MCS over Maldives Islands and blue lines for MCS over Niamey. Bottom of error bar shows 25th percentiles of relative errors and 75th percentiles are given by top of error bar.

Noteworthy, optically thick clouds are responsible of large errors in retrieved cloud water path and condensed water concentration profiles retrieved from satellite imageries (Smith, 2014; Yost et al., 2010). Parameterizations, such as presented here, could help to improve retrieval methods on cloud water path but more investigations on the benefit of such parameterizations are needed, which is beyond the scope of this study.

6.2 Parameterization of ice hydrometeors distributions

6.2.1 Observations of PSD moment

Moments of PSD are convenient for numerical weather prediction to model microphysics of hydrometeor populations, since knowing the PSD n^{th} order moment allows to roughly describe cloud processes and their hydrometeors properties. Commonly,

5 *PSD of ice hydrometeors are modeled with Gamma distributions (Heymsfield et al., 2013; McFarquhar et al., 2007). The calculation of the nth order moment is defined in Eq. (9) for PSD obtained from size distribution measurements of hydrometeors, for example with OAP (optical array probes):*

$$M_n = \sum_{D_{max}=55\mu m}^{D_{max}=1,2cm} N(D_{max}) \cdot D_{max}^n \cdot \Delta D_{max} \qquad [m^{n-3}] \tag{9}$$

The uncertainty of the nth ($n=2$ and 3 in our study) moment is:

10 $$\frac{U(M_n)}{M_n} = \sqrt{n \cdot \frac{U(D)^2}{D} + \frac{U(N)^2}{N}} \tag{10}$$
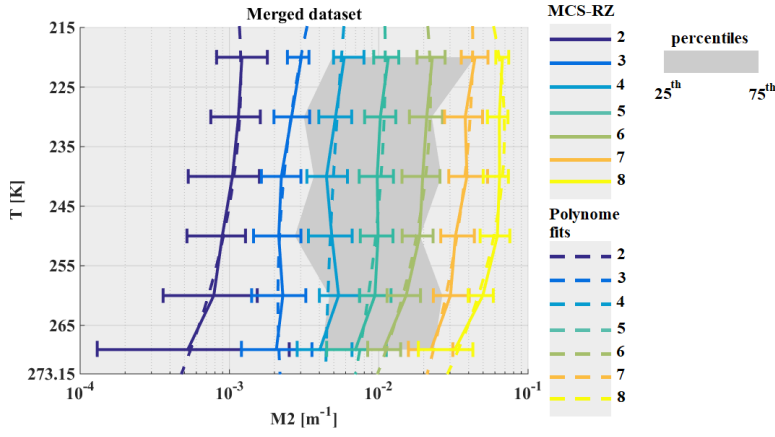
Figure 21: Same as Figure 5, but for M_2 per meter.

Figure 21 shows median second moment M_2 as a function of T for all MCS reflectivity zones for the merged global tropical dataset. Median M_2 slightly decrease with temperature for all individual MCS reflectivity zones, and distinctly increase with

15 *MCS reflectivity zone for a given T. The range of variability of median M_2 shows mainly negligible overlap, if any, of 25th and 75th percentiles of neighboring MCS reflectivity zones with the exception between MCS reflectivity zones 8 and 7 at low altitude ($T \in [265; 273.15[$).*
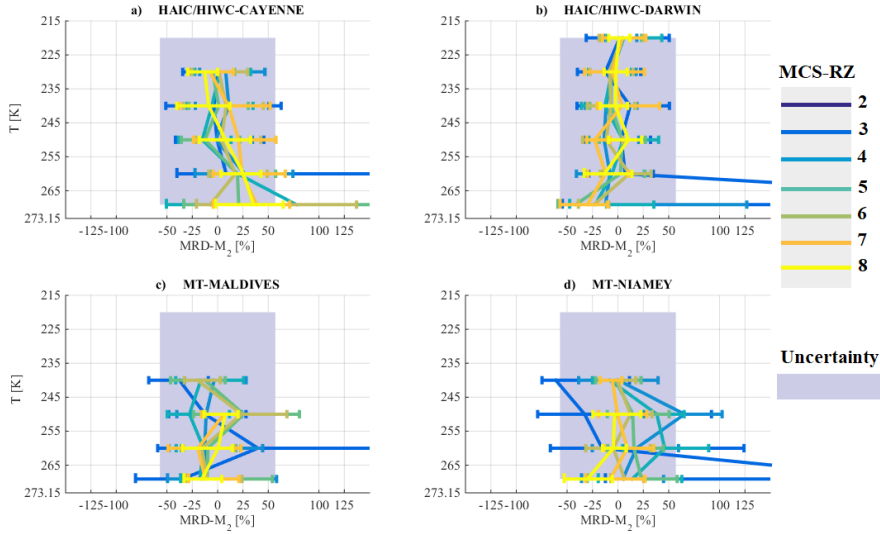
Figure 22: Same as Figure 6, but for MRD-M₂.

All 4 tropical MCS (Figure 22 (a), (b), (c), and (d)) show good agreement with the medians of M_2 in MCS reflectivity zones 3 to 8, with MRD-M_2 significantly smaller than $U(M_2)/M_2$. Few minor exceptions can be found for MCS over Cayenne (Figure 22 (b)) and Darwin (Figure 22 (c)) in the temperature range [265K; 273.15[. Also MCS over Niamey (Figure 22 (e)) show a larger MRD-M_2 in MCS reflectivity zones 2 and 3 for $T \in$ [265K; 273.15K[and $T \in$ [245K; 255K[, respectively.
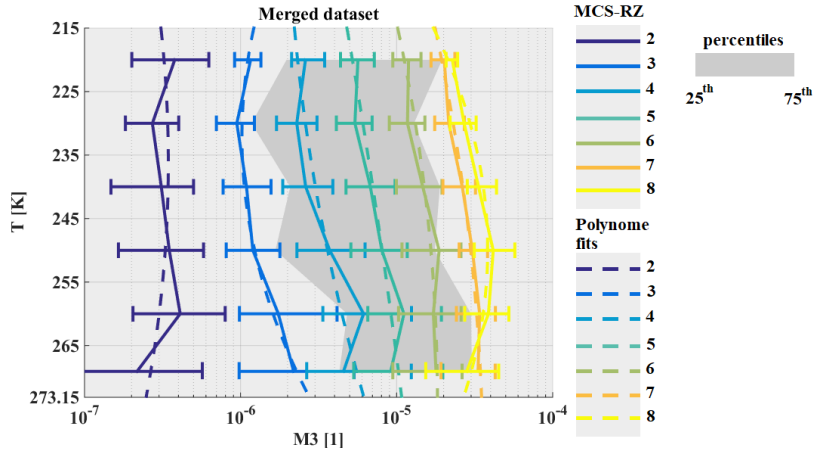
Figure 23: Same as Figure 5, but for the M_3 for unity dimension.

Figure 23 presents median third moment M_3 for global tropical dataset as a function of T and for different MCS reflectivity zones. Median M_3 in highest MCS reflectivity zones 8, 7, and to some extent zone 6 resemble the corresponding curves of median IWC (Figure 5), with a maximum value for median M_3 for $T \in$ [245K; 260K[. We also obtain a clear increase in median M_3 with MCS reflectivity zone from 2 to 8. The range of variability for M_3 reveals no overlap of 25th and 75th percentiles of neighboring MCS reflectivity zones 2-7, solely zone 7 overlaps with zone 8 for all temperatures. Third moment of MCS over Cayenne, Darwin and Maldives Islands in MCS reflectivity zones 2 to 8, shows MRD-M_3 smaller than $U(M_3)/M_3$, with few

27

minor exceptions basically in the range of T ∈ [265K; 273.15K[. MCS over Niamey tend to have MRD-M₃ that are sometimes larger than U(M₃)/ M₃. Indeed, M₃ for MCS over Niamey tend to be larger in MCS reflectivity zones 5 and 2 in the range of T ∈ [265K; 273.15K[, and in MCS reflectivity zone 4 for T larger than 255K as well as in MCS reflectivity zone 3 for T larger than 245K.

5
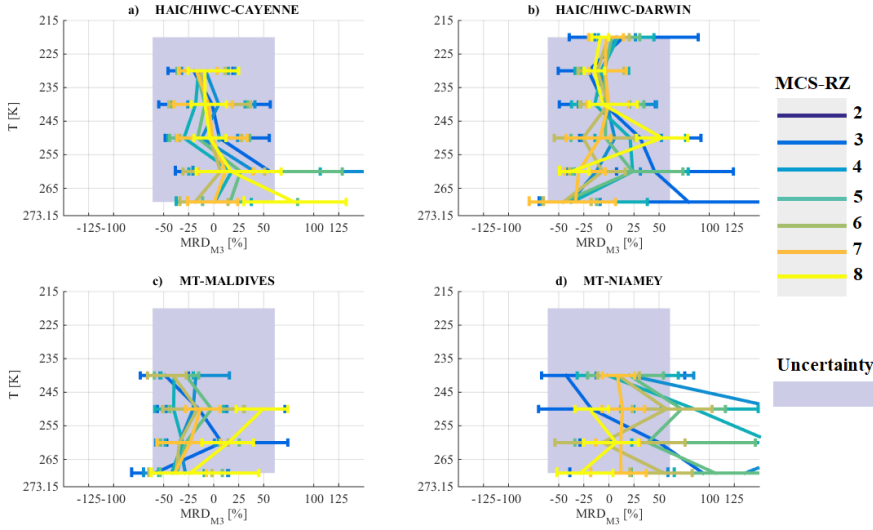
Figure 24: Same as Figure 6, but for the M₃.

Overall, this section illustrates that second and third moments of PSD are similar as a function of T and Z for all MCS locations of the underlying dataset. However, there are exceptions in MCS reflectivity zones 2, 3 and 4 in MCS over Niamey where
10 *larger third moments are calculated compared to those deduced for the merged global tropical dataset. Despite those exceptions, the next section explores the possibility to parameterize the second and third PSD moments as a function of IWC and temperature.*

6.2.2 Parameterizations of M₂ and M₃

This section presents parametrizations to predict the 2nd and 3rd moment of the PSD for the merged dataset as a function of T
15 *and IWC (for this section IWC in the equation are in [kg m⁻³]), including IWC data larger than 0.1g m⁻³. Indeed some moments can be directly linked to bulk properties of hydrometeor populations. For example, moment M₀ for ice and liquid hydrometeors is equal to the total number concentration (N_T), moments M₂ and M₃ for liquid particles are proportional to visible extinction and liquid water content. However, for ice hydrometeors the physical interpretation of moments M₂ and M₃ is less obvious since ice hydrometeors are not spherical particles. The results for α and β coefficients of the m(D_max) relationship presented*
20 *in section 5.3, illustrate that β varies between 1.5 and 2.3. This means that IWC is proportional to PSD moments between M₁.₅ and M₂.₃. Also uncertainties on the retrieved β coefficients do not allow to assess the variability of β as a function of IWC and T. Former studies performed in different cloud environments report mean values of β around 2. For example, Leroy et al., (2016) found β=2.15 for HAIC-HIWC in Darwin, Cotton et al., (2013) suggested β=2.0, Heymsfield et al., (2010) suggested β=2.1, and Brown and Francis (1995) established β=1.9. We are also aware of the fact that findings of β also depend on the*
25 *utilized size parameter (D_max, D_eq, etc…) of 2D images. Hence, we apply β=2 as an approximation, also proposed by Field et*

al., (2007), to link the second moment of hydrometeor PSD with IWC (Eq. 11). Subsequently the ratio IWC/M$_2$ is calculated and denoted A.

$$M_2 = \frac{IWC}{A} \qquad [m^{-1}] \tag{11}$$
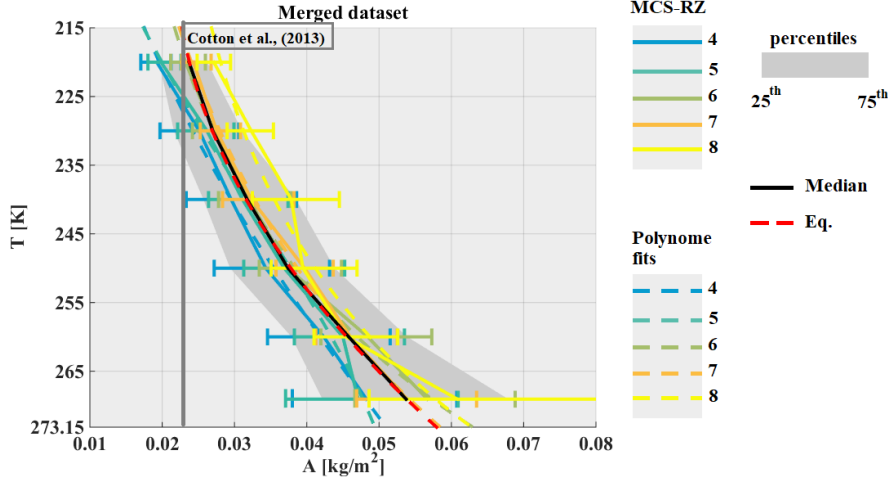
5   *Figure 25: Same as Figure 5, but for the ratio A= IWC/M$_2$ in [kg m^{-2}].*

Figure 25 shows retrieved median coefficients A for the global tropical dataset as a function of MCS reflectivity zone and T. Note that A is calculated in SI units (note that in Eq. (11) IWC is in kg m^{-3}). The black solid line gives the median of A as a function of T, thereby merging all MCS reflectivity zones for the merged dataset with IWC > 0.1g m^{-3}. The grey band gives corresponding 25th and 75th percentiles of that median A. In addition, are calculated median A for all individual MCS

10 *reflectivity zones (on Figure 25) are solely illustrated median A for zones 4 to 8) for the global tropical dataset as a function of T. In general, median A calculated for individual MCS reflectivity zones 5, 6 and 7 are very similar to the median A when merging all MCS reflectivity zones (black solid line), whereas median A calculated for MCS reflectivity zone 4 tends to have smaller A values and median A calculated for MCS reflectivity zone 8 have larger median A values than the overall median A (all MCS reflectivity zones merged) for comparable temperatures.*

15 *However, when taking into account the variability in median A calculated for individual MCS reflectivity zones and associated 25th and 75th percentiles we can state that median A generally increases with T, however it is not possible to assess that A increases with MCS reflectivity zones or IWC. As a comparison, we include the value of the pre-factor α (in SI unity) from Cotton et al. (2013) mass-size relationship (β=2.0, as is for second moment M$_2$, and α=0.0257). Clearly, α=0.0257 is not suited for deep convective systems as it represents ice crystals for T $\in$[215K; 225K[.*
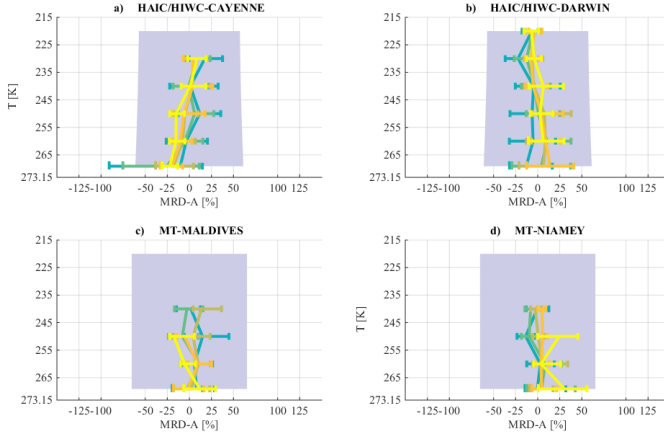
Figure 26: Same as Figure 6, but for the ratio MRD-A.

Figure 26 (a), 26(b), 26(c), and 26(d) illustrate that MRD-A are significantly smaller than U(A)/A, (same uncertainty than α: U(α)/α = U(A)/A and median MRD results centered around 0%). Comparing results of A (Figure 26) with results presented

5 *for α (Figure 15, section 5.4) it is obvious in terms of variability and MRD in each type of MCS that A is better adapted to parametrize the PSD 2nd moment as a function of T. Eq. (12) then fits the median of ratio A for the global tropical dataset (red dashed line, all MCS reflectivity zones merged), as a function of T in deep convective systems for IWC larger 0.1g m-3:*

$$A(T) = 0.0000075 \cdot T^2 - 0.0030598 \cdot T + 0.3334963 \qquad [kg.m^{-2}] \qquad (12)$$

Hence, Field et al., (2007) proposed to retrieve the third moment M_3 as function of M_2 and T. These equations are recalled

10 *here with (in our case n=3):*

$$M_n = M_2^{F(n)} \cdot D(n) \cdot exp(E(n) \cdot T_c) \qquad (13)$$

T_C denotes temperature in °C and D(n), E(n) and F(n) are given by:

$$D(n) = exp(13.6 - 7.76 \cdot n + 0.479 \cdot n^2) \qquad (14)$$

$$E(n) = -0.0361 + 0.0151 \cdot n + 0.00149 \cdot n^2 \qquad (15)$$

15 $$F(n) = 0.807 + 0.00581 \cdot n + 0.0457 \cdot n^2 \qquad (16)$$

Figure 27 provides median relative errors (whiskers represent 25th and 75th percentiles) of parametrized moments M_2 (Figure 27 (a) and Figure 27 (b)) and M_3 (Figure 27 (c) and Figure 27 (d)) compared to respective moments calculated directly (Eq. (9) from PSD measurements (merged dataset). These relative errors are shown as a function of IWC (Figure 27(a) and Figure 27(c)) and as a function of T (Figure 27(b) and Figure 27(d)). Firstly, the red line shows median relative error of M_2 retrieved

20 *from Eq. (11) compared to M_2 derived from measured PSD (Eq. 10). In addition the grey band illustrates the uncertainty U(M_2)/M_2. Figure 27 (a) illustrates that below 2g m-3, the median of this relative error is close to 0% with 25th and 75th percentiles significantly smaller than U(M_2)/M_2. However, for largest IWC beyond 2g m-3, median relative errors are getting large (40% for 4g m-3 and 75% for 4.5g m-3) and need to be corrected in order to reduce the bias between predicted M_2 and observed M_2. This is why Eq. (11) is modified with an expression shown in Eq. (17) in order to improve prediction of M_2*

25 *compared to measured M_2 (Eq. (10)) for highest IWC:*

$$M_2 = \frac{IWC}{A(T)} \cdot exp\big(0.005853 \cdot exp(1025 \cdot IWC)\big) \qquad [m^{-1}] \qquad (17)$$

The effect of the expression added in Eq. (17) is illustrated by the blue line in Figure 27 (a) and Figure 27 (b), where median relative error of predicted M_2 are now closer to 0% also for large IWC. ~~Still, Eq. (12+17) seems to underestimate measured~~

~~M_2 by about 15% for IWC of 4.5g m⁻³ instead of 75% overestimation before correction.~~ Note that in Figure 27 (b), median relative errors of the two above parametrizations (red and blue solid line) of M_2 are superposed as a function of T with a median relative error close to 0%. This means that the second part of equation (17) does not introduce any significant bias as a function of T, since the occurrence of IWC > 2g m⁻³ is smaller than 1% for the merged dataset.

Median relative error for parameterizations of second Moment of PSD

Median relative error for parameterizations of third Moment of PSD

5
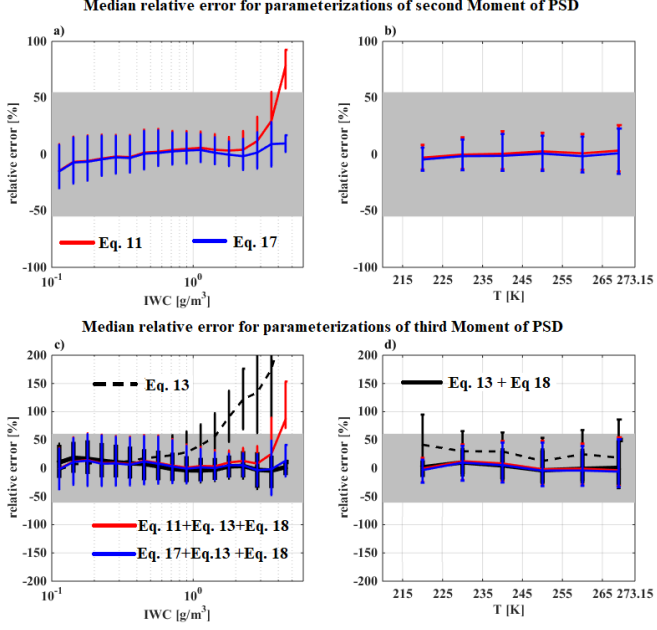
Figure 27: Relative error of parametrized M_2 and M_3 for merged dataset as a function of IWC in a) and c), and as a function of T in b) and d). Solid lines give median relative error and whiskers denote 25th and 75th percentiles of relative error. Grey bands shows measurement uncertainties for M_2 (55%; a) and b)) and M_3 (61%; c) and d)), respectively.

In Figure 27 (c) and Figure 27 (d)) are shown median relative error for parameterizations of the third moment, where the
10 median relative error for all parameterization are calculated as function of measured M_3. First, we discuss the median relative error for parametrization of 3rd moment M_3 according to Field et al., (2007) (Eq. (13); black dashed lines) using the measured M_2. Then, we can see that the parameterization of Field et al., (2007) overestimate M_3 for IWC larger than 1g m-3 and that overestimation of M_3 increase with IWC. Moreover, this overestimation of M_3 tend to decrease a bit as function of T.

To reduce this significant median relative error on measured M_3, particularly for large IWC in deep convective cloud systems,
15 we provide a M_3 correction function for Eq. (13) as function of T and IWC:

$$M_3 = [-5.605 - 1.059 \cdot log(IWC) + 0.009536 \cdot T - 0.0418 \cdot log(IWC)^2 + 0.0007889 \cdot log(IWC) \cdot T] \cdot M_2^{F(3)} \cdot D(3)$$
$$\cdot exp(E(3) \cdot T_c) \tag{18}$$

Then, three series of median relative error of M_3 where M_3 are computed with Eq. (19). First, Eq. (19) is used with measured M_2 (black solid lines) to show the efficiency of the correction applied as function of IWC and T and described in Eq. (19).
20 Then, Eq. (19) is applied to M_2 calculated using Eq. (11) where there is no correction as function of IWC to calculate M_2 (red solid lines). We can observe that M3 are overestimated for IWC larger than 3g.m-3, and that there is no bias as function of T with median relative error close to 0%. Finally, Eq. (19) is used to compute M3 from M2 calculated with Eq. (17) when impact of large IWC is taken into account. We can see median relative error close to 0% for the third example of parameterization (i.e. Eq. (17) and Eq. (18)) with no bias as function of IWC and T.

An identical investigation on median relative errors in the prediction of 2nd and 3rd moment as presented in Figure 27 has been investigated for individual MCS locations (figures not shown). For all type of tropical MCS, we observe that M_2 from Eq. (17) and M_3 from Eq. (18) tend to have smaller to equal median relative errors compared to the relative uncertainties $U(M_2)/M_2$ and $U(M_3)/M_3$, respectively. Beyond this general statement there are two noticeable observations. The first observation is that

5   *median relative errors of M_3 from Eq. (18) calculated either with M_2 from measurements (Eq. (9)) of from parametrized M_2 from Eq. (17) for MCS over Maldives Islands are close to $U(M_3)/M_3$ with 75th percentiles reaching 100% for IWC in the [0.3; 0.6] $g\ m^{-3}$. The second observation is that for MCS over Niamey, M_3 from Eq. (18) with M_2 from Eq. (9) or from Eq. (17) tend to overestimate respective moments calculated directly from PSD measurements by about 30 or 50%, respectively, in the area of higher IWC ([2; 3] $g\ m^{-3}$).*

10   *This section aims to produce parameterizations of the second and third moments of ice hydrometeor size distributions, which can be useful for the calculation of hydrometeor size distributions in numerical weather prediction using gamma distributions, but also (see the next section) for calculating rescaled ice hydrometeors size distributions (Field et al., 2007).*

6.2.3 Rescaling of measured ice hydrometeors size distributions

From bulk properties as mixing ratio and total concentration in numerical weather prediction (NWP), ice hydrometeors size

15   *distributions (or PSD) properties can be derived from moment parameterization allowing simplified prediction of cloud microphysical processes such as precipitation. Usually, ice hydrometeors size distributions for hydrometeors are modeled by gamma distributions (Heymsfield et al., 2013; McFarquhar et al., 2007). Since the method of gamma distributions is relatively well documented, we focus this study on another type of PSD parameterization, which studies 'rescaled PSD' dealing with a 'mean diameter' defined by the ratio of the third moment over the second moment.*

20   *In this section, we propose an update for the method proposed by Field et al., (2007) for deep convective cloud systems and IWC larger than 0.1g m^{-3}. For the entire dataset of this study we therefore apply the above method utilizing Eq. (19) and Eq. (20) to calculate function $\Phi_{2,3}(x)$ and x for individual measured PSD :*

$$\Phi_{2,3}(x) = N(D_{max}) \cdot \frac{M_3^3}{M_2^4} \tag{19}$$

With x being the characteristic size:

25      $$x = D_{max} \cdot \frac{M_2}{M_3} = \frac{D_{max}}{L_{2,3}} \tag{20}$$

$\Phi_{2,3}(x)$ and x are dimensionless functions. Moreover, Field et al., (2007) deduced from their dataset, $\Phi_{2,3}(x)$ depending on cloud location; i.e. tropical troposphere or mid-latitude troposphere (here we focus on the equation established for the tropics):

$$Tropics: \Phi_{2,3}(x) = 152 \cdot exp(-12.4 \cdot x) + 3.28 \cdot x^{-0.78} \cdot exp(-1.94 \cdot x) \tag{21}$$

30   *Hence, the variability of PSD in clouds, is not given by $\Phi_{2,3}(x)$ but by the variability of the 2nd and 3rd moments that allow retrieving functions x and $\Phi_{2,3}(x)$. Then, knowing $x, \Phi_{2,3}(x)$, M_2, and M_3 concentrations of ice hydrometeors can be parameterized such:*

$$D_{max} = x \cdot \frac{M_3}{M_2} \tag{22}$$

and

35      $$N(D_{max}) = \Phi_{2,3}(x) \cdot \frac{M_2^4}{M_3^3} \tag{23}$$

Figure 28 shows the probability distribution function (PDF) of observed rescaled PSD in tropical MCS as a function of the x parameter. Thick black line represents $\Phi_{2,3}(x)$ from Field et al., (2007), thin dashed grey line represents median of $\Phi_{2,3}(x)$ for a given range of x, with whiskers showing 25th and 75th percentiles of $\Phi_{2,3}(x)$. The figure illustrates that Eq. (21) from Field et al., (2007) represents rather well $\Phi_{2,3}(x)$ as a function of x in highest PDF region (dark red area) and fits well the

median plot for $x \in [0.3; 6]$. However, Field et al., (2007) performed their study for diameter larger than 100µm while this study calculates rescaled PSD for D_{max} larger than 15µm for the underlying dataset. Thus, Eq. (21) does not fit median $\Phi_{2,3}(x)$ for x smaller than 0.3. Also for x > 6, Eq. (21) decreases too fast compared to the median of $\Phi_{2,3}(x)$ calculated for the global tropical dataset of this study, although Field et al., (2007) considered ice hydrometeors up to 2cm, whilst this study extrapolates

5 *PSD until 1.2845cm only (reconstruction of partial images to calculate particle size according to Korolev and Sussman 2000).*

A likely assumption to explain the differences for large x > 6 might be that the merged tropical dataset of this study may have measured PSD with largest hydrometeors at a far higher frequency than this was the case for the dataset of Field et al., (2007).
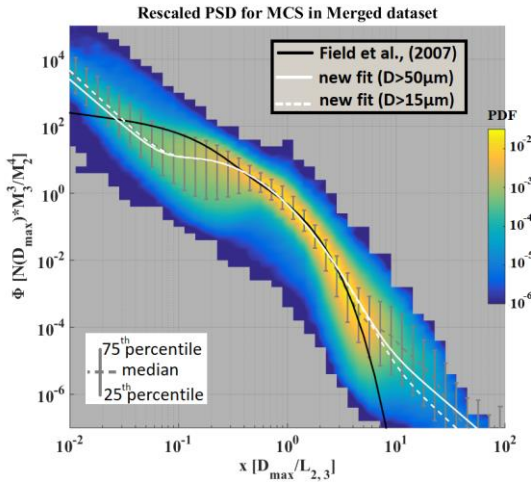
Figure 28: Probability distribution function of rescaled PSD ($\Phi_{2,3}$) on y axis as a function of hydrometeor characteristics
10 ***size (x) on x axis, for the Global tropical datasets. Black lines show fitted functions from Field et al., (2007), grey dotted lines show median rescaled PSD with error bar from 25th and 75th percentiles of rescaled PSD. Solid white line presents the new fitted function for the global tropical dataset for PSD beyond 55µm and dashed white line shows fitted function for PSD beyond 15µm (Eq. 25).***

White lines (dashed and solid) show new fitted $\Phi_{2,3}(x)$ for the global tropical dataset of this study. The white dashed and solid
15 *lines can be represented by the following equation and aim to fit the median ($\Phi_{2,3}(x)$) of Figure 28 as a function of x:*

$$\text{Tropics: } \Phi_{2,3}(x) = \left[exp(a_1) \cdot x^{a_2} \right] + \left[b_1 \cdot exp\left(-\frac{(ln(x) - b_2)^2}{b_3^2} \right) \right] \qquad (24)$$

Where b1 = 9.484, b2 = -1.895 and b3 = 1.083. Note that dashed and solid white lines use different sets of coefficients a_1 and a_2 (Table 1). For white dashed line, a_1 and a_2 are calculated for D_{max} beyond 15µm, whereas for white solid line, a_1 and a_2 are calculated for D_{max} beyond 55µm. We can notice that the function for $D_{max} \geq 15µm$ produces higher $\Phi_{2,3}(x)$ as compared to
20 *the function fitted for $D_{max} \geq 55µm$. In order to explain this difference, we recall that for MCSs over the Maldives Island concentrations of hydrometeors with $D_{max} \leq 55µm$ are higher compared to 3 other tropical MCS locations, which could affect the fitted coefficients a_1 and a_2 in the two different versions of $\Phi_{2,3}(x)$ calculations for the global tropical dataset. Another difference in small particle measurements could be a pure technical difference in small particle measurements (including shattering/out-of-focus/small sample volume artefacts) between 2D-S probe (this study) and 2D-C probe (Field et al. (2007)*
25 *study).*

Table 1 : Coefficients a1 and a2 for Eq. (25).

	a_1	a_2
Tropics: $D_{max} > 15µm$	*-5.4114*	*-3.0026*

Tropics: $D_{max} > 55\mu m$	*-5.0032*	*-2.7822*

6 Discussion and conclusion

In this study we analyze in-situ aircraft observations of the ice particle size distributions and simultaneous cloud radar observations collected in tropical MCS in order to characterize the statistical properties of ice microphysics. The results are focused on the tropical MCS that include observations from: (i) the raining season over Cayenne (South America), (ii) the North-Australian monsoon over Darwin, (iii) deep convective systems over the Maldives Island in the ITCZ, and (iv) the West-African monsoon over Niamey.

The overall data analysis of ice hydrometeor properties has been performed as a function of temperature and the range of radar reflectivity factors measured at 94GHz. Therefore, all vertical profiles of aircraft onboard radar reflectivity measurements have been gathered and statistically analyzed in order to define delimited reflectivity zones, thereby reducing possible vertical bias due to the chosen flight track/altitude in the MCS systems. Hence, this study defines 8 MCS reflectivity zones that have been determined from radar reflectivity factor percentiles (1st 10th 30th 50th 70th 90th and 99th) as a function of temperature, thereby merging all vertical reflectivity profiles of the entire global tropical dataset used for this study. Analysis of the retrieved vertical wind speeds in each MCS reflectivity zone reveals that the probability to observe a magnitude of vertical winds larger than 1m.s^{-1} are not that different in MCS reflectivity zones 1 to 5, but then strongly increase from MCS reflectivity zone 6 to 8. Generally, these probabilities increase with decreasing temperature for all MCS reflectivity zones. Also, the simple magnitude of vertical wind speeds is larger in MCS reflectivity zones 7 and 8, while in MCS reflectivity zones 1 to 6 the magnitude is rather small and similar, however the magnitude is a function of *T*. *We do not think that alone, MCS reflectivity zones can give information about the stage of a MCS in its life cycle (i.e. Formation, maturation, decaying). The analysis of geostationary satellites data would be more suited for this topic (Fiolleau and Roca 2013). But, studying the distribution of MCS reflectivity zones as function of life cycle of MCS and brightness temperature and/or visible reflectance could be a future investigation. However, this study demonstrates* that MCS reflectivity zones 7 and 8 exhibit highest probability to be related to the active convective zone and/or the most turbulent transition zone between the inaccessible part of the convective core and the stratiform part of MCS clouds, whereas MCS reflectivity zones 1 to 5 are rather associated with the decaying or so-called stratiform parts of MCS. MCS reflectivity zone 6 then represents the transition between stratiform and convective area of an MCS with a relatively small median magnitude of vertical winds, however with relatively high probability of vertical wind magnitudes beyond 1m s^{-1}.

Subsequently, the study compares microphysical properties (such as ice water content, extinction, concentrations, largest hydrometeor sizes, etc…) as a function of MCS reflectivity zone and temperature. The statistical analysis (median values, 25th and 75th percentiles) is performed for individual the MCS locations), whereas the merged dataset of the 4 tropical MCS locations serves as a reference. Relative differences of median microphysical properties in one MCS location compared to respective median properties of the reference dataset were quantified. Also uncertainties for all type of microphysical measurements and retrieved cloud parameters were calculated from Baumgardner et al. (2017).

Within the range of uncertainties, we showed that the variability of IWC, σ, $N_{T,50}$, $N_{T,500}$, M_2 and M_3 as a function of temperature and specific MCS reflectivity zones tends to be similar: For example, for IWC these conclusions apply for MCS reflectivity zones 4 to 8. MCS data from Niamey flight campaign (compared to the three other tropical MCS locations) reveal more exceptions when compared with median parameters calculated for the global tropical dataset, with a trend of larger 3rd PSD moments and larger hydrometeor sizes in the stratiform area of MCS. Assuming that largest hydrometeors ($max(D_{max})$) can be considered as a proxy for the aggregation process efficiency. Findings of this study reveal that *aggregation process efficiency is higher for convection over land than over islands and higher over islands close to large land masses than over islands in the middle of an ocean. It seems to confirm the results of Frey et al., (2011) and Cetrone and Houze (2009).*

34

From the tropical dataset a parametrization of visible extinction is developed as a function of temperature and IWC (Eq. 3). This model allows retrieving σ from OAP measurements with an accuracy smaller than the measurement uncertainty of σ ($U(\sigma)/\sigma = 57\%$; Eq. (2)) for all four types of tropical MCS. Eq. (3) reveals best accuracy to represent directly calculated σ in MCS over Darwin and Niamey.

5   Also in this study the relationship between mass and size of ice hydrometeors ($m=\alpha D^\beta$) is formulated with a classical power law approximation. A basic finding is that the variability of retrieved β throughout all MCS reflectivity zones is too large compared to its uncertainty. This would mean for example that varying β parameterization in NWP is not worthy to do. Indeed, NWP schemes are used to describe ice microphysics with PSD moments (here M_2 and M_3). Setting $\beta=2$ for the mass-size relationship allows to link IWC to the second moment directly as stated in Field et al., (2007).

10 Defining A as the ratio IWC/M_2, this study illustrates that A increases with temperature. Also A in MCS reflectivity zones 5, 6 and 7 are similar to the median A calculated for the entire dataset (Figure 16(a)). In MCS reflectivity zone 4 (smaller zones were not considered), A tends to be smaller in MCS reflectivity zones 4 and in MCS reflectivity zone 8, A tends to be larger than the median of A for the global tropical dataset. However, MCS reflectivity zones 4 and 8 share a wide range of variability with MCS reflectivity zones 5, 6 and 7. Hence, we use the variability of A as a function of temperature (parametrization in

15 Eq. (13)) to predict the 2nd PSD moment in tropical and mid-latitude MCS. Whereas Eq. (13) retrieves M_2 in all type of MCS with a good accuracy, a correction is needed for high IWC (Eq. 18).

Hence, in this study the model of PSD moments presented by Field et al., (2007), has been considerably modified for PSD in deep convective cloud systems in order to predict the 3rd moment (M_3) from the known 2nd moment (M_2), IWC, and temperature T. This new parametrization of M_3 for deep convective cloud systems and IWC larger than 0.1 g m^{-3} is given by Eq. (13), Eq.

20 (18) and Eq. (19). The prediction of M_2 (Eq. 18) is more accurate than the prediction of M$_3$ (Eq. 19), when compared with M_2 and M_3 directly calculated from the measured PSD. Indeed, the predicted M_2 have median relative errors in the range [-25%; 25%] (corresponds to 25th and 75th percentiles of relative error of M_2) with an uncertainty of measured M_2 of about 55%. The predicted M_3 have median relative errors in the range [-40%; 55%] (which corresponds to 25th and 75th percentiles of relative error of M_3) with an uncertainty of measured M_3 of 61%.

25 Furthermore, we applied on the 4 tropical datasets the method of Field et al., (2007) of PSD rescaling with 2nd and 3rd moments of the measured PSD.

Field et al., (2007) gave for their dataset a parametrized function $\Phi_{2,3}$ that models rescaled PSD in the tropics as a function of the mean diameter (ratio between the 3rd moment and the 2nd moment of the PSD). The calculated rescaled PSD for the 4 tropical datasets are in good agreement with $\Phi_{2,3}$ parametrization given by Field et al., (2007) from diameters between 0.3-6

30 times the mean diameter (dimensionless characteristic size x). Below, 0.3 times the mean diameter, $\Phi_{2,3}$ of Field et al., (2007) tend to overestimate the rescaled PSD and finally underestimate them again below 0.03 times the mean diameter. These differences can be explained because of different diameter threshold to calculate the rescaled PSD. In our study, we calculate rescaled PSD starting at 15µm (or 55µm; see table 1 and Eq. (25)) while Field et al., (2007) used PSD only beyond 100µm. Also for large mean diameters we note significant differences between the rescaled PSD for the dataset of this study and $\Phi_{2,3}$

35 parametrization from Field et al., (2007). Indeed, for diameters larger than 6 times the mean diameter, $\Phi_{2,3}$ of Field et al., (2007) decreases rapidly and therefore underestimates the rescaled PSD by about 1 order of magnitude at diameters equal to 10 times the mean diameter. We do not think that these differences are due to the difference in the cut-off diameter of PSD (last available diameter for PSD) which has been 20000µm in Field et al., (2007) against 12845µm in this study. Field et al., (2007) used PSD of ice hydrometeors measured in anvils and cirrus clouds while the entire dataset for this study has been

40 gathered closest to MCS stratiform and convective zones of deep convective systems.

This latter fact more likely explains differences between the rescaled PSD of this study and parametrized $\Phi_{2,3}$ from Field et al., (2007). Probably, the underlying dataset for this study contains more large hydrometeors in non-negligible concentrations, and related increased statistics on large hydrometeor concentrations.

The parametrization based on tropical PSD data beyond 15μm seems to degrade parametrization results for largest diameters (rescaled concentrations beyond parametrization). We suspect that this is due to very high concentrations of small hydrometeors in the range 15-55μm in MCS over Maldives Islands, which would finally suggest to recommend parametrization for tropical MCS solely based on PSD beyond 50μm, in order to retrieve ice properties in deep convective
5   clouds that could serve in NWP. *To conclude on the parameterization of ice hydrometeors distribution. We performed an update of the computation of PSD as function of IWC and T performed by Field et al., 2007 for tropical convective clouds (see Eq. (11), Eq. (17) and Eq. (18)). This parameterization was used in the microphysical scheme based on (Wilson and Ballard, 1999) used in the configuration of the Met Office Global Atmosphere version 6.1 (Walters et al., 2017). Which was the version of the Unified Model used operationally by the Met Office for global weather and climate prediction. More precisely, the ice-*
10 *snow concentrations was computed with the moment parameterization developed by (Field et al., 2007) and the mass-diameter relationship from Cotton et al., (2013). Here, we suggest to use the new parameterization developed in our study for ice-snow concentrations when IWC are larger than 0.1 g.m^{-3}. Otherwise, we suggest to keep either the original version of Field et al., (2007) parameterization with the Cotton et al., (2013) mass size relationship or the original version of Field et al., (2007) parameterization with A as function of temperature which would be a fit of the 25th percentile of A in MCS reflectivity zone 4*
15 *(see Table C12 in Appendices C). We showed that IWC tend to be similar as function of temperature and MCS reflectivity zone, suggesting that IWC-Z-T relationship developed by Protat et al., (2016) would be available for IWC larger than 0.1g.m-3 in tropical MCS. In other words there is a confident relationship between IWC, Z and T in tropical MCS. Then, for the evaluation of NWP, we suggest to define the MCS reflectivity zones using the 25th percentiles of IWC as the lower limit of each MCS reflectivity zones (see Table C2 in Appendices C). Hence, for each MCS reflectivity zone visible extinction, hydrometeors*
20 *concentrations (NT_{50}, NT_{500}, M_2 and M_3), reflectivity factors at 94GHz and vertical velocities from NWP can be compared with the findings of this study (see Table in Appendices C). This methodology should help to identify where NWP fails to represent the links between different parameters and IWC. Indeed, study the spatiotemporal variability of IWC in MCS is a complex topic. It needs a time reference and a space reference. For MCS, the time reference can be its life cycle, but there are MCS that have a more complex life cycle than others (merging of MCS, a new growing stage after a decaying stage). Concerning*
25 *the space reference, there is a common view which is to observe the MCS from its most active area; its convective part. There are two difficulties to take into account here. First, there are very few direct measurement of cloud microphysic in the very convective area of MCS. Second, MCS can be the aggregation of many convective cells that can be well or not well organized (Houze 2004). Moreover, we saw that large IWC tend to be more associated to vertical movement than lower IWC, but it is not always true.*
30 *This is why we propose to test NWP using the statistic performed in this study, by testing the different conditions of others microphysical parameters observed for a given IWC and temperature.*

Finally, several findings from this study suggest more investigations on the variability on the relationship between projected surface and mass of ice hydrometeors encountered in underlying observations. Indeed, we find that ice "density" is similar as a function of *T* and *Z* reflectivity ranges in all 4 MCS locations. Hence, this is referring to the possibility to investigate a
35 surface-mass relationship in MCS that should be a function of *T* and *Z*. Estimating that aerosol loads and corresponding CCN and IN properties may be more or less different in these four locations (continental aerosol over Africa with a strong influence of dust from Sahara, more cleaner troposphere over the Indian ocean, merging of continental and oceanic influences), we stipulate the need of investigating secondary ice production processes, that seem to regulate the concentrations of ice hydrometeors beyond 55μm.

Commenté [EF34]: R2#6

Commenté [EF35]: R2#7

Author contribution

Emmanuel Fontaine, Julien Delanoë, Alfons Schwarzenboëck and Alain Protat for conceptualized this study. John Walter Strapp, Lyle Edward Lilie, Emmanuel Fontaine, Delphine Leroy, Julien Delanoë and Alain Protat for data curation of this study. John Walter Strapp, Lyle Edward Lilie, Delphine Leroy, Julien Delanoë and Emmanuel Fontaine to perform the formal analysis. Alain Protat and Fabien Dezitter for funding acquisition for campaign observations. Alfons Schwarzenboëck, Lyle Edward Lilie, John Walter Strapp, Alain Protat Delphine Leroy, Julien Delanoë and Emmanuel Fontaine for investigations performed in this study. Lyle Edward Lilie, Delphine Leroy, Julien Delanoë and Emmanuel Fontaine for developing methodology used in this study. John Walter Strapp, Fabien Dezitter and Alfons Schwarzenboëck for the project administration. Alfons Schwarzenboëck, John Walter Strapp and Julien Delanoë for providing resources. Lyle Edward Lilie, Delphine Leroy and Emmanuel Fontaine for the development of software used in this study. Alfons Schwarzenboëck for the supervision of this study. Emmanuel Fontaine to provide visualization.

Emmanuel Fontaine for writing original draft. Alfons Schwarzenboëck, Alain Protat, John Walter Strapp, Fabien Dezitter and Julien Delanoë for writing review and editing.

Data availability

The HAIC-HIWC dataset that has been used within this study is shared within the European and North American HAIC/HIWC community for analysis and completion of aircraft industry/rulemaking and science objectives. A data sharing protocol has to be agreed upon and signed by all the parties. This means that post-processed data will be available to public not before January 2021. Therefore we cannot reply positively to demands TS5 and TS11, since rulemaking is actually ongoing within FAA and EASA aviation safety agencies, thereby processing the HAIC/HIWC data set. Concerning the dataset for the campaigns of observations of the Megha-Tropiques project: optical array probes data are available by contacting Alfons Schwarzenboëck and radar data are available by contacting Julien Delanoë.

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Appendices A

Figure A1 shows median total concentration (N_T) as a function of T and MCS reflectivity zone (N_T) for the merged datasets where concentrations of ice hydrometeors are integrating beyond 15µm:

$$N_T = \sum_{Dmax=15}^{Dmax=12845} N(D_{max}) \cdot \Delta D_{max} \qquad [L^{-1}] \qquad\qquad (A1)$$

Median N_T systematically increase with MCS reflectivity zone and altitude, however with significant overlap of 25th and 75th percentiles of neighboring MCS reflectivity zones. Measurement uncertainty on concentrations given for small hydrometeors is about ±100% (Baumgardner et al., 2017).
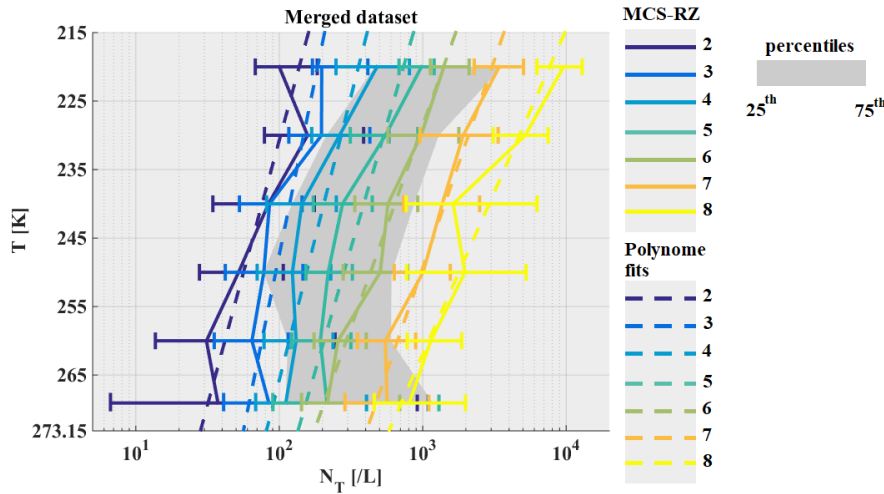
Figure A1: Same as Figure 5, but for concentrations of hydrometeors integrated beyond D_{max} =15µm in [L^{-1}].

Figure A2 (a), Figure A2 (b), Figure A2 (c), and Figure A2 (d) show MRD-N_T of MCS in the different tropical locations. For MCS over Darwin and Cayenne, in all MCS reflectivity zones MRD-N_T are smaller than the measurement uncertainty, whereas for Niamey data this is the case only in MCS reflectivity zones 2, 5, 6 and 7. MCS over Maldives Islands yield significantly larger MRD-N_T than the measurement uncertainty, and those are primarily positive. Hence, MCS over Maldives Islands have larger concentrations of hydrometeors for a same range of T and Z, than the three other types of tropical MCS. However, these larger concentrations observed do not concern zones where highest concentrations of hydrometeors were observed. For example, in MCS reflectivity zone 4 where MRD-N_T is reaching 1000%, N_T for the Maldives dataset are approximately 1000

L^{-1}, which is similar to N$_T$ observed in MCS reflectivity zones 7 and 8 for the same range of T $\in$ [235K; 245K[for the merged dataset. We recall that identical image data processing to remove shattering artefacts and to correct for out of focus images (Field et al., 2003; Korolev and Isaac, 2005; Leroy et al., 2016) have been applied for all 4 tropical datasets. Also the presence of super cooled droplets has been investigated (RICE, CDP probe), and few periods with super cooled water content have been removed for this study. Moreover, we show in section 5.5 that MCSs over Maldives Islands tend to have smaller max(D$_{max}$) especially in MCS reflectivity zones 4, 5, 6 and 7 compared to the other MCS locations and that concentrations beyond 500µm in Maldives Islands observations are in the same range as the other types of MCS.
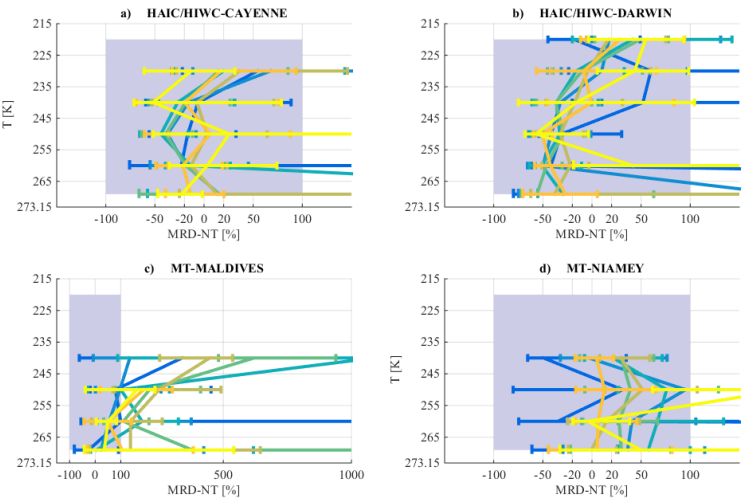
Figure A2: Same as Figure 6, but for MRD-NT.

Appendices B: impact of updraft and downdraft on Median relative errors
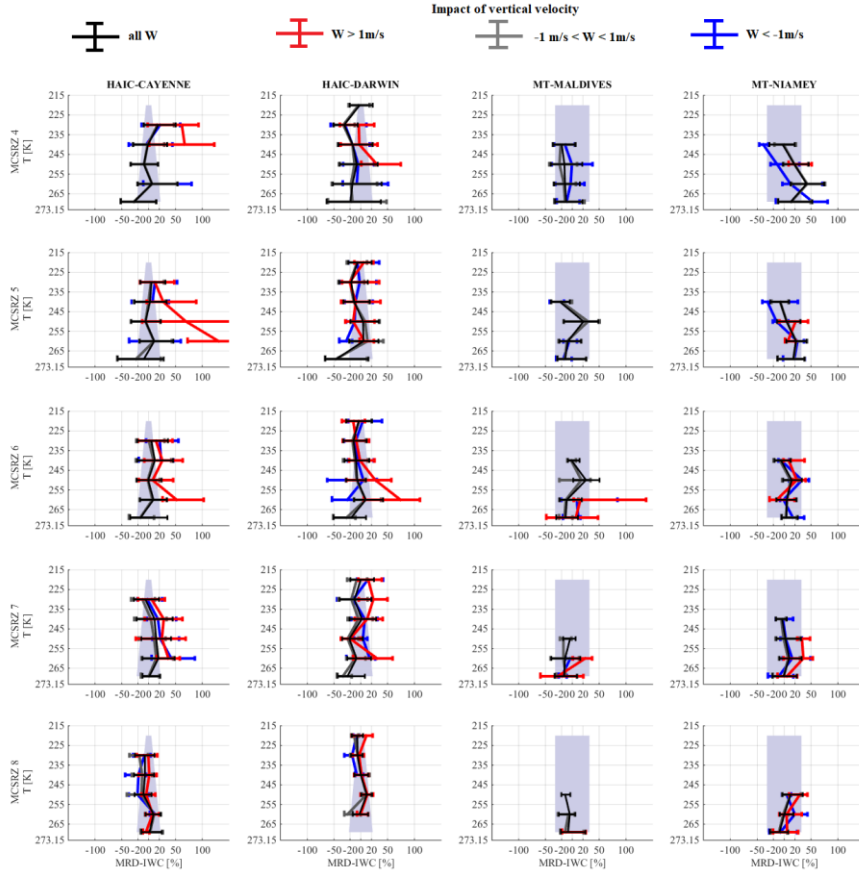
Figure B 1: Median relative difference of IWC (MRD-IWC) with regards to median IWC calculated for the merged dataset in each MCS reflectivity zone (Figure 5-a). Results are sorted as function of MCSRZ 4 (top line) to MCSRZ 8 bottom line. Blue lines represent MRD-IWC for vertical velocity smaller than -1m/s. Grey lines represent MRD-IWC for vertical velocity larger than -1m/s and smaller than 1m/s. Red lines represent MRD-IWC for vertical velocity larger 1m/s. The black lines represent MRD-IWC when there is no distinction as function of vertical velocity (same as in Figure 5-b, c, d, e).
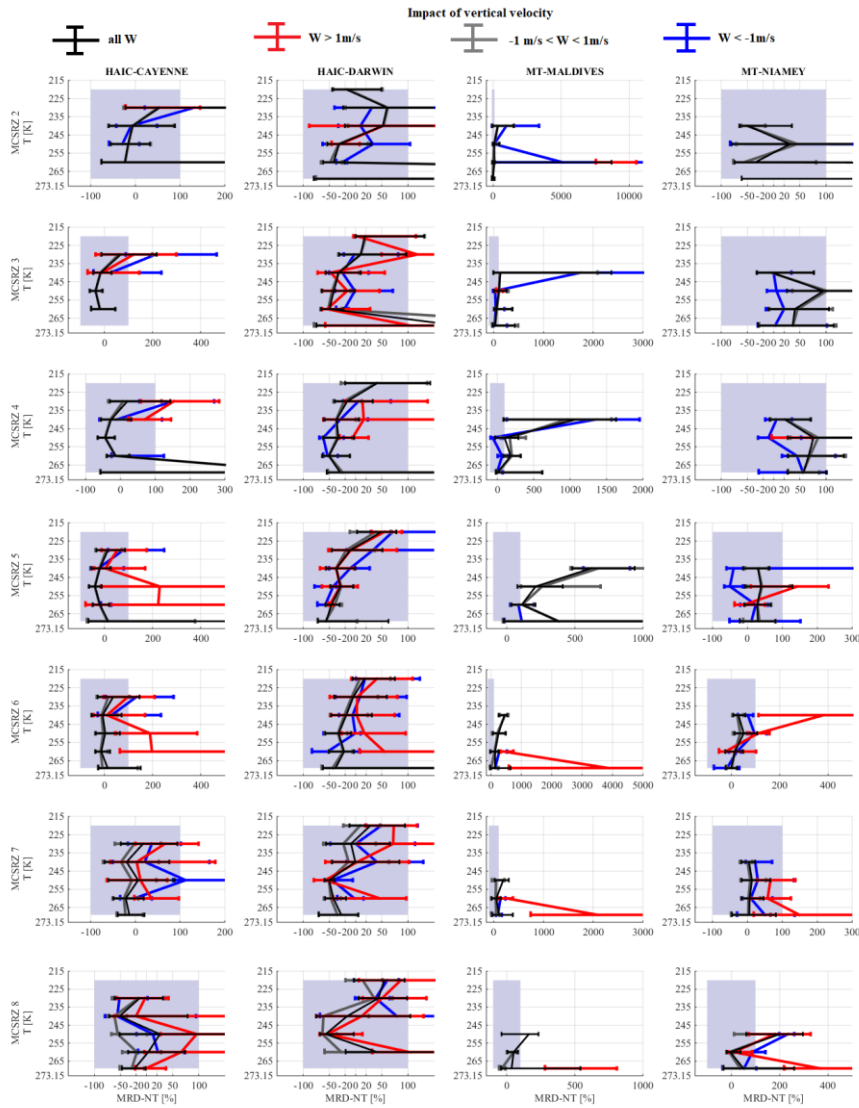
Figure B2: Median relative difference of total concentration of hydrometeors (MRD-NT) with regards to median total concentrations calculated for the merged dataset in each MCS reflectivity zone (Figure 8-a). Results are sorted as function of MCSRZ 2 (top line) to MCSRZ 8 bottom line. Blue lines represent MRD-NT for vertical velocity smaller than -1m/s. Grey lines represent MRD-NT for vertical velocity larger than -1m/s and smaller than 1m/s. Red lines represent MRD-NT for vertical velocity larger 1m/s. The black lines represent MRD-NT when there is no distinction as function of vertical velocity (same as in Figure 8-b, c, d, e).
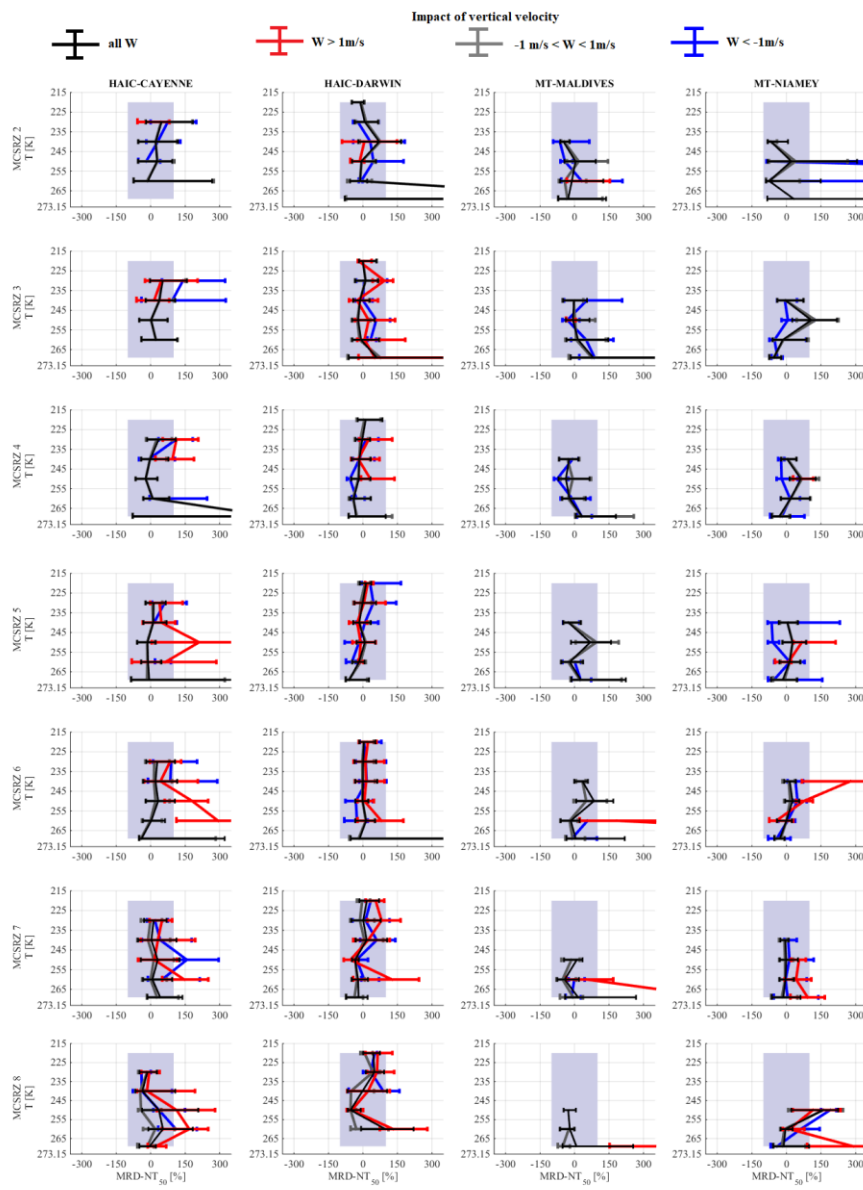
Figure B3: Median relative difference of concentration of hydrometeors summed over Dmax for Dmax larger than 50μm (MRD-NT$_{50}$) with regards to median total concentrations calculated for the merged dataset in each MCS reflectivity zone (Figure 9-a). Results are sorted as function of MCSRZ 2 (top line) to MCSRZ 8 bottom line. Blue lines represent MRD-NT$_{50}$ for vertical velocity smaller than -1m/s. Grey lines represent MRD-NT$_{50}$ for vertical velocity larger than -1m/s and smaller than 1m/s. Red lines represent MRD-NT$_{50}$ for vertical velocity larger 1m/s. The black lines represent MRD-NT$_{50}$ when there is no distinction as function of vertical velocity (same as in Figure 9-b, c, d, e).

Appendices C: Tables.

Table C 1: Percentile of Radar reflectivity factors (Z) in [dBZ], shown in solid line in Figure 1.

T [K]	1rst [dBZ]	10th [dBZ]	30th [dBZ]	50th [dBZ]	70th [dBZ]	90th [dBZ]	99th [dBZ]
172.5	-7.00	-3.45	-0.96	0.90	2.83	5.32	11.70
177.5	-8.33	-5.14	-1.96	0.43	2.81	5.49	8.69
182.5	-9.44	-5.96	-3.01	-0.56	2.39	5.51	8.92
187.5	-9.93	-6.66	-4.07	-1.67	1.08	5.33	8.53
192.5	-10.15	-6.79	-4.14	-1.85	0.63	4.97	8.78
197.5	-11.08	-6.95	-3.80	-1.06	1.48	5.18	9.24
202.5	-12.08	-7.53	-3.87	-0.74	2.13	5.37	9.82
207.5	-13.25	-8.06	-4.00	-0.53	2.69	5.75	10.22
212.5	-16.88	-8.65	-4.11	-0.44	3.05	6.28	10.66
217.5	-26.79	-10.67	-4.54	-0.44	3.37	6.93	11.27
222.5	-30.13	-12.58	-5.21	-0.30	3.88	7.71	12.01
227.5	-28.30	-13.55	-5.17	0.06	4.61	8.60	12.94
232.5	-26.65	-13.08	-4.49	0.75	5.54	9.70	14.15
237.5	-26.54	-11.80	-3.26	2.11	6.76	10.92	15.08
242.5	-24.53	-10.27	-1.76	3.62	7.96	11.76	15.76
247.5	-23.78	-8.58	-0.20	5.16	9.13	12.51	15.98
252.5	-22.15	-6.76	1.64	6.58	10.14	13.17	16.37
257.5	-22.05	-5.97	3.18	7.89	11.09	13.78	16.86
262.5	-21.30	-5.83	4.01	8.59	11.44	14.11	17.43
267.5	-21.90	-5.65	3.89	8.26	11.03	13.72	17.34
272.5	-20.68	-5.77	2.88	6.86	9.57	12.60	16.66
277.5	-17.52	-4.84	2.73	6.25	8.90	12.07	16.42
282.5	-15.52	-6.62	-1.12	2.30	5.03	8.33	15.06
287.5	-14.40	-7.55	-2.90	0.40	3.18	7.88	38.13
292.5	-13.67	-7.94	-4.07	-1.37	1.04	4.55	10.49
297.5	-12.95	-7.52	-4.00	-1.18	2.90	27.11	42.87
302.5	-10.98	-4.72	0.81	8.39	14.21	29.74	44.98

5   **Table C 2: Ice water content (IWC) in [g m⁻³] (Figure 5-a)**

MCS RZ		T [215;225[	T ∈ [225;235[	T∈ [235,245[	T∈ [245;255[	T∈ [255;265[	T ∈ [265;273,15[
2	25th	0.016	0.017	0.016	0.016	0.016	0.016
	50th	**0.024**	**0.024**	**0.025**	**0.023**	**0.025**	**0.026**
	75th	0.029	0.034	0.042	0.033	0.041	0.063
3	25th	0.042	0.032	0.031	0.040	0.043	0.052
	50th	**0.053**	**0.052**	**0.054**	**0.062**	**0.070**	**0.098**
	75th	0.062	0.076	0.084	0.093	0.111	0.148
4	25th	0.081	0.082	0.090	0.112	0.149	0.136
	50th	**0.110**	**0.119**	**0.130**	**0.160**	**0.212**	**0.198**
	75th	0.138	0.163	0.180	0.216	0.298	0.284
5	25th	0.176	0.199	0.221	0.272	0.316	0.246
	50th	**0.220**	**0.261**	**0.295**	**0.351**	**0.413**	**0.342**
	75th	0.276	0.340	0.395	0.454	0.508	0.476

6	25th	0.402	0.430	0.476	0.561	0.556	0.479
	50th	**0.538**	**0.572**	**0.628**	**0.690**	**0.701**	**0.624**
	75th	0.662	0.742	0.822	0.818	0.863	0.762
7	25th	0.869	0.767	0.994	1.057	1.102	0.928
	50th	**1.083**	**1.069**	**1.294**	**1.295**	**1.402**	**1.204**
	75th	1.365	1.424	1.640	1.704	1.797	1.526
8	25th	1.604	1.644	1.951	2.116	2.009	1.443
	50th	**1.810**	**2.051**	**2.306**	**2.515**	**2.268**	**1.827**
	75th	1.998	2.352	2.690	2.907	2.555	2.282

Table C 3: visible extinction (σ) in [m^{-1}] (Figure 6-a).

MCS RZ		T $\in$[215;225[	T$\in$ [225;235[	T$\in$ [235,245[	T $\in$ [245;255[	T$\in$ [255;265[	T [265;273,15[
2	25th	0.00047	0.00071	0.00044	0.00045	0.00031	0.00013
	50th	**0.00097**	**0.00112**	**0.00102**	**0.00088**	**0.00078**	**0.00060**
	75th	0.00125	0.00172	0.00169	0.00128	0.00184	0.00413
3	25th	0.00253	0.00188	0.00166	0.00140	0.00135	0.00118
	50th	**0.00321**	**0.00262**	**0.00225**	**0.00205**	**0.00226**	**0.00217**
	75th	0.00363	0.00352	0.00316	0.00310	0.00337	0.00453
4	25th	0.00521	0.00400	0.00342	0.00355	0.00400	0.00284
	50th	**0.00616**	**0.00529**	**0.00466**	**0.00500**	**0.00542**	**0.00410**
	75th	0.00803	0.00697	0.00640	0.00685	0.00769	0.00762
5	25th	0.00978	0.00855	0.00785	0.00765	0.00749	0.00457
	50th	**0.01237**	**0.01101**	**0.01042**	**0.01030**	**0.00997**	**0.00693**
	75th	0.01484	0.01413	0.01348	0.01292	0.01281	0.01223
6	25th	0.01972	0.01674	0.01550	0.01512	0.01169	0.00900
	50th	**0.02478**	**0.02256**	**0.02088**	**0.01969**	**0.01596**	**0.01173**
	75th	0.03040	0.02904	0.02745	0.02387	0.01995	0.01515
7	25th	0.03969	0.02892	0.03133	0.02726	0.02393	0.01722
	50th	**0.04893**	**0.04083**	**0.04149**	**0.03386**	**0.03103**	**0.02404**
	75th	0.06096	0.05435	0.05773	0.04571	0.04127	0.03271
8	25th	0.06965	0.05976	0.05243	0.05033	0.04139	0.01991
	50th	**0.07865**	**0.07116**	**0.06944**	**0.06461**	**0.05125**	**0.03443**
	75th	0.08871	0.08247	0.08206	0.07942	0.06088	0.04287

5   **Table C 4: Total concentration beyond 15μm (N_T) in [L^{-1}] (Figure 8-a).**

MCS RZ		T $\in$[215;225[	T$\in$ [225;235[	T$\in$ [235,245[	T$\in$ [245;255[	T$\in$ [255;265[	T [265;273,15[
2	25th	3.65E+01	7.73E+01	3.12E+01	2.51E+01	1.25E+01	6.01E+00
	50th	**7.41E+01**	**1.53E+02**	**8.32E+01**	**5.03E+01**	**3.11E+01**	**4.26E+01**
	75th	1.58E+02	3.62E+02	1.73E+02	1.20E+02	6.54E+02	2.14E+03
3	25th	1.67E+02	1.11E+02	5.11E+01	3.99E+01	3.24E+01	3.58E+01
	50th	**1.91E+02**	**1.92E+02**	**8.26E+01**	**7.46E+01**	**5.95E+01**	**7.92E+01**
	75th	3.79E+02	4.22E+02	1.42E+02	1.36E+02	1.10E+02	7.41E+02
4	25th	2.20E+02	1.56E+02	7.86E+01	6.92E+01	7.37E+01	6.47E+01

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MCS RZ		T ∈[215;225[	T∈ [225,235[	T∈ [235,245[	T∈ [245,255[	T∈ [255,265[	T∈ [265,273,15[
	50th	**4.65E+02**	**2.42E+02**	**1.34E+02**	**1.22E+02**	**1.23E+02**	**1.06E+02**
	75th	7.04E+02	5.41E+02	2.33E+02	2.27E+02	2.22E+02	4.02E+02
5	25th	6.63E+02	3.07E+02	1.70E+02	1.44E+02	1.19E+02	8.88E+01
	50th	**9.67E+02**	**5.45E+02**	**2.72E+02**	**2.10E+02**	**1.87E+02**	**2.14E+02**
	75th	1.17E+03	9.25E+02	4.39E+02	3.14E+02	3.11E+02	1.37E+03
6	25th	1.13E+03	5.70E+02	3.32E+02	2.73E+02	1.71E+02	1.38E+02
	50th	**1.40E+03**	**9.66E+02**	**5.64E+02**	**4.74E+02**	**2.51E+02**	**2.15E+02**
	75th	2.10E+03	1.77E+03	9.09E+02	7.59E+02	3.93E+02	6.93E+02
7	25th	2.28E+03	9.57E+02	7.26E+02	6.30E+02	3.37E+02	2.70E+02
	50th	**3.40E+03**	**1.91E+03**	**1.35E+03**	**9.98E+02**	**5.37E+02**	**5.58E+02**
	75th	5.05E+03	3.35E+03	2.45E+03	1.53E+03	8.78E+02	1.10E+03
8	25th	6.26E+03	3.08E+03	7.64E+02	7.81E+02	7.63E+02	4.61E+02
	50th	**9.55E+03**	**5.13E+03**	**1.68E+03**	**1.96E+03**	**1.13E+03**	**8.05E+02**
	75th	1.28E+04	7.37E+03	6.09E+03	5.20E+03	1.82E+03	1.99E+03

Table C 5: Total concentration since 50µm ($N_{T\,50}$) in [L^{-1}] (Figure 9-a).

MCS RZ		T ∈[215;225[	T∈ [225,235[	T∈ [235,245[	T∈ [245,255[	T∈ [255,265[	T [265,273,15[
2	25th	8.65E+00	1.72E+01	5.24E+00	3.98E+00	1.18E+00	7.57E-01
	50th	**2.13E+01**	**3.21E+01**	**1.68E+01**	**9.13E+00**	**4.49E+00**	**3.32E+00**
	75th	3.99E+01	5.77E+01	3.26E+01	1.90E+01	1.21E+01	4.28E+01
3	25th	4.16E+01	3.05E+01	1.35E+01	8.50E+00	4.42E+00	2.18E+00
	50th	**4.75E+01**	**4.70E+01**	**2.19E+01**	**1.39E+01**	**8.82E+00**	**4.79E+00**
	75th	8.35E+01	7.79E+01	3.68E+01	2.60E+01	1.74E+01	2.07E+01
4	25th	6.38E+01	4.66E+01	2.15E+01	1.47E+01	1.02E+01	7.28E+00
	50th	**1.05E+02**	**7.25E+01**	**3.56E+01**	**2.78E+01**	**1.72E+01**	**1.38E+01**
	75th	1.64E+02	1.23E+02	6.21E+01	4.49E+01	3.03E+01	2.46E+01
5	25th	1.57E+02	9.14E+01	4.70E+01	3.33E+01	1.83E+01	1.11E+01
	50th	**2.06E+02**	**1.39E+02**	**7.26E+01**	**5.66E+01**	**3.03E+01**	**2.30E+01**
	75th	2.49E+02	2.10E+02	1.14E+02	8.17E+01	4.78E+01	4.39E+01
6	25th	2.68E+02	1.55E+02	9.50E+01	7.22E+01	3.00E+01	1.78E+01
	50th	**3.28E+02**	**2.47E+02**	**1.50E+02**	**1.06E+02**	**4.91E+01**	**2.86E+01**
	75th	4.84E+02	4.12E+02	2.34E+02	1.45E+02	7.25E+01	6.47E+01
7	25th	5.65E+02	2.49E+02	2.07E+02	1.36E+02	7.20E+01	3.35E+01
	50th	**7.83E+02**	**4.92E+02**	**3.41E+02**	**1.90E+02**	**1.13E+02**	**9.02E+01**
	75th	1.12E+03	8.00E+02	6.20E+02	3.08E+02	1.84E+02	1.74E+02
8	25th	1.34E+03	7.26E+02	2.06E+02	1.90E+02	1.82E+02	7.29E+01
	50th	**1.82E+03**	**1.09E+03**	**3.86E+02**	**4.01E+02**	**2.83E+02**	**1.57E+02**
	75th	2.30E+03	1.51E+03	1.31E+03	9.29E+02	4.95E+02	3.10E+02

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Table C 6: Total concentration since 500µm ($N_{T\,500}$) in [L^{-1}] (Figure 10-a).

MCS RZ		T ∈[215;225[	T∈ [225,235[	T∈ [235,245[	T∈ [245,255[	T∈ [255,265[	T∈ [265,273,15[

	25th	0.00E+00	1.96E-02	4.08E-02	1.33E-01	8.31E-02	1.68E-02
2	**50th**	**5.20E-02**	**7.23E-02**	**1.73E-01**	**3.41E-01**	**2.86E-01**	**8.60E-02**
	75th	2.05E-01	1.88E-01	4.13E-01	7.27E-01	6.52E-01	3.37E-01
	25th	1.12E+00	4.23E-01	8.37E-01	1.09E+00	8.64E-01	3.57E-01
3	**50th**	**1.57E+00**	**8.68E-01**	**1.33E+00**	**1.61E+00**	**1.40E+00**	**6.67E-01**
	75th	2.03E+00	1.43E+00	1.91E+00	2.22E+00	2.07E+00	1.29E+00
	25th	2.77E+00	1.92E+00	2.26E+00	2.96E+00	2.73E+00	1.67E+00
4	**50th**	**3.77E+00**	**2.73E+00**	**3.15E+00**	**3.95E+00**	**3.91E+00**	**2.40E+00**
	75th	4.54E+00	3.84E+00	4.40E+00	5.06E+00	5.51E+00	3.52E+00
	25th	5.61E+00	5.55E+00	5.71E+00	5.83E+00	5.29E+00	2.82E+00
5	**50th**	**7.78E+00**	**7.26E+00**	**7.68E+00**	**7.78E+00**	**7.19E+00**	**4.15E+00**
	75th	9.34E+00	9.48E+00	1.01E+01	1.02E+01	8.98E+00	6.60E+00
	25th	1.25E+01	1.27E+01	1.19E+01	1.21E+01	9.61E+00	3.83E+00
6	**50th**	**1.55E+01**	**1.60E+01**	**1.56E+01**	**1.45E+01**	**1.24E+01**	**6.07E+00**
	75th	1.97E+01	2.02E+01	2.06E+01	1.74E+01	1.53E+01	9.17E+00
	25th	2.26E+01	2.00E+01	2.41E+01	2.01E+01	1.83E+01	8.29E+00
7	**50th**	**2.83E+01**	**2.65E+01**	**3.08E+01**	**2.52E+01**	**2.42E+01**	**1.54E+01**
	75th	3.34E+01	3.35E+01	3.96E+01	3.44E+01	3.35E+01	2.40E+01
	25th	1.95E+01	2.69E+01	3.35E+01	3.71E+01	2.67E+01	1.06E+01
8	**50th**	**2.38E+01**	**3.75E+01**	**4.89E+01**	**4.99E+01**	**3.73E+01**	**2.43E+01**
	75th	2.85E+01	5.23E+01	7.29E+01	6.87E+01	4.86E+01	3.80E+01

Table C 7: pre-factor α of mass size relationship in [g cm$^{-\beta}$] (Figure 12-a).

MCS RZ		$T \in [215;225[$	$T \in [225,235[$	$T \in [235,245[$	$T \in [245,255[$	$T \in [255,265[$	$T \in [265,273,15[$
	25th	0.00095	0.00042	0.00053	0.00086	0.00152	0.00114
2	**50th**	**0.00269**	**0.00099**	**0.00128**	**0.00172**	**0.00341**	**0.00322**
	75th	0.00574	0.00276	0.00320	0.00312	0.00876	0.00809
	25th	0.00092	0.00059	0.00099	0.00149	0.00190	0.00319
3	**50th**	**0.00126**	**0.00115**	**0.00181**	**0.00241**	**0.00341**	**0.00687**
	75th	0.00154	0.00197	0.00299	0.00379	0.00630	0.01077
	25th	0.00142	0.00126	0.00184	0.00250	0.00343	0.00385
4	**50th**	**0.00180**	**0.00198**	**0.00274**	**0.00340**	**0.00505**	**0.00592**
	75th	0.00235	0.00282	0.00404	0.00470	0.00711	0.00826
	25th	0.00195	0.00188	0.00267	0.00333	0.00422	0.00481
5	**50th**	**0.00241**	**0.00258**	**0.00351**	**0.00414**	**0.00562**	**0.00658**
	75th	0.00300	0.00336	0.00455	0.00529	0.00742	0.00950
	25th	0.00189	0.00210	0.00324	0.00419	0.00486	0.00595
6	**50th**	**0.00271**	**0.00285**	**0.00403**	**0.00513**	**0.00625**	**0.00782**
	75th	0.00334	0.00380	0.00492	0.00638	0.00793	0.01014
	25th	0.00163	0.00253	0.00325	0.00466	0.00527	0.00594
7	**50th**	**0.00245**	**0.00351**	**0.00415**	**0.00560**	**0.00637**	**0.00774**
	75th	0.00326	0.00447	0.00517	0.00668	0.00776	0.01077
	25th	0.00214	0.00302	0.00363	0.00405	0.00538	0.00637
8	**50th**	**0.00418**	**0.00485**	**0.00496**	**0.00558**	**0.00712**	**0.00953**
	75th	0.00748	0.00750	0.00679	0.00819	0.01173	0.01886

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Table C 8: exponent of mass-size relationship β [no dimension] (Figure 11-a).

MCS RZ		T ∈[215;225[	T∈ [225;235[	T∈ [235,245[	T∈ [245;255[	T∈ [255;265[	T [265;273,15[
	25th	1.67	1.54	1.58	1.66	1.74	1.66
2	**50th**	**1.86**	**1.76**	**1.78**	**1.85**	**1.95**	**1.93**
	75th	2.07	1.96	1.99	2.02	2.21	2.08
	25th	1.80	1.65	1.75	1.79	1.86	1.86
3	**50th**	**1.88**	**1.82**	**1.91**	**1.92**	**2.00**	**2.08**
	75th	1.95	1.96	2.04	2.05	2.17	2.35
	25th	1.90	1.82	1.87	1.91	1.96	1.94
4	**50th**	**1.98**	**1.94**	**1.99**	**2.02**	**2.10**	**2.10**
	75th	2.03	2.04	2.10	2.12	2.22	2.26
	25th	1.99	1.91	1.96	1.97	2.02	2.05
5	**50th**	**2.07**	**2.00**	**2.06**	**2.05**	**2.11**	**2.16**
	75th	2.12	2.08	2.14	2.14	2.21	2.29
	25th	1.91	1.92	2.01	2.04	2.03	2.04
6	**50th**	**2.06**	**2.01**	**2.09**	**2.11**	**2.11**	**2.16**
	75th	2.14	2.11	2.16	2.19	2.20	2.26
	25th	1.86	1.97	1.99	2.06	2.06	2.07
7	**50th**	**2.00**	**2.08**	**2.08**	**2.13**	**2.13**	**2.15**
	75th	2.10	2.17	2.16	2.19	2.19	2.26
	25th	1.93	1.98	1.97	2.01	2.07	2.10
8	**50th**	**2.11**	**2.13**	**2.08**	**2.13**	**2.16**	**2.21**
	75th	2.27	2.25	2.19	2.22	2.29	2.34

Table C 9: $max(D_{max})$ in [cm] (Figure 13-a).

MCS RZ		T ∈[215;225[	T∈ [225;235[	T∈ [235,245[	T∈ [245;255[	T∈ [255;265[	T [265;273,15[
	25th	0.048	0.061	0.090	0.105	0.125	0.105
2	**50th**	**0.090**	**0.095**	**0.110**	**0.140**	**0.195**	**0.165**
	75th	0.120	0.115	0.140	0.195	0.361	0.255
	25th	0.155	0.120	0.145	0.155	0.205	0.245
3	**50th**	**0.175**	**0.145**	**0.190**	**0.205**	**0.310**	**0.435**
	75th	0.195	0.180	0.265	0.295	0.620	0.762
	25th	0.205	0.170	0.195	0.215	0.280	0.332
4	**50th**	**0.235**	**0.212**	**0.260**	**0.347**	**0.525**	**0.445**
	75th	0.265	0.270	0.380	0.615	0.790	0.775
	25th	0.235	0.225	0.265	0.280	0.350	0.415
5	**50th**	**0.280**	**0.280**	**0.375**	**0.405**	**0.625**	**0.615**
	75th	0.340	0.355	0.575	0.685	0.820	0.795
	25th	0.245	0.245	0.310	0.335	0.385	0.475
6	**50th**	**0.315**	**0.310**	**0.460**	**0.665**	**0.625**	**0.735**
	75th	0.395	0.435	0.680	0.880	0.810	0.838
	25th	0.225	0.270	0.325	0.445	0.480	0.557
7	**50th**	**0.285**	**0.397**	**0.452**	**0.675**	**0.675**	**0.745**

	75th	0.375	0.595	0.645	0.846	0.810	0.825
	25th	0.335	0.315	0.395	0.445	0.445	0.455
8	**50th**	**0.455**	**0.480**	**0.555**	**0.632**	**0.595**	**0.635**
	75th	0.665	0.730	0.790	0.825	0.740	0.745

Table C 10: Second Moment of PSD (M_2) [m^{-1}] (Figure 14-a).

MCS RZ		T∈ [215;225[	T∈ [225;235[	T∈ [235,245[	T∈ [245;255[	T∈ [255;265[	T ∈ [265;273,15[
	25th	4.33E-04	5.99E-04	3.90E-04	4.41E-04	3.03E-04	1.22E-04
2	**50th**	**8.04E-04**	**9.32E-04**	**8.67E-04**	**8.18E-04**	**7.10E-04**	**5.50E-04**
	75th	9.78E-04	1.37E-03	1.42E-03	1.20E-03	1.57E-03	2.62E-03
	25th	2.26E-03	1.71E-03	1.50E-03	1.36E-03	1.26E-03	1.01E-03
3	**50th**	**2.85E-03**	**2.32E-03**	**2.03E-03**	**1.98E-03**	**2.07E-03**	**1.83E-03**
	75th	3.21E-03	3.08E-03	2.80E-03	2.80E-03	3.01E-03	3.50E-03
	25th	4.59E-03	3.60E-03	3.10E-03	3.30E-03	3.70E-03	2.71E-03
4	**50th**	**5.43E-03**	**4.73E-03**	**4.17E-03**	**4.60E-03**	**4.99E-03**	**3.72E-03**
	75th	6.99E-03	6.10E-03	5.69E-03	6.38E-03	6.91E-03	6.39E-03
	25th	8.78E-03	7.82E-03	7.20E-03	7.11E-03	7.07E-03	4.43E-03
5	**50th**	**1.13E-02**	**9.99E-03**	**9.56E-03**	**9.55E-03**	**9.19E-03**	**6.49E-03**
	75th	1.34E-02	1.27E-02	1.23E-02	1.21E-02	1.17E-02	1.07E-02
	25th	1.79E-02	1.60E-02	1.42E-02	1.40E-02	1.10E-02	8.29E-03
6	**50th**	**2.28E-02**	**2.09E-02**	**1.95E-02**	**1.83E-02**	**1.48E-02**	**1.06E-02**
	75th	2.77E-02	2.66E-02	2.53E-02	2.25E-02	1.85E-02	1.38E-02
	25th	3.57E-02	2.75E-02	2.93E-02	2.57E-02	2.27E-02	1.53E-02
7	**50th**	**4.41E-02**	**3.79E-02**	**3.86E-02**	**3.22E-02**	**2.96E-02**	**2.21E-02**
	75th	5.39E-02	4.94E-02	5.29E-02	4.31E-02	3.95E-02	3.11E-02
	25th	6.02E-02	5.30E-02	4.92E-02	4.77E-02	3.96E-02	1.85E-02
8	**50th**	**6.73E-02**	**6.39E-02**	**6.39E-02**	**6.21E-02**	**4.95E-02**	**3.23E-02**
	75th	7.41E-02	7.30E-02	7.36E-02	7.53E-02	5.84E-02	4.27E-02

5   **Table C 11: Third moment of PSD (M_3) in [1] (Figure 15-a).**

MCS RZ		T ∈[215;225[	T∈ [225;235[	T∈ [235,245[	T∈ [245;255[	T∈ [255;265[	T ∈ [265;273,15[
	25th	1.29E-07	1.30E-07	1.07E-07	1.43E-07	1.68E-07	5.16E-08
2	**50th**	**1.78E-07**	**2.09E-07**	**2.29E-07**	**2.98E-07**	**3.83E-07**	**1.92E-07**
	75th	2.12E-07	2.98E-07	4.00E-07	5.38E-07	6.36E-07	5.66E-07
	25th	7.85E-07	5.40E-07	6.75E-07	7.36E-07	8.89E-07	7.74E-07
3	**50th**	**1.06E-06**	**8.08E-07**	**9.69E-07**	**1.11E-06**	**1.56E-06**	**1.92E-06**
	75th	1.27E-06	1.08E-06	1.43E-06	1.67E-06	3.59E-06	5.23E-06
	25th	1.85E-06	1.47E-06	1.75E-06	2.15E-06	3.08E-06	2.52E-06
4	**50th**	**2.44E-06**	**1.99E-06**	**2.43E-06**	**3.57E-06**	**5.71E-06**	**3.98E-06**
	75th	3.08E-06	2.80E-06	3.61E-06	5.99E-06	1.13E-05	1.12E-05
	25th	4.13E-06	3.92E-06	4.59E-06	4.80E-06	5.95E-06	5.13E-06
5	**50th**	**5.55E-06**	**5.20E-06**	**6.64E-06**	**7.83E-06**	**1.08E-05**	**8.69E-06**
	75th	7.08E-06	6.84E-06	9.57E-06	1.13E-05	1.93E-05	1.93E-05

	25th	9.42E-06	8.92E-06	9.88E-06	9.93E-06	9.93E-06	8.90E-06
6	**50th**	**1.19E-05**	**1.17E-05**	**1.45E-05**	**1.77E-05**	**1.66E-05**	**1.75E-05**
	75th	1.43E-05	1.51E-05	1.93E-05	2.50E-05	2.54E-05	2.62E-05
	25th	1.66E-05	1.75E-05	1.98E-05	2.51E-05	2.37E-05	1.91E-05
7	**50th**	**2.02E-05**	**2.16E-05**	**2.63E-05**	**3.05E-05**	**3.35E-05**	**3.28E-05**
	75th	2.36E-05	2.71E-05	3.20E-05	3.82E-05	4.24E-05	4.25E-05
	25th	2.07E-05	2.20E-05	2.80E-05	3.13E-05	2.74E-05	1.54E-05
8	**50th**	**2.27E-05**	**2.69E-05**	**3.29E-05**	**4.16E-05**	**3.89E-05**	**2.84E-05**
	75th	2.45E-05	3.21E-05	4.30E-05	5.76E-05	5.22E-05	4.57E-05

Table C 12: coefficient *A* in [kg m^{-2}] (Figure 16-a).

MCS RZ		T $\in$[215;225[	T $\in$ [225;235[	T $\in$ [235;245[	T $\in$ [245;255[	T $\in$ [255;265[	T $\in$ [265;273,15[
	25th	0.021	0.018	0.018	0.019	0.017	0.019
2	**50th**	**0.031**	**0.025**	**0.032**	**0.031**	**0.041**	**0.048**
	75th	0.042	0.038	0.064	0.054	0.085	0.163
	25th	0.017	0.016	0.018	0.024	0.025	0.029
3	**50th**	**0.018**	**0.023**	**0.026**	**0.032**	**0.037**	**0.052**
	75th	0.020	0.030	0.036	0.041	0.051	0.071
	25th	0.017	0.019	0.023	0.027	0.034	0.037
4	**50th**	**0.020**	**0.025**	**0.029**	**0.034**	**0.042**	**0.048**
	75th	0.021	0.031	0.038	0.043	0.051	0.061
	25th	0.018	0.022	0.026	0.031	0.038	0.038
5	**50th**	**0.020**	**0.026**	**0.031**	**0.037**	**0.045**	**0.047**
	75th	0.023	0.030	0.037	0.045	0.053	0.061
	25th	0.021	0.024	0.028	0.033	0.042	0.047
6	**50th**	**0.023**	**0.027**	**0.032**	**0.037**	**0.048**	**0.057**
	75th	0.026	0.031	0.038	0.045	0.057	0.069
	25th	0.023	0.025	0.028	0.036	0.041	0.047
7	**50th**	**0.024**	**0.028**	**0.032**	**0.040**	**0.046**	**0.054**
	75th	0.027	0.031	0.038	0.044	0.053	0.064
	25th	0.025	0.029	0.032	0.035	0.041	0.048
8	**50th**	**0.027**	**0.032**	**0.038**	**0.039**	**0.045**	**0.060**
	75th	0.030	0.035	0.045	0.047	0.053	0.080

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Appendice D: summury of inter-comparison of ice microphysical properties in MCS.

Table D1 summarizes qualitatively the findings for IWC, visible extinction (σ), total concentrations ($N_{T,50}$ for D_{max}>50µm; $N_{T,500}$ for D_{max}>500µm), 2nd moment (M_2) and 3rd moment (M_3) of hydrometeor PSD, and largest hydrometeors sizes ($max(D_{max})$).

Table D1: Evaluation of parameter X (X for IWC, σ, $N_{T,55}$, $N_{T,500}$, , M_2, M_3 and $max(D_{max})$) , for each type of tropical MCS (Darwin, **Cayenne, Maldives Islands, Niamey) with respect to the global tropical dataset thereby comparing median values in corresponding MCS reflectivity zones. Two sub-columns for each type of MCS: The first column gives an evaluation of the main trend: $\cong$ if MRD-X is comparable to the uncertainty range, + if MRD-X is larger than the uncertainty range, - for smaller values. In the second sub-column are reported the number of exceptions with respect to the main trend (first column) with: Z(Y)$\cong$ or Z(Y)+ or Z(Y)-. Z number stands for a particular MCS reflectivity zone (with Z= 2, 3, 4, 5, 6, 7, 8) , Y number represents a particular T range (with**

Y=1 for T ∈ [265K; 273.15K[, Y=2 for T ∈ [255K, 265K[, Y=3 for T ∈ [245K; 255K[, Y=4 for T ∈ [235K; 245K[, Y=5 for T ∈ [225K; 235K[, and Y=6 for T ∈ [215K; 225K[.

With respect to median of	MCS over Darwin		MCS over Cayenne		Maldives Islands MCS		Niamey's MCS	
IWC	≅	4(6)+, 5(1)-	≅	4(1,5)-, 5(5)-	≅		≅	4(2)+
σ	≅	5(1)+	≅	8(1)-	≅		≅	2(4)-
$N_{T,55}$	≅	4(1)+	≅	3(1)+	≅		≅	8(3)+, 3(3)+
$N_{T,500}$	≅	8(1)+, 7(1)+	≅	8(3)+, 8(1)-	≅	7(4)+, 3(1)+	≅	8(1)-
M_2	≅	4(1)+, 5(1)+	≅	8(1)-, 2(1)+	≅		≅	4(6), 2(6)+
M_3	≅	8(1)+	≅	8(1)+, 2(1)+	≅		≅	2(1)+, 3(1,2,3)+ 4(1,2)+ 5(1)+
$max(D_{max})$	≅	2(2)+, 7(3,4)-	≅	6(3)-, 8(2)-, 8(3)+	-	8≅	+	6(1,2) ≅, 7 ≅, 8 ≅

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