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Raindrop size distribution characteristics of Indian and Pacific Ocean tropical cyclones observed at India and Taiwan sites

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Abstract

We made an effort to inspect the raindrop size distribution (RSD) characteristics of Indian Ocean and Pacific Ocean tropical cyclones (TCs) using ground-based disdrometer measurements from observational sites in India and Taiwan. Five TCs (2010–2013) from the Indian Ocean and six TCs (2014–2016) from the Pacific Ocean were measured using particle size and velocity disdrometers installed in south India and south Taiwan, respectively. Significant differences between the RSDs of Indian Ocean and Pacific Ocean TCs are noticed. For example, a higher number of small drops is observed in Indian Ocean TCs, whereas Pacific Ocean TCs have more mid-size and large drops. RSDs of Pacific Ocean TCs have higher mass-weighted mean diameter and lower normalized intercept parameter than Indian Ocean TCs. RSD values quantified based on rainfall rate and precipitation types also showed similar characteristics between Indian Ocean and Pacific Ocean TCs. The radar reflectivity and rainfall rate (Z-R) relations and shape and slope (μ-Λ) relations of both oceanic (Indian and Pacific) TCs are found to be distinctly different. Possible causes for the dissimilarities in RSD features between Indian Ocean and Pacific Ocean TCs are due to relative differences in water vapor availability and convective activity between TCs in these two oceanic basins.

Keywords: tropical cyclones (TCs), Raindrop size distribution (RSD), rainfall rate
1. Introduction

Tropical cyclones (TCs) are a severe natural hazard that cause significant property damage and loss of life when making landfall, in part due to torrential rainfall. The study of raindrop size distribution (RSD) in TCs can be useful for better understanding cloud microphysics and improving the cloud models (Tokay et al. 2008; Zhang et al. 2006), and assessing rainfall-caused erosivity (Janapati et al. 2019). There have been reports on RSD characteristics of TCs around the globe. Over the Atlantic Ocean, Merceret (1974) found no distinct differences in RSD characteristics between the rainbands and eyewall region of Hurricane Ginger. Additionally, Jorgensen and Willis (1982) did not observe much variation in radar reflectivity and rainfall rate (Z-R) relations between the eyewall and outer rainband regions at 3 km above the surface and below. Using airborne radar and disdrometer measurements, Marks et al. (1993) observed significant differences in the eyewall and outer rainband Z-R relations (eyewall: $Z = 253R^{1.3}$; outer rainband $Z = 341R^{1.25}$; total $Z = 311R^{1.27}$).

A clear demarcation in RSD characteristics from before and during the passage of Hurricane Helene (2000) was observed by Ulbrich and Lee (2002), who found that Z-R relations ($Z = 118R^{1.48}$) of TCs differ from those of tropical Z-R ($Z = 250R^{1.2}$) and default Z-R relations ($Z = 300R^{1.4}$). An analysis of seven Atlantic TCs by Tokay et al. (2008) revealed the presence of more small and mid-size drops and fewer large drops, with a maximum diameter seldom exceeding 4 mm. Chang et al. (2009) explored drop shape and RSD characteristics of typhoon rainfall during landfall over north Taiwan and found a maritime convective type RSD for typhoon systems. They mentioned that typhoon convective systems influenced by Taiwan’s terrain had RSD features of intermediate to maritime and continental clusters. Radhakrishna and Narayana Rao (2010) explored seasonal variations of cyclonic and non-cyclonic RSD characteristics over southern India and perceived large numbers of small and medium drops with an almost absence of large drops in cyclonic precipitation. With the aid of the Particle
Size and Velocity (Parsivel) disdrometer, Chen et al. (2012) analyzed the RSD characteristics of Typhoon Morakot (2009) and noted substantial differences between precipitation characteristics of the eyewall and outer rainbands. Wind profiler and disdrometer observations from Kim et al. (2013) showed strong and weak bright bands in the rainband and eyewall regions of Typhoon Kompasu, respectively. Further, they noticed a higher mass-weighted mean diameter ($D_m$) in the outer rainband than in the eyewall region. Differences between cyclonic and northeast monsoon thunderstorm rainfall RSDs was detailed by Kumar and Reddy (2013). Over east India, Bhattacharya et al. (2013) noticed stratiform features before and after Tropical Cyclone Aila in the Bay of Bengal. Kumari et al. (2014) illustrated RSD differences between two TCs that passed over southern India. Over Korea, Suh et al. (2016) analyzed the RSD characteristics of nine rainfall groups and noticed smaller $D_m$ and normalized intercept parameter ($N_w$) values in typhoon rainfall than in other rainfall categories. Higher concentrations of small drops in TC eyewalls and large drops in outer rainband regions was observed over Darwin, Australia, by Deo and Walsh (2016). Wang et al. (2016) demonstrated the microphysical characteristics in the rainbands of Typhoon Matmo (2014) over eastern China using ground-based radar and disdrometer measurements. Kim and Lee (2017) perceived different microphysical characteristics between stratiform and mixed stratiform-convective regimes of the rainbands of Typhoon Bolaven (2012) over South Korea. Janapati et al. (2017) detected clear differences in RSD characteristics in precipitation of TCs from the Bay of Bengal, before and after landfall. Recently, Wen et al. (2018) investigated the RSD characteristics of seven typhoons observed over China, and noticed higher raindrop concentrations and lower rain drop diameters for typhoon convective precipitation than the maritime convective clusters of Bringi et al. (2003).
Thus far in the literature, TC RSD have been limited to case studies or to particular oceanic regions. Additionally, there have been no comparison studies of RSD characteristics between one oceanic region and another. Hence, this study reports on RSD differences between Indian Ocean and Pacific Ocean TCs using Parsivel disdrometer data from stations in southern India and Taiwan. The remainder of this paper is ordered as follows: Section 2 outlines the data and methodology, Section 3 provides results and discussion, and Section 4 gives a summary.

2. Data and methodology

2.1 Tropical cyclones

A total of five Indian Ocean TCs (2010–2013) and six Pacific Ocean TCs (2014–2016) were measured using Parsivel disdrometers at Yogi Vemana University in Kadapa, India (14.4742°N, 78.7098°E, 138 m above sea level) and at Shu-Te University in Kaohsiung, Taiwan (120.3746°E, 22.7621°N, 9 m above sea level). The tracks of these TCs and locations of the disdrometers (indicated by red stars) are shown in Fig. 1. Track information for the Indian Ocean TCs was obtained from the India Meteorological Department (IMD) best track archive (http://www.rsmcnewdelhi.imd.gov.in). Track information for the Pacific Ocean TCs was obtained from the Japan Meteorological Agency (JMA) best track database (https://www.jma.go.jp/jma/jma-eng/jma-center/rsmc-hp-pub-eg/besttrack.html). Table 1 lists the Indian Ocean and Pacific Ocean TCs used in this study, with their names, life span, disdrometer measurement periods, total rain accumulations, and rainfall rate statistics (maximum, mean, and standard deviation). Rainfall amounts for a location are considered to be attributed to TCs if that location is within 500 km of the TC center (Deo and Walsh 2016; Jiang and Zipser 2010; Prat and Nelson 2013; Wu et al. 2015). Hence, in this study, the RSD measurements of selected TCs (as listed in Table 1) from Parsivel disdrometers in south Taiwan
and south India are considered for further analysis if the distance between the disdrometer site and the TC center is 500 km or less (Deo and Walsh 2016).

### 2.2 Parsivel disdrometer

The Parsivel (Löffler-Mang and Joss 2000; Yuter et al. 2006) is a laser-based disdrometer that can simultaneously measure precipitating particle size (liquid particles: 0.2 to 5 mm and solid particles: 0.2 to 25 mm) and fall speed (0.2 to 20 ms⁻¹) and records them in 32×32 drop size and fall velocity classes. This instrument has an optical sensor that generates a 650 nm 3 mW laser beam 180 mm long, 30 mm wide, and 1 mm high. A decrease in the laser signal occurs when precipitating particles pass through the light sheet. The signal deviation amplitude is a measure of particle size and the signal deviation duration allows estimation of particle fall velocity. Detailed explanation of the Parsivel disdrometer along with the assumptions used to determine hydrometeor size and velocity can be found in Löffler-Mang and Joss (2000), Battaglia et al. (2010), Jaffrain and Berne (2011), Friedrich et al. (2013b), Tokay et al. (2014) and references within.

Parsivel experiences some instrumental errors in strong wind, marginal effect, and splashing effect conditions. Particles falling through the edges of the sample area appear as small particles moving faster than the empirical relationship between fall velocity and particle diameter, a phenomenon known as the marginal effect. Raindrops that hit the surface of the Parsivel itself break apart and bounce back into the sampling area, a phenomenon known as the splashing effect. To minimize these measurement errors, quality control procedures are applied to disdrometer data. In this study, the first two size bins of disdrometer data are discarded because of their low signal-to-noise ratio. Further, 1-min samples with fewer than 10 drops or rainfall rates less than 0.1 mm h⁻¹ are considered noise and are thus discarded (Tokay
et al. 2013). Additionally, raindrops with diameters greater than 6 mm and fall speeds 60% above or below the Atlas et al. (1973) empirical fall velocity-diameter relation (Jaffrain and Berne 2011) are discarded (Fig. 2). During the passage of TCs at both observational sites, we did not observe any solid precipitation with either disdrometer.

The quality-controlled raw spectra are used to estimate raindrop concentration \( N(D_i) \) (m\(^{-3}\) mm\(^{-1}\)) using the following equation (Friedrich et al. 2013b; Tokay et al. 2014).

\[
N(D_i) = \sum_{j=1}^{32} \frac{n_{ij}}{A_{eff} \Delta t V(D_i) \Delta D_i} - - - - - (1)
\]

To compute \( N(D_i) \) for each diameter class (\( i = 1 \) to 32), number concentrations were summed over all velocity classes (\( j = 1 \) to 32) (Friedrich et al. 2013b). Here, \( n_{ij} \) is the number of drops reckoned in size bin \( i \) (\( i = 1 \) to 32), velocity bin \( j \) (\( j = 1 \) to 32), \( \Delta t \) (s) is the sampling time (60 seconds), \( \Delta D_i \) (mm) is the width of the \( i^{th} \) class diameter, \( V(D_i) \) (m s\(^{-1}\)) = 9.65–10.3exp(–0.6*\( D_i \)) is the fall velocity of the \( i^{th} \) size bin drops (Atlas et al. 1973), and \( A_{eff} \) (m\(^2\)) is the effective sampling area expressed by \( A_{eff} = 10^{-6} \times L \left( B - \frac{D_i}{2} \right) \) (Battaglia et al. 2010; Löffler-Mang and Joss 2000; Tokay et al. 2014), in which \( D_i \) (mm) is the \( i^{th} \) bin size drop diameter, \( L \) is the length of the Parsivel beam (180 mm), and \( B \) is the width of the Parsivel beam (30 mm).

The rainfall rate \( R \) (mm h\(^{-1}\)), sixth moment (Rayleigh) reflectivity/radar reflectivity factor \( Z \) (mm\(^6\) m\(^{-3}\)), liquid water content \( W \) (g m\(^{-3}\)), and total number concentration \( (N_t, \ m^{-3}) \) are derived (Friedrich et al. 2013a; Friedrich et al. 2013b) by the following expressions.

\[
R (\text{mm h}^{-1}) = 6\pi \times 10^{-4} \sum_{i=1}^{32} N(D_i) D_i^3 V(D_i) \Delta D_i - - - - - (2)
\]

\[
Z \ (\text{dBZ}) = 10 \log_{10} \sum_{i=1}^{32} N(D_i) D_i^6 \Delta D_i - - - - - (3)
\]
\[ W (g \ m^{-3}) = \frac{\pi}{6} \times 10^{-3} \rho_w \sum_{i=1}^{32} N(D_i) D_i^3 \Delta D_i \quad (4) \]

where, \( \rho_w (1 \ \text{g cm}^{-3}) \) is the density of water.

\[ N_e (m^{-3}) = \sum_{i=1}^{32} N(D_i) \Delta D_i \quad (5) \]

The \( n \)th order moment (in \( \text{mm}^n \ m^{-3} \)) of the drop size distribution can be expressed as

\[ M_n = \int_{D_{\text{min}}}^{D_{\text{max}}} D^n N(D) dD \quad (6) \]

where \( n = 3 \) for the third moment, 4 for the fourth moment, and 6 for the sixth moment of the size distribution.

The mass-weighted mean diameter (\( D_m, \text{mm} \)), shape parameter (\( \mu, \text{dimensionless} \)), and slope parameter (\( \Lambda, \text{mm}^{-1} \)) are obtained (Bringi et al. 2003; Tokay and Short 1996; Ulbrich 1983) from the third, fourth, and sixth moments of the size distribution as

\[ D_m = \frac{M_4}{M_3} \quad (7) \]

The slope parameter \( \Lambda (\text{mm}^{-1}) \) is given (Tokay and Short 1996) by

\[ \Lambda = \frac{(\mu + 4) M_3}{M_4} \quad (8) \]

where \( \mu \) is the shape parameter (dimensionless) and is given (Tokay and Short 1996) by

\[ \mu = \frac{(11G - 8) + \sqrt{G(G + 8)}}{2(1 - G)} \quad (9) \]

where \( G \) is

\[ G = \frac{M_4^3}{M_3^2 M_6} \quad (10) \]
The normalized intercept parameter $N_w$ (mm$^{-1}$ m$^{-3}$) is defined by Bringi et al. (2003) as

$$N_w = \frac{4^4}{\pi \rho_w} \left( \frac{10^3 W}{D_m^3} \right) - \cdots - \cdots - (11)$$

where $W$ (g m$^{-3}$) represents the liquid water content for the corresponding size distribution.

The mass spectrum standard deviation $\sigma_m$ (mm) can be expressed in terms of $D_m$ and $N(D)$ (Thurai et al. 2014; Ulbrich 1983; Williams et al. 2014) as

$$\sigma_m = \left[ \frac{\sum_{i=1}^{32} (D_i - D_m)^2 N(D_i) D_i^3 \Delta D_i}{\sum_{i=1}^{32} N(D_i) D_i^3} \right]^{1/2} - \cdots - (12)$$

### 2.3 MODIS and ERA-Interim data

Along with the disdrometer measurements, Moderate Resolution Imaging Spectroradiometer (MODIS) and European Centre for Medium-Range Weather Forecasts (ECMWF) Interim Re-Analysis (ERA-Interim) datasets over the observational sites in Taiwan (22.75°–22.875°N, 120.25°–120.375°E) and India (14.375°–14.5°N, 78.625°–78.75°E) were used for the TCs dates listed in Table 1. Convective available potential energy (CAPE, J kg$^{-1}$: available every three hours) and vertical integral water vapor (W, kg m$^{-2}$; available every six hours) from ECMWF ERA-Interim (Dee et al. 2011) with a 0.125° × 0.125° grid resolution are used. Cloud top temperatures (CTT, °C) from the MODIS level 3 data product (Platnick 2015) are used. The level 3 daily data product (MOD08_D3) of MODIS consists of 1° × 1° grid average values of atmospheric parameters related to aerosol particle properties, water vapor, and cloud optical and physical properties. Details about the MODIS cloud product algorithms are provided in Platnick et al. (2003) and King et al. (2003). CTT data, which are available at a 1° × 1° grid resolution, are interpolated to a 0.125° × 0.125° grid resolution.
3. Results

The disdrometers at the observational sites in Taiwan and India recorded a 8392 RSD samples (1-min) for six Pacific Ocean TCs and 3776 RSD samples (1-min) for five Indian Ocean TCs. The variations of mean raindrop concentration ($N(D)$, m$^{-3}$ mm$^{-1}$) with drop diameter ($D$, mm) for Indian Ocean and Pacific Ocean TCs are illustrated in Fig. 3. Throughout this paper, raindrops with diameters of 1–3 mm are considered as mid-size drops, and drops below and above this range are considered, small and large drops, respectively (Janapati et al. 2017; Kumar and Reddy 2013; Kumari et al. 2014; Tokay et al. 2008). Figure 3 clearly demonstrates that the raindrop concentration of mid-size and large drops is higher for Pacific Ocean TCs than Indian Ocean TCs. The Pacific Ocean TCs have higher mean rainfall rates ($R$, mm h$^{-1}$), mass-weighted mean diameters ($D_m$, mm), and lower normalized intercept parameters ($N_w$, mm$^{-1}$ m$^{-3}$) than Indian Ocean TCs (Fig. 3). A higher concentration of small drops and lower concentration of mid-size and large drops in Indian Ocean TCs results in lower $D_m$ values than Pacific Ocean TCs.

Further, to recognize dissimilarities in rain parameters ($\log_{10}R$, $\log_{10}W$, $D_m$, and $\log_{10}N_w$) of Indian Ocean and Pacific Ocean TCs, the probability distribution functions (PDF) of these parameters are computed and illustrated in Fig. 4. The Pacific Ocean TCs have larger values than Indian Ocean TCs for $\log_{10}R > 0.5$, where $R$ is in mm h$^{-1}$, and the Indian Ocean TCs show peak distributions at lower rainfall intensities ($\log_{10}R = 0$) (Fig. 4a). The liquid water content ($\log_{10}W$) PDF shows relatively greater frequency in Indian Ocean TCs for $\log_{10}W < -0.6$ (here $W$ is in g m$^{-3}$) than in Pacific Ocean TCs (Fig. 4b). A clear variation in PDF distributions of $D_m$ for Indian Ocean and Pacific Ocean TCs can be seen (Fig. 4c). The Indian Ocean and Pacific Ocean TCs have peak PDF distributions of $D_m$ at around 0.8 mm and 1.4 mm, respectively. Like $D_m$, the normalized the intercept parameter ($\log_{10}N_w$) also showed
distinct differences in PDF distributions between Indian Ocean and Pacific Ocean TCs (Fig. 4d). The PDF of $\log_{10} N_w$ shows a higher percentage at lower $\log_{10} N_w$ values in the Pacific Ocean TCs, and a higher percentage at higher $\log_{10} N_w$ values in the Indian Ocean TCs (Fig. 4d). Additionally, to show the dissimilarities between Indian Ocean and Pacific Ocean TCs rain parameters, a Student’s t-test is executed for $\log_{10} R$, $\log_{10} W$, $D_m$, and $\log_{10} N_w$, and the results reject the null hypothesis $H_0(\log_{10} R_{\text{Pacific}} = \log_{10} R_{\text{Indian}}; \log_{10} W_{\text{Pacific}} = \log_{10} W_{\text{Indian}}; D_{m, \text{Pacific}} = D_{m, \text{Indian}}; \log_{10} N_{w, \text{Pacific}} = \log_{10} N_{w, \text{Indian}}$) at significance levels of 0.05 and 0.01.

3.1 RSD in different rainfall rate classes

The mean raindrop concentrations of Indian Ocean and Pacific Ocean TCs are classified into six rainfall rate classes (C1:0.1–1, C2:1–2, C3:2–5, C4:5–10, C5:10–20, C6: >20 mm h$^{-1}$) and are shown in Fig. 5. The rain statistics of these six rainfall rate classes for Indian Ocean and Pacific Ocean TCs are provided in Table 2. For C1 and C2, there are higher concentrations of mid-size and large drops in Pacific Ocean TCs than in Indian Ocean TCs (Fig. 5a and b). Additionally, raindrops with diameters of > 1.4 mm and 1.6 mm in C3 and C4, respectively, have greater concentrations in Pacific Ocean TCs (Fig. 5c and d). In C5 and C6 (Fig. 5e and f), raindrops larger than 2 mm in diameter are more common in Pacific Ocean TCs than Indian Ocean TCs. From Fig. 5, it can be seen that even after separating the Pacific Ocean and Indian Ocean TCs raindrop spectra into different rainfall rate classes, mid-size and large drops are more common in Pacific Ocean TCs than Indian Ocean TCs. For both oceanic TCs, it can be seen that the concentration of large drops and spectral width increase with increased rainfall rate.

Variations of $D_m$ and $\log_{10} N_w$ values in the six rainfall rate classes of both oceanic TCs are shown in Fig. 6 with a box and whisker plot. It is obvious from Fig. 6a that Pacific Ocean
TCs have higher $D_m$ values than Indian Ocean TCs. In contrast, $D_m$ values increase with increased rainfall rate classes for the TCs in both oceans. In contrast to $D_m$, the $\log_{10}N_w$ values are higher for Indian Ocean TCs than Pacific Ocean TCs. Higher mid-size and large drop concentrations in Pacific Ocean TCs result in higher $D_m$ values for Pacific Ocean TCs. The mean and standard deviation values of $D_m$, $\log_{10}N_w$, $\mu$, and $\Lambda$ for Pacific Ocean and Indian Ocean TCs are provided in Table 3. For both oceanic TCs, increased rainfall rates correlate with increasing $D_m$ values due to the increase in the mid-size and large drop concentration with increased rainfall rate.

3.2 $D_m$-$R$ and $N_w$-$R$ relations

The normalized intercept parameter ($\log_{10}N_w$) and mass-weighted mean diameter ($D_m$) infer the RSD features, and these parameters varied with rainfall intensity for different precipitating cloud systems (Chen et al. 2013; Marzano et al. 2010; Thurai et al. 2010). Fig. 7 shows scatter plots of $D_m$ and $\log_{10}N_w$ with rainfall rates for both oceanic TCs. An apparent distinction in the distribution of $D_m$ with rainfall rate can be seen between Indian Ocean and Pacific Ocean TCs. The $D_m$ values in Pacific Ocean TCs (Fig. 7a) are distributed between 0.4 and 3 mm, with few points around 3–3.5 mm, whereas the $D_m$ values for Indian Ocean TCs are scattered from 0.4 to 2 mm, with few points between 2–2.5 mm. Despite this, as rainfall rate increases, the distribution of $D_m$ narrows for both oceanic TCs, which is consistent with previous studies (Chang et al. 2009; Kumar and Reddy 2013; Wen et al. 2018). Lower variation of $D_m$ with increased rainfall rate could be due to the RSD reaching equilibrium at higher rainfall rates, in which raindrop breakup and coalescence reach a near balance (Hu and Srivastava 1995), and further rainfall rates increases under RSD equilibrium conditions are due to an increase in number concentration (Bringi and Chandrasekar 2001). The power law fitting equations derived for $D_m$-$R$ and $\log_{10}N_w$-$R$ are also shown in Fig. 7. The $D_m$-$R$ relations
obviously show that the Pacific Ocean TCs have higher coefficient and exponent values than Indian Ocean TCs. This implies that for a given rainfall rate, Pacific Ocean TCs have higher $D_m$ values than Indian Ocean TCs, which can be seen in Fig. 6. In contrast, the coefficient and exponent values of $\log_{10}N_w$-$R$ relations are higher for Indian Ocean TCs than Pacific Ocean TCs, indicating the higher concentration of small drops in Indian Ocean TCs. Over east China, Chen et al. (2016) estimated the $D_m$-$R$ and $N_w$-$R$ relations for a continental squall line at four different locations, with coefficient and exponential values of $D_m$-$R$ relations of 1.642–1.725 and 0.1–0.13, respectively. The coefficient values of $D_m$-$R$ relations reported by Chen et al. (2016) are higher than the coefficient values of both oceanic TCs in this present study. In contrast, the coefficient and exponent values of $\log_{10}N_w$-$R$ relations of the continental squall line ranged were 2.843–2.855 and 0.053–0.073, respectively, and their coefficient values were lower than the coefficient values of both oceanic TCs in this study. This clearly demonstrates that both oceanic TCs have higher concentrations of small drops than the continental squall line observed over east China.

### 3.3 Shape and slope ($\mu$-$\Lambda$) relations

The $\mu$-$\Lambda$ relations provide useful information for understanding RSD characteristics and retrieving RSD parameters from polarimetric radar observations through the constrained-gamma method (Brandes et al. 2004; Cao et al. 2008; Zhang et al. 2001; Zhang et al. 2006; Zhang et al. 2003). These relations were found to vary by region and rain type (Seela et al. 2018; Tang et al. 2014; Zhang et al. 2003), which necessitates investigation of each region’s representative $\mu$-$\Lambda$ relations. Fig. 8 shows scatterplots for the $\mu$ and $\Lambda$ values of Indian Ocean and Pacific Ocean TCs. To estimate the $\mu$-$\Lambda$ relations of Indian Ocean and Pacific Ocean TCs, we adopted criteria similar those of Cao et al. (2008). That is, if the sum of the count of particles from drop channels 3–21 is less than 1000 or the rainfall rate is less than 5 mm h$^{-1}$, those
datasets would not be used to derive $\mu$-$A$ relations. Because $\mu$ and $A$ values greater than 20 and 20 mm$^{-1}$, respectively, are ascribed to measurement error rather than storm physics (Zhang et al. 2003), $\mu$-$A$ relations are estimated for $\mu < 20$ and $A < 20$ mm$^{-1}$, and are shown in Fig. 8. For rainfall in Indian Ocean TCs, 50.13% of the data points are associated with $\mu > 20$ and $A > 20$ mm$^{-1}$, whereas for Pacific Ocean TCs, 13.32% of the data points are associated with $\mu > 20$ and $A > 20$ mm$^{-1}$. The red and blue solid lines in Fig. 8a and Fig. 8b represent the polynomial least squares fit for the data points of Pacific Ocean and Indian Ocean TCs, respectively. The computed $\mu$-$A$ relations of both oceanic TCs are depicted in Fig. 8, and these relations vary greatly between one another. The green solid line in Fig. 8 represents the equation from Zhang et al. (2003). Current $\mu$-$A$ relations, as well as previously reported $\mu$-$A$ relations of TCs in different parts of the world (Chang et al. 2009; Chen et al. 2012; Chu and Su 2008; Wen et al. 2018), are provided in Table 4.

3.4 The mass-mean diameter and standard deviation of mass spectrum ($D_m$-$\sigma_m$) relations

Fig. 9 shows scatterplots of mass-weighted mean diameter and the standard deviation of mass spectrum for Indian Ocean and Pacific Ocean TCs. The data points shown in Fig. 9a and b are those that satisfy the quality control procedure of Williams et al. (2014), i.e., each 1-min raindrops spectra is considered if 1) there are at least 50 raindrops in at least three different diameter bins, 2) the reflectivity factor is greater than 10 dBZ, and 3) the rainfall rate is greater than 0.1 mm h$^{-1}$, and $\sigma_m$ values corresponding to $D_m < 0.5$ mm are discarded. After applying this quality control procedure, 3611 and 8297 min of raindrop spectra are observed in Indian Ocean and Pacific Ocean TCs, respectively. If fitting is performed for data with $D_m > 0.5$ mm, the fitted equation becomes $\sigma_m = 0.36 D_m^{1.35}$ and $\sigma_m = 0.29 D_m^{1.71}$ for the Pacific Ocean and Indian Ocean TCs, respectively. Using large data sets (24,872 min) of two-dimensional video disdrometer (2DVD) measurements over Huntsville, Alabama, Williams et al. (2014)
computed the $\sigma_m - D_m$ relation as $\sigma_m = 0.30 D_m^{1.36}$. A similar relation ($\sigma_m = 0.266 D_m^{1.65}$) was evaluated by Thurai et al. (2014) for 10 months of 2DVD observations over Alabama. Thurai et al. (2017) estimated $\sigma_m - D_m$ relations ($\sigma_m = 0.48 D_m^{0.94}$) for two precipitation events measured in Colorado and Huntsville, Alabama, using 2DVD. The differences in the $D_m - \sigma_m$ relations of Thurai et al. (2017) and our results could be due to Thurai et al. (2017) using a droplet spectrometer and the truncation effect of the Parsivel disdrometer used in this study.

### 3.5 RSD in stratiform and Convective precipitation

It has been well documented that RSD features significantly change between convective and stratiform precipitation types (Tokay and Short 1996; Ulbrich and Atlas 2007). To classify precipitation into stratiform and convective types, different researchers adopted various classification criteria (Bringi et al. 2003; Das et al. 2017; Krishna et al. 2016; Steiner et al. 1995; Tokay and Short 1996). Among previous precipitation classifications studies, Bringi et al. (2003) documented the RSD characteristics of different precipitation types over a wide range of climatic regimes and observed profound variations between stratiform and convective regimes in maritime and continental clusters. The RSDs of Indian Ocean and Pacific Ocean TCs are categorized into stratiform and convective types by adopting the threshold criteria (i.e., standard deviation of rainfall rate) of Bringi et al. (2003). In this study, 10 consecutive 1-min RSD samples were considered to be stratiform type if the mean value of $R \geq 0.5 \text{ mm h}^{-1}$ and the standard deviation of $R (\sigma_R) \leq 1.5 \text{ mm h}^{-1}$, and convective type if the mean value of $R \geq 5 \text{ mm h}^{-1}$ and the standard deviation of $R (\sigma_R) > 1.5 \text{ mm h}^{-1}$. Samples not meeting these criteria were discarded. With these classification criteria, 66.67% of data points in the Pacific Ocean TCs are stratiform type and 33.33% are convective type. For the Indian Ocean TCs, 82.35% of the data points are stratiform type and 17.65% are convective type.
The raindrop concentrations of convective and stratiform regimes of Indian Ocean and Pacific Ocean TCs are shown in Fig. 10. For both oceanic TCs, a relatively higher drop concentration can be seen for convective regimes than stratiform regimes (Fig. 10a and b). For both oceanic TCs, the stratiform regimes have nearly exponential distributions, whereas the convective regimes have broad distributions, which might be due to the collisional breakup of large drops in convective rain (Hu and Srivastava 1995). To compare the raindrop concentration of Indian Ocean and Pacific Ocean TCs with respect to precipitation type, Fig. 10a and b are re-plotted into Fig. 10c and d. Even within the different precipitation types we see a strong distinction in RSDs, with a higher concentration of mid-size and large drops in Pacific Ocean TCs. It is also worth noting that larger numbers of small drops can be seen in Indian Ocean TCs.

The distribution of the mean $D_m$ and $\log_{10}N_w$ values in the stratiform and convective regimes of Indian Ocean and Pacific Ocean TCs are illustrated in Fig. 11. The gray rectangular boxes in Fig. 11 are the maritime and continental clusters defined by Bringi et al. (2003). For both oceanic TCs, convective regimes have higher mean $D_m$ and $\log_{10}N_w$ values than stratiform regimes. In contrast, Pacific Ocean TCs have higher $D_m$ and lower $\log_{10}N_w$ values than Indian Ocean TCs in both convective and stratiform precipitations. The Indian Ocean TCs have smaller drop diameter values than the maritime convection of Bringi et al. (2003). The mean and standard deviation values of $D_m$, $\log_{10}N_w$, $\mu$, and $\Lambda$ in the stratiform and convective regimes of the Pacific Ocean and Indian Ocean TCs are listed in Table 5. If we compare our $D_m$ and $\log_{10}N_w$ distributions with those of the maritime and continental clusters of Bringi et al. (2003), only Pacific Ocean convective precipitation is near the maritime-like clusters, with the rest having lower $D_m$ values than the convective clusters of Bringi et al. (2003). Additionally, Bringi et al. (2003) proposed two different microphysical processes that lead to large $D_m$ and
log_{10}N_w variations in stratiform rain. Larger $D_m$ and smaller log_{10}N_w values occur due to the melting of large snowflakes and smaller $D_m$ and larger log_{10}N_w values are due to the melting of tiny graupel or smaller rimed ice particles. As shown in Fig. 11, Indian Ocean TCs stratiform precipitations have lower $D_m$ and larger log_{10}N_w values than Pacific Ocean TCs, implying that Indian Ocean TCs stratiform precipitation is associated with melting of tiny graupel or smaller rimed ice particles, whereas Pacific Ocean TCs feature melting of large snowflakes.

3.6 Radar reflectivity and rainfall rate (Z-R) relations

Z-R relations play a vital role in quantitative precipitation estimation from radar measurements, and these relations were found to vary by geographical location and storm type and strongly depend on RSD characteristics (Rosenfeld and Ulbrich 2003; Seela et al. 2017). The uncertainties in estimating rainfall rate from weather radars can be minimized using indigenous Z-R relations rather than default or tropical Z-R relations (Ulbrich and Lee 2002). In Z = AR^b relations, the presence of large or small drops can be inferred from the coefficient A and the exponent b representing microphysical processes. If b is greater than unity, then collision-coalescence (size or mixed controlled) is the characteristic feature. If b equals unity, then the collision, coalescence, and breakup processes (number controlled) are associated with homogeneous rainfall (Atlas and Williams 2003; Atlas et al. 1999; Steiner et al. 2004). The Z-R relations for Indian Ocean and Pacific Ocean TCs are deduced by applying linear regression to logarithmic values of rainfall rate ($R$, mm h^{-1}) and radar reflectivity ($Z$, mm^6 m^{-3}), and are provided in Fig. 12. A clear demarcation in the coefficient and exponent values of Z-R relations can be seen between the Indian Ocean and Pacific Ocean TCs. For the observational site in India (Kadapa), Jayalakshmi and Reddy (2014) estimated Z-R relations for seasonal rainfall (southwest monsoon (SW): $Z = 300.5R^{1.375}$ and northeast (NE) monsoon: $Z = 163.324R^{1.35}$) as well as for precipitation type (SW stratiform: $Z = 334.13R^{1.424}$, NE stratiform: $Z = 245.35R^{1.283}$).
SW convective: $Z = 265.59R^{1.341}$, NE convective: $Z = 122.41R^{1.430}$. The coefficient $A$ in the $Z-R$ relations of Indian Ocean TCs (A = 148.44) is smaller than the seasonal rainfall coefficients, which indicates that the raindrop sizes are relatively smaller in TCs than in seasonal rainfall. Over northern Taiwan, Seela et al. (2018) computed the $Z-R$ relations for summer (stratiform: $Z = 276.13R^{1.41}$, convective: $Z = 237.88R^{1.41}$, total: $Z = 266.42R^{1.38}$) and winter (stratiform: $Z = 127.67R^{1.54}$, convective: $Z = 142.94R^{1.52}$, total: $Z = 129.76R^{1.55}$) rainfall using Joss-Waldvogel disdrometer measurements. For the same observational site over northern Taiwan, Chang et al. (2009) evaluated the $Z-R$ relations ($Z = 206.83R^{1.45}$) of typhoon rainfall using 2DVD measurements. The current $Z-R$ relations of Pacific Ocean TCs (stratiform $Z = 368.28R^{1.49}$, convective: $Z = 328.73R^{1.42}$, total: $Z = 346.03R^{1.42}$) are different from those of seasonal and typhoon rainfall, and these variations could be due to either the use of different instruments to estimate $Z-R$ relations or Taiwan’s complex orography. The estimated $Z-R$ relations of Indian Ocean and Pacific Ocean TCs will enhance the quantitative precipitation estimation of TCs rainfall for these two oceanic basins.

4. Discussion

To determine the possible rationale for RSD variations between Indian Ocean and Pacific Ocean TCs, the CAPE(J kg$^{-1}$), water vapor (Kg m$^{-2}$), vertical profiles of temperature ($^\circ$C), and relative humidity values from ERA-Interim, and CTT from MODIS are considered for disdrometers’ measurement periods (as listed in Table 1). Figure 13 shows a box and whisker plot of CAPE and water vapor values for the disdrometer observational periods of Indian Ocean and Pacific Ocean TCs. It is apparent that Pacific Ocean TCs have relatively higher water vapor and strong convective activity (higher CAPE) than Indian Ocean TCs. Relatively higher water vapor with vigorous updrafts and downdrafts leads to the growth of cloud particles (both liquid and solid) to a sufficiently larger size (by aggregation, riming, and
collision-coalescence processes) in Pacific Ocean TCs than in Indian Ocean TCs. The MODIS-obtained CTT values are slightly higher for Pacific Ocean TCs than Indian Ocean TCs (Fig. 14). Melting of large (small) particles in the Pacific (Indian) TCs results in relatively higher (lower) $D_m$ and lower (higher) $\log_{10}N_w$ values in the Pacific (Indian) TCs (Fig. 11). A Student’s t-test is applied to the CAPE, water vapor, and CTT values of the Indian Ocean and Pacific Ocean TCs. The test results showed a significant difference at the 0.01 level in CAPE and column water vapor between Indian Ocean TCs and Pacific Ocean TCs, whereas, there was not a significant difference in CTT. Further mean vertical profiles of temperature and relative humidity for Pacific Ocean and Indian Ocean TCs are shown in Fig. 15. The temperature profiles of Pacific Ocean TCs show relatively higher values than Indian Ocean TCs (Fig. 15a) at all pressure levels. However, the relative humidity profiles showed higher values below 925 hPa and above 775 hPa (Fig. 15b) for the Pacific Ocean TCs. Higher temperature and lower relative humidity values can be seen for Pacific Ocean TCs between 775 and 925 hPa (~2.2–0.76 km), which shows that it is possible for small drops in the Pacific Ocean TCs to evaporate between these pressure levels. The above explanation provides possible reasons for the occurrence of more large drops in Pacific Ocean TCs and more small drops in Indian Ocean TCs.

5. Summary

For the first time, RSD characteristics of Indian Ocean and Pacific Ocean TCs are compared using Parsivel disdrometers installed at observational sites in India and Taiwan. The contribution of mid-size and large drops is higher in Pacific Ocean TCs than in Indian Ocean TCs. The probability distribution of rain integral parameters for Indian Ocean and Pacific Ocean TCs showed distinct distributions. RSDs classified into different rainfall rate classes as well as precipitation types (stratiform and convective) showed a greater concentration of mid-
size and large drops in Pacific Ocean TCs. In different rainfall rate classes and precipitation types, higher (lower) mass-weighted mean diameter (normalized intercept parameter) values are observed for Pacific Ocean TCs. The derived empirical relations ($D_m$-$R$, $\log_{10}N_w$-$R$, $\mu$-$A D_m$-$\sigma_m$, $\log_{10}N_w$-$D_m$ and $Z$-$R$) are found to differ between the Pacific Ocean and Indian Ocean TCs, confirming that must adopt TC-specific empirical relations in remote sensing and radar rainfall estimation algorithms. Relatively higher convective activity and water vapor in the Pacific TCs resulted in a greater number of large drops in Pacific TCs than Indian TCs through different microphysical processes.

Acknowledgments

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**Figure 3.** Mean raindrop concentration of Indian Ocean and Pacific Ocean tropical cyclones (TCs). Numbers of 1-min raindrop size distributions samples of TCs are shown in legend parenthesis. The error bars represent the standard error of each raindrop diameter bin sample. The mean values of $D_m$ (mass-weighted mean diameter, mm), $R$ (rainfall rate, mm h$^{-1}$), and $\log_{10}N_w$ (the normalized intercept parameter, $N_w$ in mm$^{-1}$ m$^{-3}$) for Indian Ocean and Pacific Ocean TCs rainfall are depicted in the figure.

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**Figure 5.** Mean raindrop concentration ($N(D)$, m$^{-3}$ mm$^{-1}$) of Indian Ocean and Pacific Ocean tropical cyclones (TCs) in six rainfall rate ($R$) classes (C1:0.1–1, C2:1–2, C3:2–5, C4:5–10, C5:10–20, and C6: >20 mm h$^{-1}$).
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Figure 14. Box and whisker plot of cloud top temperature ($^\circ$C) for the disdrometer observational periods of Indian Ocean and Pacific Ocean tropical cyclones (TCs).

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Table 1: Duration, rainfall accumulation, and rainfall rate statistics (maximum, mean, and standard deviation (std)) of Indian Ocean and Pacific Ocean tropical cyclones (TCs).

<table>
<thead>
<tr>
<th>Oceanic Region</th>
<th>TC name</th>
<th>TC life time</th>
<th>TC observation period by Parsivel</th>
<th>Rainfall accumulation (mm)</th>
<th>Rainfall rate (mm h⁻¹)</th>
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Table 2. Rainfall rate statistics of Indian Ocean and Pacific Ocean tropical cyclones (TCs) in six rainfall rate classes (C1-C6).

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Table 3: Mean and standard deviation (std) values of $D_m$ (mass-weighted mean diameter, mm), $\log_{10}N_w$ (where $N_w$ is the normalized intercept parameter in mm$^{-1}$ m$^{-3}$), $\mu$ (shaper parameter, dimensionless), and $A$ (slope parameter, mm$^{-1}$) for Indian Ocean and Pacific Ocean tropical cyclones (TCs) in six rainfall rate classes (C1-C6).

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Table 4: The $\mu$-$\Lambda$ relations of current study tropical cyclones (TCs) and other parts of the world.

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<tr>
<td>Present study</td>
<td>South Taiwan, Pacific Ocean TCs</td>
<td>six TCs</td>
<td>Parsivel</td>
<td>$\Lambda=0.021\mu^2 + 0.654\mu+2.088$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$\mu= -0.0227\Lambda^2 +1.317\Lambda-2.232$</td>
</tr>
<tr>
<td>Chen et al. (2012)</td>
<td>Fujian</td>
<td></td>
<td>Parsivel disdrometer</td>
<td>$\Lambda=0.0253\mu^2 + 0.633\mu+1.524$</td>
</tr>
<tr>
<td>Chang et al. (2009)</td>
<td>NCU, north Taiwan</td>
<td>Typhoons</td>
<td>Two-dimensional Video disdrometer</td>
<td>$\Lambda=0.0136\mu^2 + 0.6984\mu+1.5131$</td>
</tr>
<tr>
<td>Chu and Su (2008)</td>
<td>NCU, North Taiwan</td>
<td>four types of weather systems (typhoon, cold front, stationary front, convective cloud)</td>
<td>Two-dimensional Video disdrometer</td>
<td>$\Lambda=0.017\mu^2 + 1.303\mu+1.833$ (for low order moment)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$\Lambda = 0.007\mu^2 + 1.362\mu+1.569$ (for low order moment)</td>
</tr>
<tr>
<td>Wen et al. (2018)</td>
<td>China</td>
<td>Seven typhoons</td>
<td>Two-dimensional Video disdrometer</td>
<td>$\mu= -0.019\Lambda^2 + 1.09 \Lambda-3.119$</td>
</tr>
</tbody>
</table>
Table 5 Mean and standard deviation (std) values of $D_m$ (mass-weighted mean diameter, mm), $\log_{10}N_w$ (normalized intercept parameter $N_w$, mm$^{-1}$ m$^{-3}$), $\mu$ (shape parameter), and $\Lambda$ (slope parameter, mm$^{-1}$) for stratiform and convective precipitations of Pacific Ocean and Indian Ocean tropical cyclones (TCs).

<table>
<thead>
<tr>
<th>Rain type</th>
<th>Pacific Ocean TCs</th>
<th></th>
<th></th>
<th>Indian Ocean TCs</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$D_m$ (mm)</td>
<td>$\log_{10}N_w$ ($N_w$ in mm$^{-1}$ m$^{-3}$)</td>
<td>$\mu$ (-)</td>
<td>$\Lambda$ (mm$^{-1}$)</td>
<td>$D_m$ (mm)</td>
<td>$\log_{10}N_w$ ($N_w$ in mm$^{-1}$ m$^{-3}$)</td>
</tr>
<tr>
<td>Stratiform</td>
<td>1.32 0.32</td>
<td>3.35 0.41</td>
<td>2.19 1.56</td>
<td>3.73 1.4</td>
<td>0.92 0.26</td>
<td>4.02 0.55</td>
</tr>
<tr>
<td>Convective</td>
<td>1.65 0.38</td>
<td>3.69 0.37</td>
<td>2.66 2.31</td>
<td>4.02 1.99</td>
<td>1.21 0.27</td>
<td>4.26 0.31</td>
</tr>
</tbody>
</table>
Figure 1. Tracks of Indian Ocean and Pacific Ocean tropical cyclones and the locations of Parsivel disdrometer (red color stars) over India and Taiwan.
Figure 2. Quality control procedure applied to raw raindrop size distributions of Pacific Ocean and Indian Ocean tropical cyclones measured by Parsivel disdrometers over (a) Taiwan and (b) India, respectively. The black solid line is the empirical fall speed-diameter relations from Atlas et al. (1973), and the black dotted lines are the threshold curves (± 60% of Atlas et al. (1973) curve), used for filtering the data.
Figure 3. Mean raindrop concentration of Indian Ocean and Pacific Ocean tropical cyclones (TCs). Numbers of 1-min raindrop size distributions samples of TCs are shown in legend parenthesis. The error bars represent the standard error of each raindrop diameter bin sample. The mean values of $D_m$ (mass-weighted mean diameter, mm), $R$ (rainfall rate, mm h$^{-1}$), and $\log_{10} N_w$ (the normalized intercept parameter, $N_w$ in mm$^{-1}$ m$^{-3}$) for Indian Ocean and Pacific Ocean TCs rainfall are depicted in the figure.
Figure 4. The probability distribution functions (PDF) of (a) $\log_{10}R$, where $R$ is rainfall rate (mm h$^{-1}$) (b) $\log_{10}W$, where $W$ is liquid water content (g m$^{-3}$), (c) mass-weighted mean diameter, $D_m$ (mm), (d) $\log_{10}N_w$, where $N_w$ is the normalized intercept parameter (mm$^{-1}$ m$^{-3}$), for Indian Ocean and Pacific Ocean tropical cyclones (TCs).
Figure 5. Mean raindrop concentration \( N(D), \text{m}^{-3} \text{mm}^{-1} \) of Indian Ocean and Pacific Ocean tropical cyclones (TCs) in six rainfall rate \( (R) \) classes (C1:0.1–1, C2:1–2, C3:2–5, C4:5–10, C5:10–20, and C6: >20 mm h\(^{-1}\)).
Figure 6. Box and whisker plot of mass-weighted mean diameter, $D_m$ (mm) and $\log_{10}N_w$, where $N_w$ is the normalized intercept parameter (mm$^{-1}$ m$^{-3}$) for Indian Ocean (blue) and Pacific Ocean (red) tropical cyclones in six rainfall rate ($R$) classes (C1:0.1–1, C2:1–2, C3:2–5, C4:5–10, C5:10–20, and C6: >20 mm h$^{-1}$). The center line of the box indicates the median, and the bottom and top lines of the box indicate the 25$^{\text{th}}$ and 75$^{\text{th}}$ percentiles, respectively. The bottom and top of the dashed vertical lines indicate the 5$^{\text{th}}$ and 95$^{\text{th}}$ percentiles, respectively.
Figure 7. Scatter plots of $D_m$ (mass-weighted mean diameter, mm) and $\log_{10} N_w$ (where $N_w$ is the normalized intercept parameter in mm$^{-1}$ m$^{-3}$) with rainfall rate for Indian Ocean and Pacific Ocean tropical cyclones (TCs).
Figure 8. Scatterplots of $\mu$ versus $\Lambda$ for (a) Pacific Ocean and (b) Indian Ocean tropical cyclones (TCs). The gray solid circles and stars in (a) and (b), respectively, are data points with rainfall rates $> 5$ mm h$^{-1}$. The red and blue lines in (a) and (b) represent the least squares fit applied (expression of $\mu$ in terms of $\Lambda$) to filter data of Pacific Ocean and Indian Ocean TCs, respectively. The green line corresponds to the $\mu$-$\Lambda$ relation of Zhang et al. (2003).
Figure 9. Scatter plot of mass-weighted mean diameter ($D_m$) and standard deviation of mass spectrum ($\sigma_m$) for Indian Ocean and Pacific Ocean tropical cyclones (TCs).
Figure 10. Variation of raindrop concentration \((N(D), \text{m}^{-3} \text{mm}^{-1})\) with drop diameter for precipitation types for Indian Ocean and Pacific Ocean tropical cyclones (TCs).
Figure 11. Variation of $\log_{10} N_w$ (where $N_w$ is the normalized intercept parameter in mm$^{-1}$ m$^{-3}$) with $D_m$ (mass-weighted mean diameter in mm) in stratiform and convective regimes of Indian Ocean and Pacific Ocean tropical cyclones (TCs). The horizontal gray dashed line is the Marshall-Palmer value of $\log_{10} N_w (3.9)$ for exponential shape. The green dash dotted line is the stratiform and convective separation line of Bring et al. (2003).
Figure 12. Radar reflectivity-rainfall rate ($Z-R$) relations for Indian Ocean and Pacific Ocean tropical cyclones (TCs) and their precipitation types (CON: convective, STF: stratiform).
Figure 13. Box and whisker plot of (a) convective available potential energy (CAPE, J Kg\(^{-1}\)) and (b) vertical integral of water vapor (kg m\(^{-2}\)) for the disdrometer observational periods of Indian Ocean and Pacific Ocean tropical cyclones (TCs). The center line of the box indicates the median, and the bottom and top lines of the box indicate the 25\(^{th}\) and 75\(^{th}\) percentiles, respectively. The bottom and top of the dashed vertical lines indicate the 5\(^{th}\) and 95\(^{th}\) percentiles, respectively.
Figure 14. Box and whisker plot of cloud top temperature (°C) for the disdrometer observational periods of Indian Ocean and Pacific Ocean tropical cyclones (TCs).
Figure 15. Vertical profiles of (a) temperature (°C) and (b) relative humidity (%) for the disdrometer observational periods of Indian Ocean and Pacific Ocean tropical cyclones (TCs).