Cross Validation of Rainfall Characteristics Estimated from the TRMM PR, a Combined PR–TMI Algorithm, and a C-POL Ground Radar during the Passage of Tropical Cyclone and Nontropical Cyclone Events over Darwin, Australia

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ABSTRACT

This study cross validates the radar reflectivity Z ; the rainfall drop size distribution parameter (median volume diameter D_o); and the rainfall rate R estimated from the Tropical Rainfall Measuring Mission (TRMM) satellite Precipitation Radar (PR), a combined PR and TRMM Microwave Imager (TMI) algorithm (COM), and a C-band dual-polarized ground radar (GR) for TRMM overpasses during the passage of tropical cyclone (TC) and non-TC events over Darwin, Australia. Two overpass events during the passage of TC Carlos and 11 non-TC overpass events are used in this study, and the GR is taken as the reference. It is shown that the correspondence is dependent on the precipitation type whereby events with more (less) stratiform rainfall usually have a positive (negative) bias in the reflectivity and the rainfall rate, whereas in the D_o the bias is generally positive but small (large). The COM reflectivity estimates are similar to the PR, but it has a smaller bias in the D_o for most of the greater stratiform events. This suggests that combining the TMI with the PR adjusts the D_o toward the “correct” direction if the GR is taken as the reference. Moreover, the association between the TRMM estimates and the GR for the two TC events, which are highly stratiform in nature, is similar to that observed for the highly stratiform non-TC events (there is no significant difference), but it differs considerably from that observed for the majority of the highly convective non-TC events.

1. Introduction

Tropical cyclones (TCs) are associated with extreme amounts of rainfall that cause disastrous consequences, such as flooding, landslides, and death. For effective forecasting and cloud modeling studies, the accurate representation of the characteristics of rainfall, such as the temporal and spatial distribution of intensity and the drop size distribution (DSD), is essential. The latter is a fundamental quantity for radar meteorology and remote sensing whereby it is used to describe quantities such as the rainfall rate R , the liquid water content

(LWC), and the radar reflectivity Z [Munchak et al. (2012) and the references therein]. Obtaining accurate rainfall information over remote regions—for example, over oceans, where the TC duration is generally greatest—is difficult, however.

Quantitative precipitation estimates (QPEs) from spaceborne instruments can be used to address this shortcoming. The Precipitation Radar (PR; the first spaceborne weather radar) of the Tropical Rainfall Measuring Mission (TRMM) satellite has successfully provided estimates of rainfall for the tropics and subtropics (38°N–38°S) during its operational period from 1998 to 2015 (limited data were available in 2015). For a reliable estimate of precipitation, functions of

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calibration were implemented in the PR to ensure that the measured Z is unbiased compared to a known reference (Kozu et al. 2001). Nonetheless, there could still be biases in the Z - R relationship or the retrieval algorithm, and routine cross validation against ground-based measurements is instrumental for diagnosing the performance of the satellite-based estimates. Central to the evaluation of the PR measurement is the TRMM ground validation (GV) program, which produces quality-controlled ground radar (GR) data using GR at Houston, Texas (HSTN); Melbourne, Florida (MELB); Darwin, Australia (DARW); and Kwajalein Atoll, Marshall Islands (KWAJ).

Several studies have cross validated the PR reflectivities against GRs over different regions (Li et al. 2017; Park et al. 2015; Wang and Wolff 2009; Wen et al. 2011). These studies, in general, show that the disagreement between the PR and GR is larger at larger reflectivities, which is usually observed in convective events, and the average discrepancy between the PR and the GR varies between radars over different regions. Cross validation of the PR rainfall rates has also been performed by some studies (Kirstetter et al. 2013; Liao and Meneghini 2009; Liao et al. 2001; Wolff and Fisher 2008). These studies provide some insight into the association of the PR and GR rainfall rates; nonetheless, a clear consensus in the association between the two is missing because a mixture of both overestimation and underestimation by the PR is reported (see Table 2).

The PR is a single-frequency radar, hence DSD information retrieval is not straightforward. Algorithms have been developed to estimate the drop size parameters from the PR, and a few studies have compared these with dual-polarized GR estimates (Bringi et al. 2012; Chandrasekar et al. 2003a,b). In an early study, Chandrasekar et al. (2005) compared the drop size parameters estimated from S-band polarimetric (S-POL) GRs with the respective TRMM overpass events. The PR attenuation adjustment factor ϵ and the attenuation-corrected reflectivity Z_c were utilized to compute the median volume diameter D_o . The study was performed using two overpass events, and the GR measurements were taken from the Texas and Florida Underflight Experiment (TEFLUN) and the Large-Scale Biosphere-Atmosphere Experiment (LBA) field campaigns. Chandrasekar et al. (2005) found that the PR underestimates the D_o by 8%. In a recent study, Bringi et al. (2012) compared the D_o estimated from the KWAJ S-POL GR with those estimated from the PR and a combined TRMM Microwave Imager (TMI) and PR algorithm (Munchak and Kummerow 2011) for two overpass events. The PR D_o was estimated using the method described by Kozu et al.

(2009). Bringi et al. (2012) found that the PR overestimates the D_o by 11.7%–24.6%, while the combined algorithm had a relatively smaller bias (−0.8% to 9.7%). These studies advance our knowledge on the estimation of DSD parameters using the PR but, similar to the cross validation of rainfall rates, a consensus between the association of PR- and GR-estimated DSD parameters, over different regions, has not been established.

The primary aim of the GV program is to understand the differences in the precipitation retrievals for different meteorological and hydrological regimes (Schwaller and Morris 2011). The skill of the 2A25 algorithm varies over different terrains (ocean/land surface) and precipitation types: it is known to be more reliable over the oceans and during intense rainfall events (Meneghini et al. 2004, 2000). DSD cross-validation studies have used only non-TC events, and there is a lack of studies involving extreme events like TCs. Moreover, a comprehensive study, similar to Bringi et al. (2012), that compares the rainfall rate and DSD parameters for the DARW GR is lacking.

In this study we use TCs together with non-TC events to compare the precipitation characteristics (namely, the radar reflectivity, the DSD, and the rainfall) estimated using the PR and the Munchak and Kummerow (2011) TMI and PR combined algorithm (COM) with the DARW GR. A new framework that differs in several ways from the methodology used by the existing combined algorithm (i.e., 2B31) and is expected to provide an improved estimation of rainfall characteristics is utilized by the COM. This study seeks to investigate whether there is an added advantage of using the microwave (MW) estimates with the PR. There has been a limited validation of the COM [which is only at KWAJ by Bringi et al. (2012)], and even though the TRMM mission has ended, these results are relevant for the GPM combined algorithm, as the input datasets and methodology are similar (Greco et al. 2016). For the cross validation here, recalibrated DARW GR data are used (Louf et al. 2018). Two TC and 11 non-TC overpass events are used. Coincident TRMM and GR overpasses during the passage of TCs over Darwin are rare because of a relatively smaller occurrence of TCs (in comparison to non-TC events) and compounded by the fact that there are not many GR sites at Darwin. Also, the frequency of TRMM overpass over Darwin is low (about two overpasses per 24 h). The D_o is one of the main parameters used in defining the analytical form of the DSD (Bringi et al. 2009; Testud et al. 2001; Ulbrich and Atlas 1998); hence, we use it here to examine the representation of the DSD, consistent with other studies (e.g., Bringi et al. 2012; Atlas et al. 1999). The outline of the paper is as follows: section 2

describes the data and methodology, [section 3](#) presents the results and the discussion, and [section 4](#) summarizes the results.

2. Data and methodology

a. Darwin C-POL radar

The DARW C-band dual-polarized radar (C-POL), located at 12.248°S, 130.925°E and operated by the Australian Bureau of Meteorology (BoM), is part of the TRMM GV program and provides information on tropical rainfall ([Keenan et al. \(1998\)](#) and the references therein). A detailed description of the radar system is provided by [Keenan et al. \(1998\)](#). For the computation of the rainfall rate and DSD parameters, the horizontally polarized equivalent reflectivity factor Z_h , the differential reflectivity factor Z_{dr} , and differential propagation phase Φ_{dp} parameters are used, where

$$D_o(\text{mm}) = 0.0203Z_{dr}^4 - 0.1488Z_{dr}^3 + 0.2209Z_{dr}^2 + 0.5571Z_{dr} + 0.801, \quad -0.5 \leq Z_{dr} \leq 1.25 \text{ dB}, \quad (1)$$

$$D_o(\text{mm}) = 0.0355Z_{dr}^3 - 0.0321Z_{dr}^2 + 1.0556Z_{dr} + 0.6844, \quad 1.25 \leq Z_{dr} \leq 5 \text{ dB}. \quad (2)$$

For the computation of the rainfall rate, the BoM employs the hybrid method of [Thompson et al. \(2018\)](#), which utilizes the Z_h , Z_{dr} , and K_{dp} variables.

b. TRMM PR

We use version 7 (V7) of the PR rain profiling algorithm (also known as 2A25). The following PR data are used: attenuation-corrected reflectivity Z_c (2A25), rainfall rate R (2A25), rainfall type (2A23), and attenuation adjustment factor ε (2A25). A detailed description of the rainfall profiling algorithm is given by [Iguchi et al. \(2009\)](#).

At 13 GHz, the PR suffers from significant attenuation and this is corrected using a combination of the surface reference technique (SRT) and the Hitschfeld–Bordan method ([Iguchi et al. 2000](#)). Briefly, the attenuation adjustment factor ε is used to adjust the initial coefficient α_0 in the relation between attenuation coefficient k and effective radar reflectivity factor Z_e ($k = \varepsilon\alpha_0Z_e^\beta$) in such a way that the path-integrated attenuation (PIA) estimated using the SRT matches with the PIA estimated using the Hitschfeld–Bordan method.

[Kozu et al. \(2009\)](#) note that estimating the attenuation adjustment factor is approximately related to estimating the DSD. Hence, using their appendix and following [Bringi et al. \(2012\)](#), we derive the D_o estimator for convective and stratiform rainfall fields, which are given as follows:

the last is also used to compute the specific differential propagation phase K_{dp} . In the C band, the signal suffers from significant attenuation, which is corrected for by the BoM using the [Bringi et al. \(2001\)](#) method.

A set of algorithms, developed by [Bringi et al. \(2009\)](#) using 6 months of disdrometer data during the Darwin wet season (November–March), is employed to retrieve the GR-based DSD parameter D_o . Note that the wet season would consist of TC- and non-TC-related DSD cases, so the algorithm gives a climatological representation. Previous studies have shown that there is a statistical difference between TC- and non-TC-related DSDs that necessitates the implementation of a variable DSD algorithm for rainfall retrieval ([Deo and Walsh 2016](#); [Radhakrishna and Rao 2010](#)). Implementing these changes in the DARW GR, the PR, and the COM for a more accurate cross validation is, however, beyond the scope of this study. The D_o algorithms for different Z_{dr} thresholds are as follows:

$$\ln(D_o) = -0.10 + 0.185 \ln(R) - 1.81 \log_{10}(\varepsilon) \quad \text{convective rainfall}, \quad (3a)$$

$$\ln(D_o) = 0.0514 + 0.1631 \ln(R) - 1.6743 \log_{10}(\varepsilon) \quad \text{stratiform rainfall}. \quad (3b)$$

Note that [Kozu et al. \(2009\)](#) used TRMM V6 to derive the parameters, whereas we use V7. The set of parameters in their appendix is still valid for convective rainfall in V7, but it differs for stratiform rainfall (T. Iguchi, National Institute of Information and Communications Technology, 2017, personal communication). A new set of parameters (provided by Toshio Iguchi) is used here for the stratiform rainfall. The accuracy in estimating D_o using Eqs. (3a) and (3b) also differs: [Kozu et al. \(2009\)](#) note that the estimation is more accurate for convective rainfall, where the SRT-based path attenuation is generally more reliable. The SRT is based on the notion that a difference between the measurements during rain and rain-free periods (a reference background) provides the information about the PIA. The method is more reliable during heavy precipitation, since there is a significant contrast between the raining column and the background reference (the attenuation is large) unlike during weak precipitation, when the contrast is weaker, and the algorithm does not have sufficient information to deviate from the default $Z-R$

FIG. 1. Schematic of the volume matching technique. (a) Averaging of PR bins in the vertical at the intersection of the PR with the GR and (b) averaging of the GR in the horizontal at the intersection of the PR with the GR.

relationships and implied DSD properties. Moreover, ocean surfaces have less variability than land surfaces, hence the reliability is also larger over the former (Meneghini et al. 2004, 2000).

c. TRMM COM

At the core of the Munchak and Kummerow (2011) TRMM PR+TMI combined algorithm is a Hitchfeld–Bordan reflectivity profiling algorithm, similar in many respects to the 2A25 algorithm. Instead of Z – R and Z – k power laws, Z – D_o power laws are fit to the 2A25 Z – R relationships for stratiform and convective rain. From these power laws and a gamma distribution

$$N(D) = N_o D^\mu \exp \left[-\frac{(3.67 + \mu)}{D_o} \right] \quad (4)$$

with a shape parameter μ equal to 3, all integral parameters can be determined, including R , k , and the extinction coefficient, single-scatter albedo, and the asymmetry parameter at each TMI frequency, which are input into the delta-Eddington radiative transfer model (Kummerow 1993). The TMI brightness temperatures are simulated at the PR resolution and then convolved to TMI resolution.

In each PR profile, three parameters are retrieved: ϵ_{DSD} , ϵ_{ICE} and ϵ_{CLW} . The ϵ_{DSD} modifies the Z – D_o power law such that $D_o = \epsilon_{\text{DSD}} a Z^b$. Likewise, ϵ_{ICE} modifies

the Z – D_o relationship in ice phase regions of the profile and ϵ_{CLW} modifies the cloud liquid water profile. Because of the large size (approximately $40 \text{ km} \times 70 \text{ km}$ at 10 GHz) of the TMI field of view (FOV), an optimal estimation technique (Rodgers 2000) is used to optimize ϵ_{DSD} , ϵ_{ICE} , and ϵ_{CLW} over FOVs containing many PR profiles. TMI brightness temperatures and SRT PIA estimates are used as observational inputs to the optimal estimation procedure. Alternatively, the COM algorithm has the flexibility to run in radar-only mode, where only ϵ_{DSD} is modified to match the SRT PIA inputs (PIA algorithm). The flexibility allows us to examine the impact of the TMI observations on the D_o retrieval without having to account for subtle algorithm differences between COM (in radar-only mode) and 2A25.

d. Methodology for aligning the PR and the GR

Because of the difference in the measurement geometry of the PR and the GR (Fig. 1), the observations from both instruments need to be transformed onto a common coordinate system for a meaningful comparison. We accomplish this using the Schwaller and Morris (2011) volume matching method, which computes the PR and the GR averages at the geometric intersection of the PR with the individual GR rays. Unlike some of the other techniques, which are mostly gridded approaches (Bolen and Chandrasekar 2000, 2003; Schumacher and

Houze 2000; Wang and Wolff 2009), this method computes the averages where there are actual observations; in other words, there is no interpolation, extrapolation, or oversampling of observations.

The matching process involves computing the averages for each PR ray at each GR sweep intersection. The along ray average of the PR at the intersection is computed in the vertical and includes those bins (at a resolution of 0.250 km) that fall within the vertical resolution (beamwidth) of the GR sweep (Fig. 1a). The GR average at the intersection is computed in the horizontal, centered around the PR ray footprint (Fig. 1b), and within the PR horizontal beamwidth. In essence, the aforementioned procedure reduces the PR vertical resolution to the number of GR sweeps and the GR horizontal resolution to the number of PR rays. For a detailed description of the volumetric matching method see Schwaller and Morris (2011).

e. Statistical metrics

For the comparison to the PR, with the DARW GR taken as the reference, we use a combination of statistics. The Pearson correlation coefficient r is used to measure the degree of linear association, the root-mean-square error (RMSE) to measure the average magnitude of error, and the bias (and relative bias) measures the difference between the average PR and GR values. The formulas of the statistics are as follows:

$$r = \frac{\sum(\text{PR} - \overline{\text{PR}})(\text{GR} - \overline{\text{GR}})}{\sqrt{\sum(\text{PR} - \overline{\text{PR}})^2} \sqrt{\sum(\text{GR} - \overline{\text{GR}})^2}}, \quad (5)$$

$$\text{bias} = \frac{\sum_{i=1}^n (\text{PR}_i - \text{GR}_i)}{n}, \quad (6)$$

$$\text{relative bias} = \frac{\text{bias}}{\overline{\text{GR}}}, \quad (7)$$

$$\text{root-mean-square error (RMSE)} = \sqrt{\frac{1}{n} \sum_{i=1}^n (\text{PR}_i - \text{GR}_i)^2}, \quad (8)$$

$$\text{relative RMSE} = \frac{\text{RMSE}}{\overline{\text{GR}}}, \quad (9)$$

where $\overline{\text{PR}}$ and $\overline{\text{GR}}$ are the mean of the PR and GR measurements, respectively.

The uncertainty in these statistics is computed using a bootstrapping method (Efron and Tibshirani 1993) that involves resampling of the data. About 10 000 resamples are created upon which bootstrapping is applied at the 95% confidence level. The 50th percentile is presented

as the statistic, and the 2.5nd and 97.5th percentiles as the upper and lower bounds, respectively, for the errors (confidence interval). The overlapping error bars between two or more sets of statistics imply a difference is not significant at the 95% confidence level.

3. Results and discussion

a. Case descriptions

Overpass events during the passage of TC Carlos (year 2011) are used as case studies for the cross validation of PR and COM rainfall characteristics during the passage of TCs. TC Carlos, after forming near Darwin (track shown in Fig. 2a), stayed in the vicinity of Darwin for more than a day before heading southwest. During its passage, the TC brought copious amount of rainfall in excess of 300 mm day⁻¹ over the Darwin region (<http://www.bom.gov.au/cyclone/history/carlos.shtml>).

Two TRMM overpass events over the Darwin site occurred during the passage of TC Carlos: (i) on 15 February 2011 (Fig. 2a) and (ii) on 17 February 2011 (Fig. 2b). Figures 2a and 2b show the GR reflectivity plan position indicators (PPIs; which is a display of measurements at a radial distance from the GR) of the two TC events, respectively, at an altitude of 3.5 km. The 15 February event (Fig. 2a) has larger spatial coverage of rainfall than the 17 February event (Fig. 2b), which could be related to the distance of the TC center from the Darwin station, as the former is closer (112 km) than the latter (167 km).

In addition to these two TC events, 11 non-TC events are also used to examine the correspondence of the spaceborne instruments with the DARW GR (Table 1 lists the overpass events and their corresponding TRMM orbit numbers). These non-TC events are from the 2011 and 2012 Australian summer/monsoon seasons, which usually fall from November to April. Unlike TC events, which are of synoptic scale, non-TC events could be of a relatively smaller size (some are less than 1 km, especially convective events). Thus, TRMM overpass events that had at least 100 grid points within 100 km from the Darwin site are used for non-TC events. The events considered here encompass both stratiform and convective rainfall with some being highly stratiform and some being highly convective. As an example, Figs. 2c and 2d show the PPIs of widespread events that occurred on 13 January 2012 and 13 March 2012 respectively. These two events are also frequently used in the latter sections of this paper as case studies for non-TC events. Their spatial coverage of reflectivity is large (somewhat similar in size to the two TCs in the radar field of view) and their precipitation type is largely stratiform (similar to the two

FIG. 2. GR reflectivity at a constant altitude of 3.5 km for the two TC Carlos events (15 and 17 Feb 2011) and for two non-TC widespread events (13 Jan and 13 Mar 2012) within a radial distance of 150 km around the GR. The plot in red in (a) shows the track of TC Carlos.

TC events), which makes them suitable to be used for a comparative analysis against the TC events, especially for precipitation- and terrain-type separation.

b. Comparison of reflectivity

Using the volume matching technique discussed in section 2, data are transformed onto a common 3D coordinate system. Since the PIA is used both in the 2A25 and the COM, its analysis is also included at times to understand the differences (if there are any) between the latter two products. Figure 3 shows the matched PR–GR and COM–GR reflectivity PPIs of the two TC and the two non-TC case events (shown in Fig. 2) for the 1.3° GR elevation sweep. A good spatial match of the PR and the COM with the GR is observed. The missing data in the PR near the GR origin point are attributed to ground clutter in the PR at low altitudes that has been accordingly filtered by the PR algorithm. The PR–GR spatial pairing is also missing at some coordinates because of the rejection of bins during averaging in either the PR or the GR.

The data are stratified into two regions—altitudes less than 4 km and greater than 4 km—and the reflectivity comparison are performed for these two regions (the D_o and the rainfall estimates are analyzed only for the

TABLE 1. TC and non-TC overpass events and their corresponding TRMM orbit number. The events are arranged with respect to the percentage of convective activity, given in the last column.

No.	Event	TRMM orbit	Convection
1	17 Jan 2012	80 728	0
2	17 Nov 2011	79 773	2.1
3	27 Feb 2012	81 369	3.2
4	10 Mar 2012	81 559	6.7
5	14 Feb 2011	75 484	9.8
6	13 Jan 2012	80 667	10.8
7	17 Feb 2011	75 523	14.1
8	13 Mar 2012	81 598	16.0
9	18 Jan 2012	80 750	35.6
10	21 Jan 2012	80 789	46.3
11	20 Nov 2011	79 819	68.6
12	25 Jan 2012	80 850	79.1
13	9 Nov 2011	79 651	80.0

FIG. 3. Matched reflectivity profiles (dBZ) from the (left) GR, (middle) PR, and (right) COM for the events shown in Fig. 2 at the 1.3° GR elevation sweep.

former). This altitude roughly divides the liquid and frozen hydrometeor regions. Regions below the 0°C isotherm, which is located at about 5 km, are mostly dominated by liquid hydrometeors, and we have chosen less than 4 km to minimize the inclusion of frozen hydrometeors. At higher altitudes, frozen hydrometeors are

more dominant. The melting layer is also at the 0°C isotherm, which is usually seen as a bright band in the radar signature.

The scatterplot in Fig. 4 shows the distribution of the reflectivity in the PR and the COM against the GR for the two TC and the two non-TC case events for elevations

FIG. 4. Scatterplot of the matched reflectivity profiles (dBZ) for altitude less than 4 km from the (left) PR and (right) COM against the GR for the events shown in Fig. 2.

less than 4 km. There is a strong positive linear association between TRMM and the GR for the four case events. The scatter difference, however, could be both small (as in non-TC event 1) and large (as in TC events 1 and 2 and in non-TC event 2).

The statistics are presented next. Figure 5 shows the r , RMSE, and bias for the four case events with rainfall of each event further separated into convective, stratiform, over the land, and over the ocean. Considering separation into rainfall types, it is evident that there is a larger degree of disagreement between the satellite estimates and the GR during convective rainfall than during stratiform rainfall. For example, the correlation in convective rainfall is consistently weaker than that in stratiform rainfall, and the RMSE and the bias are consistently larger for the convective group than for the stratiform group. Note that the deviation in the correlation and the bias between the convective and

stratiform groups is much larger in TC event 1 (Figs. 5a and 5c, respectively) than in the other events. The more positive bias during convective rainfall shows a somewhat greater degree of overestimation by the satellite estimates during such rainfall. This could largely be due to the nature of convective-type rainfall, which can be highly variable within the PR footprint and can rapidly change with time.

Considering terrain separation (over the ocean and the land), a clearly better performance of the PR over the ocean in comparison to that over the land is not evident. For example, events 1, 3, and 4 have a larger correlation and a smaller RMSE in the PR over the ocean than that over the land but for event 2 it is the opposite. Also, the bias for events 1 and 3 over the ocean is smaller than that over the land, whereas for events 2 and 4 it is the opposite. While this could roughly point to a better performance over the ocean, a further

FIG. 5. Statistics of (left) r , (middle) RMSE, and (right) bias of the matched reflectivity profiles for the events shown in Fig. 2 for altitude less than 4 km. Events have been further separated into convective (Conv), stratiform (Strat), over the land, and over the ocean. The error bars show the 95% confidence interval.

computation shows that the terrain separation results are also dependent on the rainfall type over the area: for events 1, 3, and 4 there is a greater percentage of convective rainfall over the land than over the ocean, whereas for event 2 it is the opposite. As discussed earlier, the performance is weaker when more convective rainfall is present.

Figure 6 shows the statistics for the matched reflectivity profiles of all the events (2 TC and 11 non-TC) for altitudes less than 4 km. The events are arranged in the order of increasing percentage of convective rainfall, the values of which are shown in Fig. 6d. The r (Fig. 6a) for the majority of the events (11 out of 13 events for both the PR and COM) is in between 0.6 and 1, which shows a reasonable correlation between the spaceborne instruments and the DARW GR. Also, for most of the events, there is marginal to no difference in the r between the PR, the COM, and the PIA, which shows that

the different spaceborne data have almost the same degree of linear association with the GR.

The RMSE (Fig. 6b) ranges from 1 to 7.56 dBZ (4.5%–16%), and for the majority of the events (11 out of 13) there is statistically no significant difference in the RMSE between the spaceborne measurements. However, there is a systematic increase in the error with an increase in the percentage of convection in the rainfall events.

The bias (Fig. 6c) is not that large; it ranges from -2.4 to 1.4 dBZ (-5.75% to $+3.4\%$) and the bias in the COM and the PIA is either statistically the same or smaller than in the PR. Considering the degree of convective rainfall, the majority of the events (six out of eight) below the 20% level have a positive bias, whereas all the events (five) above the 20% level have a negative bias. This suggests that the spaceborne instruments could be mostly biased high during highly stratiform rainfall (or

FIG. 6. Statistics of (a) r , (b) RMSE, and (c) bias for the TC and non-TC events for altitude less than 4 km. (d) GR average reflectivity of each event. The TC events are marked as red [the first red point from the left (event 5) is the 15 Feb 2011 event and the second red point (event 7) is the 17 Feb 2011 event]. The error bars show the 95% confidence interval.

overestimating the reflectivity when considering the DARW GR as the reference) and they could be biased low during more convective rainfall (or for the case of DARW GR as the reference, they underestimate the reflectivity). Placing the TC events into context, it is evident that the association of the PR and the COM with the GR during the passage of TC Carlos is similar to that during the more stratiform rainfall events.

One of the factors that could lead to an error in the PR estimate is the nonuniform beamfilling (NUBF), which is the presence of nonuniformity in the reflectivity within a radar field of view. NUBF is corrected for in the 2A25 V7 algorithm but not in the COM and PIA algorithms. However, the NUBF correction requires an assumption of nonuniformity that can lead to overestimates if the assumed coefficient of variation is too high (Iguchi et al. 2009). This can explain the overestimation of PR relative to the COM and the PIA. It is also known that the PR suffers from significant attenuation, especially in convective rainfall, and an

attenuation correction tends to perform quite well for convective rainfall but it slightly overcorrects for stratiform rainfall (Wang and Wolff 2009). This further explains the positive bias in the spaceborne instruments during highly stratiform rainfall and vice versa for highly convective rainfall events. The overestimation of the COM and the PIA relative to the GR can be possibly explained by attenuation of the C-band reflectivity that is not fully corrected by the Bringi et al. (2001) method. This is evident in the outer range rings of Fig. 3a, where a large positive difference between the PR (or the COM) reflectivity and the GR reflectivity exists at the 225° azimuth. Since this difference is present even outside the convective cores, there should not be a large error in the PR attenuation correction, since there is not a significant attenuation along the PR line of sight in this situation. However, there is significant attenuation along the GR line of sight in this situation and small underestimates in the attenuation correction can lead to these biases (Fig. 7).

FIG. 7. Reflectivity difference with respect to the GR at 3-km altitude (a) for the PR and (b) for the COM for TC 1 (14 Feb 2011).

The statistics for reflectivities measured at altitudes greater than 4 km are also presented (shown in Fig. 8). These are for 11 events, as 2 events have a small sample (less than 10) above the 4-km level. While the linear association (r) is almost the same as that for the less-than-4-km group, there are some notable differences in

the other statistics. First, the error (RMSE) increases for the majority (nine) of the events (the RMSE for the different spaceborne measurements are almost the same). Second, the bias of the greater-than-4-km group is less than that of the less-than-4-km group for almost all of the events (the difference is in the range -5.17 to

FIG. 8. As in Fig. 6, but for altitude greater than 4 km.

FIG. 9. As in Fig. 4, but for D_o .

0.23 dBZ) and the difference is larger in the events with a larger percentage of stratiform rather than convective rainfall. The bias for the different spaceborne measurements is the same for most of the events except for event 5 (which is TC event 1) and for event 6, where the bias in the COM and the PIA is larger than that in the PR.

The results obtained here for the reflectivity comparison are consistent with most of the studies over other regions (Kim et al. 2014; Liao and Meneghini 2009; Park et al. 2015; Schwaller and Morris 2011). For example, Park et al. (2015) show that for elevations less than 4 km, the bias for widespread events is small with a slight overestimation by the PR (less than 1 dBZ), whereas for convective cases the bias is negative (greater than -4 dBZ) and the RMSE is larger than that in widespread cases, as also reported here. The usually negative bias for the more convective events suggests greater attenuation at the PR frequency than the GR frequency and the larger RMSE could be due to the

nature of convective storms (a greater degree of small-scale spatial variability). Another contributing factor could be NUBF for small-scale events. Park et al. (2015) also show that for elevations greater than 4 km, the bias becomes negative (1–3 dBZ smaller in the PR than in the GR) and the RMSE increases in the widespread events, whereas there is not much variation for convective events as reported here. Such differences are attributed to a mismatch in the brightband height, and the scattering differences in the PR and the GR for mixed-phase hydrometeors in and above the melting layer (Park et al. (2015) and the references therein). In addition, hydrometeors in stratiform events are mainly dry snow that gives weak radar returns. Hence, a PR sensitivity of 18 dBZ may be another contribution to the negative bias (shown in Fig. 8c).

c. Comparison of D_o

The consistency of the aforementioned results with other studies provides the impetus to examine the D_o

FIG. 10. As in Fig. 5, but for D_o .

and the rainfall estimates. The D_o estimates for the rainfall region (altitudes less than 4 km) are presented next. Figure 9 shows the corresponding scatterplots of D_o for the two TC and the two non-TC case events (shown in Fig. 2). A positive linear association between the PR (or the COM) and the GR is evident but the association is weak, particularly at smaller D_o values. Unlike the two TC events, the scatter for the two non-TC events is mostly above the line of perfect agreement. Also, the D_o in the PR is greater than 1 mm, whereas in the COM and in the GR there are values less than 1 mm.

Figure 10 shows the D_o statistics for the two TC and the two non-TC case events with further separation into rainfall and terrain types. Similar to the reflectivity estimates, it is evident that there is a larger degree of disagreement between the satellite estimates and the GR during convective rainfall than during stratiform rainfall. For the PR, the r of the convective group is

weaker than that of the stratiform group (except for event 3), whereas the RMSE and the bias for the convective group are consistently larger than that for the stratiform group. For separation into terrain types, the results are similar to that obtained for the reflectivity estimates whereby the PR has a larger deviation over the land for events 1, 3, and 4 in comparison to event 2.

Figure 11 shows the statistics for the matched D_o profiles of all the events (2 TC and 11 non-TC) in the rainfall region. The linear association (r ; Fig. 11a) between the spaceborne instruments and the GR is generally not strong. Also, the RMSE (Fig. 11b) is larger for the more convective events, which shows more variability between the spaceborne and the GR D_o as events become more convective.

A similar trend is also observed in the bias (Fig. 11c), where it increases with an increase in the convection; the bias ranges from -0.08 to 0.57 mm (or -6% to 58%) in

FIG. 11. As in Fig. 6, but for D_o .

the PR. Also, for the majority of the events, the bias is positive both in the PR and the COM, which shows that TRMM tends to mostly overestimate the D_o with respect to the DARW GR. However, the bias in the COM appears to be smaller than that in the PR, especially for the majority of the less convective events (i.e., events with less than 20% convection). Moreover, it could be concluded that the association of the PR and the COM D_o estimates with the GR during the passage of TC Carlos is similar to that during the more stratiform rainfall events (congruent with the results obtained for the reflectivity estimates).

The results obtained here for the PR and the COM D_o are consistent with Brangi et al. (2012), who found that the PR overestimates the D_o with respect to the KWAJ GR for the two cases they examined (the bias ranged from 11.7% to 24.6%). They also show that the bias in the COM is smaller than that in the PR (−0.8% to 9.7%). We note that in most cases in Fig. 11c, the biases of PR and the PIA algorithm are similar to each other, but the COM algorithm can differ and is often closer to zero, particularly in the cases with low convective fraction. This suggests that the addition of

measurements from TMI, specifically the strong positive relationship between liquid water path and brightness temperature over water surfaces, is providing information that adjusts the DSD in rainfall over ocean that is not present in the radar-only algorithms, which rely on the default stratiform and convective DSD assumption in profiles without significant attenuation (Kozu et al. 2009).

d. Comparison of rainfall rate

Finally, we compare the rainfall rates estimated from the spaceborne instruments and the GR. These are performed for altitudes less than 4 km. Figure 12 shows the scatterplots of the rainfall rate from the PR and the COM against the GR for the four case events. Both the PR and the COM have a positive linear relationship with the GR but the data points deviate considerably from the line of perfect agreement, especially for events 1, 2, and 4.

The statistics for the case events, including separation into rainfall and terrain types, are presented in Fig. 13. It is evident that there is a larger degree of overestimation by the PR during convective rainfall

FIG. 12. As in Figs. 4 and 9, but for rainfall rate.

than during stratiform rainfall for the two TC events (for the two non-TC events the results are mixed). This follows the clear larger overestimation of reflectivity estimates during convective than during stratiform rainfall for the two TC events (Figs. 5c and 5f). However, the COM consistently has a larger degree of overestimation for the convective group for both the TC and non-TC events. For separation into terrain types, a clear pattern is not evident.

Figure 14 shows the statistics for the rainfall profiles of all the events (2 TC and 11 non-TC). The correlation (Fig. 14a) of the PR and the COM with the GR for most of the events (11) is greater than 0.5 and it is the same for both the instruments. The correlation, nonetheless, decreases with an increase in the percentage of convection.

Consequently, the RMSE tends to increase with an increase in the percentage of convection, which is more evident in the PR. For the greater stratiform

events (below 20% convection), the COM has a similar RMSE as the PR for events 1–3 (the RMSE for these events is also small) but for events 4–8 the COM generally has a larger RMSE than the PR. For the more convective events (greater than 20% convection), a statistically significant difference in the error between the PR and the COM is not evident for most of the events.

The bias is shown in Fig. 14c and some important conclusions are as follows. The bias decreases (becomes more negative) with an increase in the percentage of convection and this trend is prominent in both the PR and the COM. For the highly stratiform rainfall events, there is a mixture of a good match and overestimation with respect to the GR. For the highly convective events, the spaceborne instruments generally underestimate the rainfall observed by the GR. Also, the bias in the COM is greater than that in the PR for more than 50% of the events.

FIG. 13. As in Figs. 5 and 10, but for rainfall.

This is somewhat similar to the results obtained by Brangi et al. (2012), who report an increase in the bias in the COM rainfall with respect to the KWAJ GR. The biases they report are, however, negative in both the PR and the COM. The bias of the COM algorithm relative to the PIA and PR algorithms can also be explained in the context of the reflectivity and D_o biases. In the events with significant positive bias, the reflectivity bias (relative to GR) is also positive but the D_o bias, while positive, is less strongly positive than PR and PIA algorithms. The combination of high reflectivity and smaller D_o must result in a positive rainfall bias. Other possibilities could be (i) the NUBF correction is too much, (ii) the vertical hydrometeor phase is incorrect, or (iii) the GR D_o is too low as a result of an insufficient attenuation correction of the Z_{dr} . Furthermore, the rainfall statistics are dominated by the highest rates when compared to the Z and D_o statistics (Figs. 6 and 10), which are more normally distributed

and thus have even contribution from light and moderate rates.

Comparing the results obtained here with studies over other regions, especially for the PR, show mixed results. Table 2 shows a list of some of these studies and the corresponding biases between the PR and GR estimates of rainfall. It is evident that there is a mixture of overestimation and underestimation of the rainfall by the PR over the different regions. Nonetheless, the study here shows some clear pattern as discussed above. The results here are also congruent with the findings of Kirstetter et al. (2013). For example, their correlation coefficient of 0.68 between PR and GR rainfall estimates agrees well and using an error model they show that the bias and the RMSE in R increases as the convective part increases (i.e., more underestimation of R and an increase in RMSE). They further quantified the error sources in PR rainfall estimates, like rainfall type classification and NUBF, and

FIG. 14. As in Figs. 6 and 11, but for rainfall rate.

showed that the overestimation at lighter rain rates mainly comes from the convective Z - R relationship and that the underestimation at high rain rates is related to NUBF effects.

4. Summary

In this study we use 2 TC and 11 non-TC rainfall events to compare the reflectivity, the median volume diameter D_o , and rainfall rates estimated using the TRMM PR (2A25, V7), the combined algorithm (COM) developed by Munchak and Kummerow (2011), and the DARW GR, which is one of the TRMM ground validation sites. This is the first study that cross validates the PR and the COM-derived DSD and rainfall rates against a GR during the passage of TCs. The cross validation of the PR and the COM over Darwin, Australia, and the use of several non-TC events for a comparative study are some of the other originalities of this research.

The correspondence of the spaceborne instruments (i.e., the PR and the COM) with the DARW GR, taken as the reference, is shown to be largely dependent on the percentage of convection in the rainfall event.

Moreover, putting the two TC events into context, which are highly stratiform in nature, the association of the TRMM estimates with the GR for these two events is similar to that observed for the highly stratiform non-TC events (there is no significant difference) but it differs considerably from that observed for the majority of the highly convective non-TC events.

The PR and the COM mostly overestimate the reflectivities of events with a greater percentage of stratiform rainfall, and they mostly underestimate the reflectivities as events become more convective. Moreover, the bias in the COM is either the same or smaller than that in the PR, which could be a positive result of blending the TRMM microwave estimates with the PR.

Considering the D_o estimates, the linear association between the spaceborne instruments and the GR is shown to be weak. Moreover, the PR and the COM overestimate the D_o for most of the events and the magnitude of overestimation increases as the events become more convective. Also, the bias in the COM is the same as that in the PR for the majority of the highly convective events, but it is generally smaller in the COM for the highly stratiform events. This shows that combining the TMI with the PR

TABLE 2. PR and GR rainfall rate comparison from previous studies. The 2A25 version used by the respective studies is also shown in the bias column.

Region	Study by	Bias (% of mean)	Rainfall/terrain
Korea	Kim et al. (2014)	+16–80 (V6)	Stratiform
		+26–150 (V6)	Convective
KWAJ	Wolff et al. (2005) Wolff and Fisher (2008)	+6 (V6)	—
		−13.7 (V6)	Ocean
MELB	Wolff et al. (2005) Wolff and Fisher (2008)	−9.1 (V6)	—
		+4.1 (V6)	Ocean
	Liao and Meneghini (2009)	+7 (+8) (V6)	Land (coast)
		+9 (V6)	Stratiform
Southern United States	Kirstetter et al. (2013)	−19 (V6)	Convective
		−18 (V7)	Land
		−23 (V6)	

improves the DSD retrieval in the highly stratiform events where the PR is less reliable.

Considering the rainfall estimates, the linear association and the bias between the spaceborne instruments and the GR decreases as events become more convective. For the highly stratiform rainfall events, there is a mixture of a good match and overestimation with respect to the GR. For the highly convective events, the spaceborne instruments generally underestimate the rainfall observed by the GR. Also, the bias in the COM is greater than in the PR for more than 50% of the events.

This cross-validation study gives some insight into the correspondence between the TRMM-based and the DARW GR-based estimates of rainfall characteristics during different rainfall regiments. TRMM could be used to characterize the DSD of TC rainfall events; however, its limitations need to be taken into consideration. For a more general conclusion, the study should be extended with more cases, especially during the passage of TCs, over a longer period of time and over different regions. It would also be worthwhile to further perform a similar cross validation of the rainfall characteristics estimated using the Global Precipitation Measurement (GPM; Hou et al. 2014)-based Dual-Frequency Precipitation Radar (DPR) with more TC rainfall events.

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