1 **Contrasting Tropical Cyclone and non-Tropical Cyclone related Rainfall Drop Size**

2 **Distribution at Darwin, Australia**

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Abstract

3 In this study the rainfall drop size distribution (DSD) during the passage of seven tropical
4 cyclones (TCs) over Darwin is compared and contrasted with that associated with non-tropical
5 cyclone (non-TC) events, using the impact disdrometer data at the Darwin Atmospheric
6 Radiation and Measurement (ARM) site. The disparity of the DSD with respect to rainfall types
7 (between TC and non-TC conditions) and distance from TC centre is also examined. It is shown
8 that TC DSDs are statistically different from the non-TC DSDs, the former encompassing a
9 larger concentration of small to moderate drop sizes. The TC mass-weighted mean diameter
10 (D_m) is lower than the non-TC values at all rain rates and also for the different precipitation
11 types (convective, transition and stratiform). The TC DSD varies with distance from the TC
12 centre, as rainfall near the TC centre (< 60 km) comprises of relatively smaller drops which
13 are strongly evident at small to moderate rain rates (< 30 mm hr⁻¹). Such variations in the DSD
14 have implications for the parameters used in the algorithm that converts radar reflectivity to
15 rainfall rate in TCs, as well as for the analytical expressions used in describing the observed
16 DSD employed in cloud modelling parameterizations.

Keywords

17 Disdrometer, Cloud microphysics, Mass-weighted mean diameter, Drop concentration

1. Introduction

The rainfall drop size distribution (DSD) plays an important role in radar rainfall estimation and cloud-modelling studies (Tokay and Short, 1996; Radhakrishna and Rao, 2010; Handwerker and Straub, 2011; Tang et al., 2014). The pre-factor A and exponent b of the widely used radar reflectivity (Z) to rainfall rate (R) (Z - R) algorithm ($Z=AR^b$) are strongly dependant on the DSD. In cloud-modelling studies, knowledge of the DSD is important for understanding rainfall growth mechanisms through different microphysical processes (such as evaporation, collision and coalescence) and for parameterization of these processes. As such, knowledge of the rainfall DSD is essential for accurate representation of rainfall especially by (i) platforms employing radar remote sensing, for example satellite platforms (e.g. the GPM; Hou et al. (2014)) and ground-based weather stations, and (ii) numerical weather prediction models (NWP) (Niu et al., 2010; Gatlin et al., 2015).

The challenge, however, is that there is no unique DSD for different rainfall regimes. Several studies have shown that the rainfall DSD has spatial-temporal variation not only within a storm system but also from storm to storm and over different climatic regimes (Tokay and Short, 1996; Tokay et al., 1999; Bringi et al., 2003; Rosenfeld and Ulbrich, 2003; Ulbrich and Atlas, 2007; Radhakrishna et al., 2009; Niu et al., 2010; Konwar et al., 2014; Thurai et al., 2016). Such variability in the DSD corresponds to variation in the radar rainfall algorithm and cloud modelling parameterization and, therefore, it becomes important to investigate the DSD characteristics of different rainfall regimes and over different regions.

Synoptic scale systems such as tropical cyclones (TCs) are associated with copious amounts of rainfall which often causes devastating effects such as widespread flooding, landslide and fatalities (Rappaport, 2000; Dare et al., 2012; Dare, 2013). Rainfall information during such events which aids in disaster mitigation and risk analysis, is mainly derived from radar platforms (space-borne and ground-based) and NWP model forecasts. A better

understanding of the TC-related DSD is thus one of the aspects for improvement in rainfall representations from these platforms. TC-related rainfall DSD has been examined by some studies (Merceret, 1974; Wilson and Pollock, 1974; Jorgensen and Willis, 1982; Willis, 1984; Ulbrich and Lee, 2002; Maeso et al., 2005; Tokay et al., 2008; Chang et al., 2009; Radhakrishna and Rao, 2010; Bhattacharya et al., 2013) using aircraft (airborne foil impactors and probes) and ground-based disdrometer measurements. An excellent review on the early studies is presented by Tokay et al. (2008). Most of these studies show an abundance of small to medium-sized drops with fewer large drops in TCs. A recent study by Radhakrishna and Rao (2010), on the difference in DSD between TC and non-TC events during the southwest and northeast monsoon season at Gadanki (India), shows that the TC DSD differs statistically from the non-TC DSD and that the TC DSD also varies seasonally and over different regions. A variation in the radar rainfall estimation and the gamma distribution parameters between TC and non-TC environments has been established by Radhakrishna and Rao (2010).

The above studies have advanced our understanding of TC DSDs, especially over the Atlantic, the northwest Pacific, and the north Indian Ocean basins. The same topic, however, has received little attention over the Australian and the southwest Pacific region, despite these regions being vulnerable to the catastrophic effects of TC heavy rainfall (Dare et al., 2012; Chen et al., 2013; Dare, 2013). TCs are known to contribute significantly to the total climatological rainfall over the Australian region, as high as 50 % over some areas (Jiang and Zipser, 2010; Dare et al., 2012; Dare, 2013). Accurate representation of rainfall is important for this region as it has direct implications for disaster mitigation, agriculture and energy (Dare et al., 2012). Moreover, rain gauge data are sparse over a significant portion of Australia (Jones et al., 2009), especially the northern and western regions which are prone to TCs (Dare and Davidson, 2004). In these regions, remote sensing data become even more important.

This study thus examines the TC DSDs using the Atmospheric Radiation and Measurement (ARM) disdrometer data at the Darwin (Australia) site. It seeks to establish if there is any difference between TC and non-TC related DSD over this region and also under different types of precipitating systems (e.g. convective and stratiform) during the Australian summer monsoon season. Differences in the TC DSD with distance from the TC centre are also investigated. We pose the following question: if there is a difference, then how does it relate to the radar rainfall estimation parameters and the analytical expression (the gamma function) used to represent the observed DSD? The following section (section 2) describes the data and methodology, followed by results and discussion in section 3 and finally the summary in section 4.

2. Data and Methodology

The primary instrument we use for this study is the impact type Joss-Waldvogel disdrometer (JWD) (Joss and Waldvogel, 1969) model RD-80 located at the ARM research facility, Darwin (130.90E, 12.43S), Australia. The JWD uses a piezoelectric mechanism where the impact of a raindrop on a Styrofoam cone is converted to an electric pulse proportional to the size of the rain drop. The JWD sorts the drops into 20 diameter classes (or bins) in the range 0.3 to 5.5 mm every 1 minute. The bins have varying diameter intervals ranging from 0.1 to 0.5 mm. The JWD is a reliable standalone instrument but as with any other measurement instrument, it suffers from some limitations and the reader is referred to Tokay et al. (2001) and Tokay et al. (2002) for a detailed description. Briefly, the major limitations include its inability to resolve larger drops (e.g. greater than 5.5 mm, where they are assigned to the largest bin size) and its underestimation of small drops during intense rainfall due to the ringing of the cone upon the impact of the drops (which is known as disdrometer recovery dead time) and an increase in the background acoustic noise during such intense events (the small drops cannot be distinguished from the noise). Nonetheless, the JWD is widely used for DSD studies (Kozu

and Nakamura, 1991; Tokay and Short, 1996; Tokay et al., 2001; Ulbrich and Atlas, 2007; Radhakrishna and Narayana Rao, 2009; Radhakrishna and Rao, 2010; Giangrande et al., 2014).

The integral rainfall parameters of drop concentration ($N(D)$), rain rate (R), reflectivity (Z) and the mass-weighted mean diameter (D_m) are computed using the standard formulae (Sharma et al., 2009) as follows:

$$N(D_i) = \frac{n_i}{F \cdot t \cdot v(D_i) \Delta D_i} \quad (\text{m}^{-3} \text{mm}^{-1}) \quad (1)$$

$$R = \frac{\pi}{6} \frac{3.6}{10^3} \frac{1}{F t} \sum_{i=1}^{20} n_i D_i^3 \quad (\text{mm hr}^{-1}) \quad (2)$$

$$Z = \frac{1}{F t} \sum_{i=1}^{20} \frac{n_i D_i^3}{v(D_i)} \quad (\text{mm}^6 \text{m}^{-3}) \quad (3)$$

$$D_m = \frac{\sum_{i=1}^{20} N(D_i) D_i^4 \Delta D_i}{\sum_{i=1}^{20} N(D_i) D_i^3 \Delta D_i} \quad (\text{mm}) \quad (4)$$

where n_i is the number of drops measured in drop size class i , F is the Styrofoam cone area (50 cm²), t is the sampling time (60 s), D_i is the average diameter (mm) of the drops in class i , ΔD_i is the diameter (mm) interval of drop class i and $v(D_i)$ is the fall velocity (m s⁻¹) (Gunn and Kinzer, 1949) of a drop with diameter D_i .

The study period spans 2006 – 2013 and a total of 7 TCs passed within 500 km of the Darwin site (tracks shown in Figure 1) during this period. The date and position of the TCs were obtained from the IBTrACS archive (Knapp et al., 2010) where the data has a temporal resolution of 6 hours. A 1-min rainfall spectrum is considered to be TC-related if a TC centre came within 500 km of the ARM site. This 500 km criterion is consistent with other studies such as Lonfat et al. (2004), Dare et al. (2012) and Chen et al. (2013). Following Tokay and Short (1996), Tokay et al. (2001) and Cao and Zhang (2009), spectra with $R < 0.1$ mm hr⁻¹ are considered to be within the noise level and therefore are eliminated for this study.

Given the limitations of the JWD instrument, a comparison is made between the accumulated JWD and the rain gauge TC rainfall to evaluate the quality of the data. A Novalynx tipping-bucket rain gauge (model 260-2500E-12) that has a sampling resolution period of 1-min is collocated with the JWD at the ARM site. Note that tipping bucket rain gauges are known to also have errors and the reader is referred to studies of Chen and Chandrasekar (2015), Habib et al. (2008) and Wang et al. (2008) for an understanding of their accuracy and limitations. Table 1 shows the dates of the TCs and the JWD and tipping bucket (TB) accumulated rainfall (AR) for rainfall rates greater than 0.1 mm hr^{-1} . Except for TC George (2007) and Carlos (2011), there is a good correspondence between the two sets of AR. Differences for TC George and Carlos were still less than 10 %. In addition, during the passage of TC George, the rain gauge had 19 minutes of missing records which explains the discrepancy during this TC. This comparison validates the disdrometer data used for the study.

We employ here the widely used gamma function (Ulbrich, 1983; Kozu and Nakamura, 1991; Tokay and Short, 1996) as the analytical expression to describe the observed DSD:

$$N(D) = N_o D^\mu \exp(-\Lambda D) \quad (5)$$

where N_o ($\text{mm}^{-1}\text{m}^{-3}$), μ (dimensionless) and Λ (mm^{-1}) are respectively the intercept, shape and slope parameters. These gamma DSD parameters could be effectively used to study the natural variations in the characteristics of precipitation (Konwar et al. (2014) and the references therein). The μ parameter describes the breadth and the shape of the DSD where less (greater) than 1 denotes concave upward (downward) shape and zero denotes an exponential shape (Ulbrich, 1983). The Λ parameter describes the truncation of the DSD tail along D i.e. a larger (smaller) Λ truncates the DSD towards smaller (larger) D . The N_o parameter is the drop concentration ($N(D)$) when D approaches its minimum value.

The gamma DSD parameters are computed using a moments-based method that utilises three moments of the gamma DSD function (Tokay and Short, 1996; Smith, 2003). One of the

issues with this moments method is that bias could be introduced in the estimated parameters (Smith and Kliche, 2005) and thus spectra with a sufficient number of drops is recommended. To minimise this issue of small sample size, an extra criteria of eliminating spectra with less than 10 drops is implemented, consistent with other studies (Tokay and Short, 1996; Tokay et al., 2001; Tokay et al., 2002; Cao and Zhang, 2009; Radhakrishna and Narayana Rao, 2009; Niu et al., 2010; Lam et al., 2015). Considering a sample size of > 10 drops together with rainfall rate $> 0.1 \text{ mm hr}^{-1}$ and the TC rainfall distance criteria of $< 500 \text{ km}$, a total of 33,211 1-min spectra, constituting of 14,164 TC related and 19,047 non-TC related spectra, are used.

Different combinations of moments have been suggested, e.g. 3rd, 4th, and 6th (Kozu and Nakamura, 1991; Tokay and Short, 1996), 2nd, 3rd and 4th (Smith, 2003; Cao and Zhang, 2009) and 2nd, 4th and 6th (Ulbrich and Atlas, 1998) (referred to as M346, M234 and M246 respectively) to estimate the gamma parameters. Smith (2003) and Cao and Zhang (2009) suggested using middle order moments, e.g. M234, as they showed that these are associated with a lower least square error. We therefore utilise M234 to estimate the TC and non-TC gamma parameters. Smith (2003) and Cao and Zhang (2009) utilise non-TC DSDs; hence to further justify the use of M234 we compute the root mean square error (*RMSE*) between the observed and estimated drop concentration for both TC and non-TC events, using each moment combination (the formulae are given in appendix A), which demonstrates that M234 has a lower error (Table 2). Interestingly, the error in estimating the TC DSDs is larger than for the non-TCs for the different moment combinations. The *RMSE* is also stratified with respect to rainfall rate (rainfall classes shown in Table 3) and is shown in Figure 2. A notable difference between the TC and non-TC related error is evident especially for rainfall rates $< 20 \text{ mm hr}^{-1}$ (class 7) where the *RMSE* related to the latter is lower than the former. Nonetheless, of the combination of moments used, both the TC and non-TC events show the smallest *RMSE* for M234 at almost all rainfall rates.

To ascertain the statistical significance of some of the results, the two-sample Kolmogorov-Smirnov (2KS) test (Press et al., 2007) at the 95 % confidence level is utilised. The 2KS test tests the null hypothesis that two samples are from the same population. The uncertainty (error) on some of the statistics is also evaluated at the 95 % confidence interval calculated using a bootstrapping technique (Efron and Tibshirani, 1993) which involves re-sampling of the data. Some 10,000 random re-samples, with replacement, are constructed on which the bootstrapping is applied. The 50th percentile (median) is presented as the statistic and the 2.5 and 97.5 percentile as the 95 % confidence interval.

3.0 Results

3.1 Individual TCs

The time series of the drop concentration ($N(D)$), D_m , R , surface wind speed and distance from the TC centre to the site for the 7 TCs are examined first. As an illustration, Figure 3 shows the time series for TC Carlos (Figure 3a) and George (Figure 3b) which have the highest accumulated rainfall amount (AR – see Table 1). The 1-min surface wind speed data were obtained from the ARM surface observation instrument and the IBTrACS 6-hourly time and position were linearly interpolated to obtain the 1-min resolution data. Some notable observations are as follows. The $N(D)$ is larger closer to the TC centre. The D_m is mostly below 3 mm (with a large frequency of 1 – 2 mm); nonetheless there are some cases of > 3 mm, for example during TC Laurence and TC Alessia (figure not shown). The D_m , however, is observed to be strongly dependent on the rain rate R , with generally higher values for higher R (see Figure 4k).

When stratified with respect to rainfall rate or reflectivity, the DSDs should appear similar (Radhakrishna and Rao (2010) and the references therein). Hence for an explicit comparison, we stratified the DSD of each TC into 10 rainfall rate categories (the rainfall categories are listed in Table 3). The average $N(D)$ for each rainfall rate category was computed

and is shown in Figure 4 (a-j). Smaller rain rates (especially rain rates $< 1 \text{ mm hr}^{-1}$) are dominated by smaller drops (fewer moderate drops) whereas moderate and larger rainfall rates generally have a combination of small and moderate size drops. There is a systematic gain of drop concentration by moderate diameter classes with an increase in rainfall rate. The magnitude of the peaks, however, varies for each rainfall group where the higher rain rates tend to have a larger drop concentration. As evident, the peaks at lower rain rates ($< 1 \text{ mm hr}^{-1}$) are lower (below $400 \text{ m}^{-3}\text{mm}^{-1}$ for the majority of the TCs) whereas for rain rates $> 1 \text{ mm hr}^{-1}$ the peaks are around $400 \text{ m}^{-3}\text{mm}^{-1}$ and above. The peaks systematically shift slightly towards the moderate diameter classes with increasing R . An interesting observation is that the distribution systematically shifts from mono-modal (single peak) to bimodal (two peaks) with an increase in rain rate. This bi-modal nature is dominant for rainfall rates $3 - 60 \text{ mm hr}^{-1}$.

The average DSD varies among the TCs and with rain rate. Examining TCs with higher rainfall contributions, TC Carlos (black solid line), with the highest accumulated rainfall amount (AR) of 777 mm (Table 1), has a higher drop concentration at low to moderate rain rates ($< 20 \text{ mm hr}^{-1}$) and a relatively lower drop concentration at higher rain rates ($> 20 \text{ mm hr}^{-1}$). TC George (red solid line) with second highest AR (367 mm) encompasses mostly moderate drop concentration at all rain rates. TC Laurence, with third highest AR (315 mm), has almost the lowest drop concentration at all rain rates.

The corresponding average drop diameter (D_m) with respect to rain rates R is shown in Figure 4k. The D_m is lower at lower rain rates and increases systematically with an increase in R for all TCs. There is no statistical difference between the D_m of most TCs for the majority of the rainfall rates (except for TC Alessia and to some extent TC Laurence). The D_m of TCs is also compared with the non-TCs (solid blue line) which show that except for TC Alessia and to some extent TC Laurence, the other five TCs have statistically lower D_m values than the non-

TC values. This result points towards a difference between TC and non-TC DSD which is discussed in detail in the subsequent section.

3.2 Contrasting TC and non-TC DSD

The TC DSDs are combined to ascertain how their average compares with the non-TC DSD. Figure 5, a plot of average TC and non-TC DSD, shows that the TC DSDs are statistically different from the non-TC DSDs, with TCs demonstrating a higher drop concentration at lower diameter classes (< 2.6 mm) and the non-TCs demonstrating a higher concentration than the TCs for diameters > 2.6 mm. This implies that TCs have a larger concentration of small to medium size drops in comparison to non-TCs, as also reported by Radhakrishna and Rao (2010) over India.

How do the TC and non-TC DSD compare with respect to the rain rates? First we compare the relative frequencies of the rain rates of the TC and non-TC 1-min DSDs as shown in Figure 6a. The two distributions are found to be statistically different (using the KS test). Non-TCs tend to have a higher frequency at lower rain rate (< 2 mm hr⁻¹) whereas TCs have a higher frequency for low to moderate rain rates ($2 - 40$ mm hr⁻¹). Above 40 mm hr⁻¹, a significant difference is absent. This could be related to the small sample size at higher rain rates that then gives a noisier data set, thus removing the signal. This result, as anticipated, demonstrates that TCs typically have larger rain rates than non-TCs.

Second, we compare the DSDs with respect to the rain rates. To accomplish this, drop concentrations of each diameter class are grouped into the 10 rainfall classes (classes listed in Table 3) and for each rainfall and diameter class the average TC and non-TC DSD and the ratio (TC/non-TC), to compare the latter two averages, are computed and are shown in Figure 6 (b-d). Results show that there is a systematic shift in the maximum drop concentration from lower diameter to higher diameter as rain rate increases (in both TC and non-TC events) as discussed in section 3.1. It is quite evident, in both the TC (Figure 6b) and non-TC (Figure 6c) average

DSD plots, that lower rain rates tend to have a larger drop concentration at smaller diameter classes, which shows that smaller drops dominate at smaller rain rates. As rain rate increases, the peak (or maximum) concentration shifts to moderate diameter classes, with small concentrations at smaller diameters especially at higher rain rates ($> 20 \text{ mm hr}^{-1}$). Overall, both the TC and the non-TC rainfall have maximum drop concentration around $1 - 30 \text{ mm hr}^{-1}$. Comparing the two averages, Figure 6d shows that the ratio (TC/non-TC) at lower rain rates ($< \sim 10 \text{ mm hr}^{-1}$) is > 1 (as high as 2.6) at small diameters ($< \sim 1 \text{ mm}$) whereas for rain rates $> 10 \text{ mm hr}^{-1}$ the > 1 ratio systematically shifts to moderate diameters ($1 - 3 \text{ mm}$). The contour lines show regions where the ratio is > 1 . The above results signify that at lower rain rates ($< 10 \text{ mm hr}^{-1}$) TCs have relatively more small drops ($< 1 \text{ mm}$) whereas the non-TCs have more moderate to large drops ($> 1 \text{ mm}$) and at higher rain rates ($> 10 \text{ mm hr}^{-1}$) TCs have more moderate drops ($1 - 3 \text{ mm}$) with almost negligible concentration of large drops ($> 3 \text{ mm}$), whereas the non-TCs have more large drops ($> 3 \text{ mm}$).

To further verify the above results, the corresponding average drop diameter (D_m) at each rainfall class for the TC and non-TC rain is computed and is shown in Figure 7a. The D_m of both TC and non-TC events are smaller at smaller rain rates and increases with an increase in the rainfall rate. However, a statistically significant difference in the magnitude of the D_m is observed with the TC D_m consistently lower than the non-TC values at all rainfall classes. This affirms that TCs comparatively have smaller drop sizes than the non-TCs at all rain rates.

DSDs are known to vary with precipitation types (Rosenfeld and Ulbrich, 2003), such as convective, transition and stratiform rainfall, hence we examine the TC and non-TC DSD for these variations. Following Rao et al. (2001), samples are grouped respectively into convective, stratiform or transition rainfall if the D_m/R ratio is less than 0.1, greater than 0.5 or in between the latter two thresholds. Figure 7b, a plot of the relative frequency of D_m for the different rainfall types, shows that the TC and non-TC DSDs differ for the three rainfall types. TCs have

a relatively higher frequency of smaller D_m for the three rainfall types (statistically significant at the 95 % level using the KS test).

The above set of results implies that there have to be some differences in the precipitation formation mechanism or the cloud microstructure between TCs and non-TCs which would lead to such differences in the DSD. It is well known that the precipitation formation is governed mostly by the cloud microphysical processes and that the latter is a function of the dynamics (the updraft/vertical wind motion (Rosenfeld and Ulbrich, 2003; Houze, 2014). Comparing TC and non-TC updrafts, the study by Heymsfield et al. (2010), on convective precipitation, shows a significantly weaker TC updraft than in non-TCs (both over the land and over the ocean) at low to mid altitudes (3 – 11 km). These altitudes are the crucial regions for the microphysical processes (Houze, 2014). A stronger updraft could affect the drop sizes in two ways. The first is drop sorting, in which the small drops could be advected high up in the updrafts with the larger drops falling under the influence of gravity. Second, the large updrafts could suspend the drops aloft, therefore increasing the time for the collision and coalescence process which would then increase the drop sizes. Above the 0°C isotherm, the suspension of drops (liquid or ice) by the updraft would also allow growth of particles through riming. These mechanisms thus could shift the non-TC DSD towards relatively larger drop diameters.

In addition to stronger updrafts, relatively higher temperatures could also shift the DSD towards larger drops by evaporating the smaller drops. To investigate this, we compute the surface temperature and relative humidity distribution over Darwin for the TC and non-TC events (figure not shown). Non-TCs have a higher frequency of higher temperatures (TC and non-TC means of 23.4 and 24.5 °C respectively) and lower humidity (TC and non-TC means of 96 and 88 % respectively). Relatively larger temperatures and drier conditions during non-TC events imply more evaporation of smaller drops.

3.3 TC distance stratification

The distribution of precipitation varies within a TC system, with heavy rainfall generally occurring in the vicinity of the eye wall. We therefore investigate if there is any difference in the TC rainfall DSD with respect to the distance from the TC centre.

To examine the differences in the DSD with respect to the distance from the TC centre, samples are grouped into distance < 60 km, $60 - 200$ km and > 200 km. These criteria distinguish TC regions, dividing the storm approximately into eye wall, inner rainband and outer rain band (Lonfat et al., 2004; Yokoyama and Takayabu, 2008). Note that individual TC structure would vary, however (see discussion at the end of the section). The average D_m of the distance groups with respect to the rainfall rate (Figure 8) shows that rainfall closer to the TC centre, in comparison with further from the TC centre, has relatively smaller drop diameters at low to moderate rain rates (this is statistically significant). It is apparent from Figure 8 that the D_m of the < 60 km group at rain rates < 30 mm hr⁻¹ is lower than the D_m of the other two groups. For the same rain rate range, the D_m differences of the $60 - 200$ km and the > 200 km groups, however, are mixed whereby for rain rates < 1 mm hr⁻¹ the two groups have almost the same D_m and for rain rates $1 - 30$ mm hr⁻¹ the $60 - 200$ km has slightly larger values. Above 30 mm hr⁻¹ there is an absence of a statistically significant difference between the D_m of the three groups.

While the above results point to a variation in the DSD with distance from the TC centre, it should be noted that these are based on a small sample of TCs (7 TCs). Moreover, the distance considered here is average values that distinguish eye wall and outside eye wall regions and that the actual TC size and structure would vary, with some TCs having much smaller eye wall radii (e.g. Kimball and Mulekar (2004)). A more detailed analysis could consider the variation in the actual size of TCs but this is outside the scope of this study.

The actual reason for the difference between the DSD with distance, especially the presence of relatively smaller drops near the TC centre, is not clear at the moment. A possible

factor could be the presence of a large quantity of small size liquid or ice particles aloft that subsequently fall as raindrops. The presence of a large quantity of small ice particles aloft near the TC centre has been reported by some studies, for example the study by Houze et al. (1992), who analysed the mesoscale distribution of ice particles in the inner core of hurricane Norbert (1984). Using aircraft observations at an altitude of 6 km, they report the presence of a high concentration of small ice particles at the edge of the eye wall region. The authors attribute the above observation as likely resulting from secondary ice particle production through the riming mechanism at ~ 0 to -5°C by the process identified by Hallett and Mossop (1974) (see Houze (2010) and the references therein). A large concentration of ice particles is produced by this process (Black and Hallett, 1986). Thus, the above process could partially explain the observation of smaller drops near the centre of TCs observed over Darwin. Another possibility for this observation could be that smaller drops at distances further from the TC centre evaporate, thus shifting the DSD more towards relatively larger drops, especially at low to moderate rain rates where the smaller drops are in abundance. A humidity and temperature analysis (figure not shown) shows that the relative humidity decreases with an increase in distance from the TC centre (a relatively lower mean at larger distances) and the temperature is somewhat higher at distances further from the TC centre. Thus, a relatively drier environment and a higher temperature could cause more evaporation of the smaller drops at larger distances, which shifts the DSD at low to moderate rain rates towards relatively larger drops.

3.4 Comparison of TC DSD between Darwin and other regions

Radhakrishna and Rao (2010) have demonstrated the variation of TC DSD over different regions. Hence, we compare the TC DSD at Darwin with those over India (Radhakrishna and Rao, 2010), the Atlantic (Tokay et al., 2008) and the western Pacific (Chang et al., 2009). To facilitate this, we group together data having reflectivity between 39 to 41 dBZ (around 40 dBZ) following Tokay et al. (2008) and compute the average liquid water content (LWC), rain

rate R and D_m . Table 4 shows the respective TC rainfall parameters (LWC , R and D_m) over Darwin and for the regions mentioned above. The parameter values over Darwin are somewhat similar to those over the Atlantic and during the north-east monsoon season (NEM) over the Bay of Bengal (BOB-India) but they are quite different from those over the western Pacific and during the south-west monsoon (SWM) season over the BOB. As evident, the LWC and the average rain rate at Darwin are higher and the D_m is lower than those over the western Pacific and during the SWM season over the BOB. The difference in the rainfall parameters between the western Pacific and the Atlantic (or for that matter over Darwin) could be correlated with terrain-influenced convective systems during the passage of TCs over western Pacific (Chang et al., 2009). Over the BOB, the microphysical processes related to stronger updrafts during the SWM have been attributed to the variation in the rainfall parameters compared to those occurring during the NEM. With the parameters over Darwin similar to those over NEM, these arguments could also hold to explain the difference between that over Darwin and SWM. As discussed previously, stronger updrafts shift the DSD towards relatively larger D_m .

3.5 Radar Z-R Parameters

A difference in the DSD between TC and non-TC related rainfall events implies that the parameter A and b of the radar rainfall estimation algorithm $Z=AR^b$ will also differ. Hence, we examine the degree of variation in the radar rainfall estimation parameters between TC and non-TC related events and also with respect to the different precipitation types and distance from the TC centre. The coefficient A indicates the size of the drops (larger A for larger drops) and the power b indicates the microphysical processes. A larger b (greater than 1) signifies size or mixed controlled case, namely collision and coalescence, whereas $b \sim 1$ signifies number controlled case (collision, coalescence and breakup) that produces equilibrium DSD (Atlas et al., 1999; Rosenfeld and Ulbrich, 2003; Sharma et al., 2009). Figure 9 shows the A and b parameters of TC and non-TC related rainfall events and for the different conditions (rainfall

types and distance from the TC centre). Non-TCs have larger A than TCs, with values of 310 and 234 respectively (Figure 9a), but there is no difference in the b values (Figure 9b). Under different rainfall types, a statistically significant difference exists between the TC and non-TC A parameter for the convective and stratiform types (Figure 9a; non-TC values are larger) and the b parameter for the transition type (Figure 9b; non-TC value is larger). A larger coefficient A implies larger drops during non-TC events, consistent with our previous results. A relatively larger b during non-TC events (particularly for the transition type) implies that rainfall processes during those events are governed by more size-controlled processes.

The TC Z - R relation reported here differs from that obtained in other regions. For a comparison we present some of these relations in Table 5 (these are without separation into convective, stratiform and transition types). The coefficient A of TCs over Darwin (234) is comparatively lower than that over the Atlantic (which generally has a higher value compared to other regions) and the BOB SWM season but it is higher than that over Taiwan and the BOB NEM season. The power b (1.3) is lower than that over other regions (except during the passage of TC Debbie over the Atlantic). These differences in the Z - R relation could be attributed to the inherent differences in the nature of the TC DSDs.

Figure 9c shows the radar parameters for the three distance groups. The A of the two > 60 km groups is almost similar (~ 250) but it is smaller for the < 60 km group (~ 125). The b of the < 60 km group (1.40) is larger than the > 60 km groups (1.32 and 1.30 for 60 – 200 and > 200 km respectively). A smaller A for the < 60 km group denotes smaller drops near the TC centre, consistent with our earlier findings. A larger b near the TC centre implies that rainfall processes have more size-controlled processes. While these results point to a variation in the radar parameters with distance, as mentioned before, the variation in TC DSD (hence the radar parameters) could be a function of the TC sample size and depend very much on the actual size and structure of the TC. These results also contrast with those of Jorgensen and Willis (1982),

who did not find any statistical difference in the radar parameters for TC Fredric (1979) when stratified into eye wall and outside eye wall regions. A possible reason could be a difference in the TC rainfall DSD between the two regions as smaller drops at distances near the TC centre is observed here. Another possibility could be the difference in the instruments being used (or the measurement methodology) and thus the representation of the actual DSD on the surface. While we use the ground-based disdrometer measurements, Jorgensen and Willis (1982) used drop size measurements made from optical array spectrometer probes onboard a research aircraft. Friedrich et al. (2012) report that DSD measurements made aloft (such as using radar) do not usually represent the DSD observed at the surface as processes that occur close to the surface (e.g. raindrop breakup or evaporation) cannot be captured by these instruments. Hence, the difference in the Z - R relation between Jorgensen and Willis (1982) and that obtained here could also be due to the above factor.

3.6 Analytical Expression - Gamma Function

As discussed in section 2, we use M234 to estimate the TC and non-TC gamma distribution parameters. Figure 10 shows the frequency distribution of the gamma parameters. The TC and non-TC distributions are statistically different at the 95 % level. It is apparent that TCs have larger frequencies of slope (μ ; mm^{-1}), shape (Λ) and intercept ($\log_{10}N_o(\text{m}^{-3}\text{mm}^{-1})$) parameters at values 4 – 14, 4 – 15 and 4 – 10 respectively, whereas non-TCs have a higher frequency at parameter values < 4 . There is a negligible difference at larger parameter values. Correspondingly, the TC mean and median values are larger than for the non-TCs as shown in Table 6. Physically, a larger μ and Λ respectively indicates a narrower DSD shape for TC and a truncation of the tail of the DSD towards smaller D . The larger N_o indicates a larger concentration of smaller drops in TCs. These are consistent with our previous findings.

Figure 11 shows the gamma parameters with respect to the rainfall rate (using the 10 rainfall classes). Overall, the Λ , μ and N_o parameter values decrease with an increase in rain

rate which respectively show that with an increase in rain rate the tail of DSD shifts towards larger D , the breadth of the DSD shape increases and the concentration of smaller drops decreases.

Comparing the TC and non-TC distributions, the Λ parameter of the two (Figure 11a), is statistically different, with the TC values consistently larger than the non-TC at all rain rates. This indicates that the tail of the TC DSD truncates more towards relatively smaller D than non-TCs at all rain rates. Comparing the μ parameter (Figure 11b), TCs have higher averages than non-TCs at most of the rain rates (except at classes 2, 3 and 6 where there is no significant difference). A larger deviation between the two is prominent at higher rain rates. This shows that TCs have a relatively narrower DSD than non-TCs at most of the rain rates but is more pronounced at higher rainfall rates. Comparing the intercept parameter, there is no statistical difference between the TC and non-TC distribution (Figure 11c) at most of the rainfall classes, except at classes 1, 4 and 5 where the TC values are higher than the non-TC. Physically, this means that TCs have a relatively larger concentration of smaller drop at lower rain rates, in agreement with our earlier findings.

Figure 12 shows the frequency distribution of the gamma parameters with respect to rainfall types (convective, transition and stratiform). Overall, the stratiform and transition distributions are more spread and right skewed than the convective distribution which is relatively narrower, has only small to moderate parameter values and nearly normally distributed. The distribution of the parameters of the three rainfall types for the TC and non-TC events are also statistically different at the 95% level. The corresponding average and median values of each parameter are shown in Table 7. TCs tend to have higher average and median values than non-TCs for the three rainfall types.

a) Gamma Parameter with TC distance

Given that the TC DSD shows variation with distance from the TC centre, accordingly we have investigated the variation in the gamma parameters with distance from TC centre. Figure 13 shows a plot of the gamma DSD parameters of the three distance groups against rainfall rate. The plot shows that the gamma DSD parameters of the three distance groups differ to some extent. The Λ parameter of the less than 60 km group is larger for rainfall rates less than 10 mm hr^{-1} (class 6); the μ parameter of the less than 60 km group is larger at most of the rain rates (except for groups 5, 6 and 10 where there is no statistical difference) and the N_o parameter of the three groups differs at class 1 where the less than 60 km group has a lower value.

4.0 Summary

In this study we have compared and contrasted the rainfall DSD between TC and non-TC related events using the ARM impact disdrometer data at Darwin, Australia, for the period 2006 – 2013, with the aim of establishing if there is any significant difference between TC and non-TC rainfall DSD and also the relationship with rainfall type and distance from TC centre. We also wish to determine that if there is a difference in the DSD, then how does it impact on the parameters of the widely used radar reflectivity (Z) to rainfall rate (R) relationship ($Z=AR^b$) and the gamma DSD model, the latter mostly used for cloud-modelling parameterizations.

Results show that statistically significant differences exist between the DSD of TCs and non-TCs with TCs, comparatively, having smaller drop diameters. The drop diameter (D_m) of both types of rainfall events increases with increase in rain rate, however, the TC drops are consistently smaller than the non-TCs at all rain rates. A similar pattern is observed when the data are partitioned into rainfall types (convective, transition, and stratiform) with TCs having a larger frequency of smaller D_m than the non-TCs for the three rainfall types.

Moreover, it is shown that the TC DSD varies with distance from TC centre. While the D_m of each distance group increases with rain rate, the D_m of the < 60 km group at low to moderate rain rates ($< 20 \text{ mm hr}^{-1}$) is statistically smaller than that further from the TC centre.

A comparative analysis using data at 40 dBZ reflectivity shows that the TC DSD at Darwin differs from that during the SWM over the BOB (India) and from that over the western Pacific (Taiwan). Possible factors could be the strength of the updrafts and the influence of geography (e.g. terrain).

Variation in the DSD thus induces variation in the radar rainfall estimation and the gamma DSD model parameters. A statistically significant difference in the radar parameters exists between the TC and non-TC rainfall, under different rainfall types and with respect to distance from TC centre. The TC Z - R relation obtained here differs from other regions.

Differences in the gamma DSD model parameters are evident for the different conditions. TCs have higher slope and shape parameter values than non-TCs, the former observed at all rain rates and the latter at moderate to high rainfall rates. However, there is an absence of significant difference in the intercept parameter. With precipitation type, a difference in the distribution is observed at small and moderate values of the gamma parameters with TCs (non-TCs) generally having a higher frequency of moderate (low) values. TCs thus have larger average values of the respective gamma parameters. With respect to distance, the slope parameter value of the less than 60 km group is significantly larger than the greater than 60 km groups at small to moderate rain rates (less than 20 mm hr^{-1}). The shape parameter values of the former group are also higher than the latter group at almost all rain rates but there is no major difference in the intercept parameter between the groups.

The inherent differences in the Z - R relation parameters and the gamma DSD parameters between TC and non-TC rainfall events and also under different condition (e.g. rainfall types and distance from TC centre) suggests that a dynamic Z - R and gamma DSD relation should be

utilised in radar rainfall retrievals and cloud microphysical parameterisations, based on the dynamical and microphysical context of the rainfall. Similar suggestions have been made by other studies such as Bringi et al. (2003) and Atlas and Ulbrich (2006).

Appendix A

The formulae to compute the shape, μ (dimensionless), slope, Λ (mm^{-1}), and intercept, N_o ($\text{mm}^{-1}\text{m}^{-3}$), gamma fitted parameters using moments M234, M246 and M346 are as follows:

(a) for M234 (Smith, 2003):

$$\eta = \frac{M_2 M_4}{M_3^2} \quad (\text{A.1})$$

where M_k is the k^{th} moment of the gamma function given as:

$$M_k = \sum_{i=1}^{20} D_i N(D_i) \Delta D_i \quad (\text{A.2})$$

and D_i is the average diameter (mm) of the drops in class i , ΔD_i is the diameter (mm) interval of drop class i and $N(D_i)$ is the drop concentration of drop class i .

$$\mu = \frac{4-3\eta}{\eta-1} \quad (\text{A.3}); \quad \Lambda = \frac{M_2}{M_3(\eta-1)} \quad (\text{A.4}); \quad N_o = \frac{M_2 \Lambda^{\mu+3}}{\Gamma(\mu+3)} \quad (\text{A.5})$$

(b) for M246 (Ulbrich and Atlas, 1998):

$$\eta = \frac{M_4^2}{M_2 M_6} \quad (\text{A.6})$$

$$\mu = \frac{(7-11\eta) - [(7-11\eta)^2 - 4(\eta-1)(30\eta-12)]^{\frac{1}{2}}}{2(\eta-1)} \quad (\text{A.7})$$

$$\Lambda = \left[\frac{M_2(\mu+3)(\mu+4)}{M_4} \right]^{\frac{1}{2}} \quad (\text{A.8})$$

$$N_o = \frac{M_2 \Lambda^{\mu+3}}{\Gamma(\mu+3)} \quad (\text{A.9})$$

(c) for M346 (Tokay and Short, 1996):

$$\eta = \frac{M_4^2}{M_3 M_6} \quad (\text{A.10})$$

$$\mu = \frac{11\eta - 8 + [\eta(\eta + 8)]^{\frac{1}{2}}}{2(1 - \eta)} \quad (\text{A.11}); \quad \Lambda = \frac{\mu + 4}{D_m} \quad (\text{A.12})$$

$$N_o = \frac{M_3 \Lambda^{\mu+4}}{\Gamma(\mu + 4)} \quad (\text{A.13})$$

The root mean square error (*RMSE*) of the drop concentration, $N(D)$, from observed and the gamma fitted distribution is computed as:

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (N(D_i)_e - N(D_i)_o)^2} \quad (\text{A.14})$$

where $N(D_i)_e$ and $N(D_i)_o$ are the gamma fitted and observed drop concentration respectively at drop class i for each drop spectra.

Acknowledgement

The authors thank the Australian Research Council Centre of Excellence for Climate System Science, and their respective institutions for supporting this work. Anil Deo and Kevin Walsh are supported by the Australian Research Council grant DP150102272. Anil Deo also acknowledges the Australian government-sponsored Endeavour Postgraduate Award for funding his doctorate degree at the University of Melbourne.

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Table 1: Disdrometer and rain gauge accumulated rainfall (AR) of the seven TCs

Cyclone	Dates (UTC)	Disdrometer AR (mm)	Tipping bucket AR (mm)
George	02 – 04/03/2007	397.54	367.00
Helen	29/12/2007	109.50	103.20
Laurence	11– 13/12/2009	323.40	315.60
Carlos	14 – 18/02/2011	729.00	777.41
Twenty	27 – 31/03/2011	104.98	111.00
Grant	23/12/2011	43.35	45.00
Alessia	23 – 24/11/2013	72.21	69.60
		Total = 1780.00	Total = 1788.81

Table 2: *RMSE* between the observed and estimated drop concentration using moments M234, M246 and M346

	<i>RMSE</i> (mm ⁻³ m ⁻¹)		
	M234	M246	M346
TC	197.13	225.90	246.4
Non-TC	116.17	137.2	155.65

Table 3: Rainfall rate classes or categories

Class	Rainfall rates (mm hr ⁻¹)
1	0.1 – 0.3
2	0.3 – 0.5
3	0.5 – 1
4	1 – 3
5	3 – 5
6	5 – 10
7	10 – 20
8	20 – 30
9	30 – 60
10	> 60

Table 4: Liquid water content (LWC), rain rate (R) and D_m around reflectivity 40 dBZ (39 – 41) of TCs over Darwin compared with that over the western Pacific; Atlantic; and Bay of Bengal (BOB - India) during the southwest and northeast monsoon (SWM and NEM) seasons

Region	LWC (gm ⁻³)	R (mm hr ⁻¹)	D_m (mm)
Darwin	0.80	16.65	1.75
Western Pacific (Chang et al., 2009)	-	12.1	1.88
Atlantic (Tokay et al., 2008)	0.90	18.5	1.67
SWM BOB (Radhakrishna and Rao, 2010)	~ 0.64	~ 13.7	~ 1.89
NEM BOB (Radhakrishna and Rao, 2010)	~ 0.82	~ 17	~ 1.72

Table 5: Z - R relation ($Z = AR^b$) coefficient (A) and power (b) of TCs over different regions.

The values presented are without rainfall type (convective, stratiform or transition) stratification

Region	Studies	A	b
Atlantic	Scott (1974)	300	1.24
	TC Felice (1970)	260	1.35
	TC Debbie (1969)	350	1.35
	Wilson and Pollock (1974)	300	1.35
Western Pacific	Jorgensen and Willis (1982)	207	1.45
India	Chang et al. (2009)	275	1.39
	Radhakrishna and Rao (2010), BOB SWM	142	1.55
	Radhakrishna and Rao (2010), BOB NEM		

Table 6: TC and non-TC mean and median gamma parameters. The values in the brackets accompanying the mean are the 95 % confidence interval.

		TC	Non-TC
Mean	Λ (mm ⁻¹)	10.79 (10.54, 10.89)	10.47 (10.30, 10.62)
	μ	7.87 (7.71, 8.01)	7.82 (7.70, 7.95)
	N_o (m ⁻³ mm ⁻¹)	5.09×10^{75} (3.57×10^{60} , 1.52×10^{76})	2.11×10^{52} (1.17×10^{49} , 6.38×10^{52})
Median	Λ (mm ⁻¹)	7.42	6.94
	μ	6.18	5.66
	N_o (m ⁻³ mm ⁻¹)	4.26×10^5	1.39×10^5

Table 7: TC and non-TC mean and median slope, Λ (mm⁻¹); shape, μ and intercept, N_o (m⁻³mm⁻¹), parameters of the convective, transition and stratiform rainfall types

		Precipitation Type		
		Convective TC(non-TC)	Transition TC(non-TC)	Strati. TC(non-TC)
Mean	Λ (mm ⁻¹)	6.8 (5)	8.2 (7.4)	14 (12.3)
	μ	8.42 (6.10)	6.64 (6.35)	8.86 (8.59)
	N_o (m ⁻³ mm ⁻¹)	4.70×10^5 (6.40×10^4)	1.53×10^6 (5.35×10^5)	5.24×10^7 (9.40×10^6)
Median	Λ (mm ⁻¹)	6.60 (4.74)	6.75 (6.21)	8.85 (8.16)
	μ	8.15 (5.76)	5.51 (5.38)	6.05 (5.75)
	N_o (m ⁻³ mm ⁻¹)	3.70×10^5 (5.41×10^4)	1.53×10^6 (5.35×10^5)	5.74×10^5 (2.02×10^5)

Figure 1: Tracks of the 7 TCs passing over Darwin (location shown by a red dot) for the period 2006 to 2013.

Figure 2: Root mean square error (*RMSE*) in the drop concentration, $N(D)$, between observed and the gamma fitted distributions using moments two, three and four (M234); two, four and six (M246) and three, four and six (M346) of the TC and non-TC drop spectra.

Figure 3: Time series (UTC) of drop concentration ($N(D)$ - coloured plot), D_m (black line with $N(D)$), distance from TC centre (solid red line), wind speed (solid blue line) and rainfall rate (black line with distance and wind speed plot) of TC Carlos (a) and George (b). The colour bar denotes the drop concentration of the respective TC and the secondary y-axis shows the magnitudes of D_m , distance and rainfall rate.

Figure 4: Average drop concentration ($N(D)$) of individual TCs with respect to rainfall rates (a) 0.1 – 0.3, (b) 0.3 – 0.5, (c) 0.5 – 1, (d) 1 – 3, (e) 3 – 5, (f) 5 – 10, (g) 10 – 20, (h) 20 – 30, (i) 30 – 60 and (j) $> 60 \text{ mm hr}^{-1}$ for the 20 diameter classes. (k) Average D_m of non-TC and individual TC DSD spectra with respect to the 10 rainfall classes. The error bars are the 95 % confidence interval.

Figure 5: Average drop concentration of the TC and the non-TC rainfall DSD spectra with respect to the 20 diameter classes. The error bars are the 95 % confidence interval.

Figure 6: (a) Normalised frequency distribution of rain rates of TC and non-TC drop spectra. Average DSD of (b) TC and (c) non-TC rainfall events. (d) TC versus non-TC ratio of average DSD with respect to rain rate and diameter class.

Figure 7: (a) Average D_m of TC and non-TC drop spectra for the 10 rainfall classes. The error bars are the 95 % confidence interval. (b) Normalised frequency distribution of D_m with respect to convective (black), transition (blue) and stratiform (red) rainfall type of TC (solid lines) and non-TC (dashed lines) drop spectra.

Figure 8: Mean D_m of TC and the three distance groups from TC centre (< 60 km, 60 – 200 km and > 200 km) with respect to the 10 rainfall classes. The error bars are the 95 % confidence interval.

Figure 9: Radar rainfall estimation parameters. (a) Pre-factor, A , and (b) power, b , for TC and non-TC (i.e. All) and rainfall types (convective, transition and stratiform) of TC and non-TC; and pre-factor, A (red plot) and power, b (blue plot) with respect to (c) distance from TC centre.

Figure 10: Normalised frequency distribution of (a) slope, λ ; (b) shape, μ ; and (c) intercept, N_o , gamma fitted parameters calculated using moments two, three and four (M234) of the of TC and non-TC drop spectra.

Figure 11: Distribution of (a) slope, λ ; (b) shape, μ ; and (c) intercept, $\log_{10}(N_0)$, gamma fitted parameters (calculated using M234) of the of TC and non-TC drop spectra with respect to rain rate.

Figure 12: Frequency distribution of (a) slope, λ ; (b) shape, μ ; and (c) intercept, $\log_{10}(N_o)$, gamma fitted parameters (calculated using M234) of the of TC and non-TC drop spectra with rainfall type (black plot – convective, blue plot – transition and red plot – stratiform).

Figure 13: Distribution of (a) slope, λ ; (b) shape, μ ; and (c) intercept, $\log_{10}(N_0)$, gamma fitted parameters of the < 60 km, 60 – 200 km and > 200 km distance groups against rain rate.