



Microphysical characteristics of torrential predecessor rain events over the Yangtze River Delta Area and the related tropical cyclones

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ABSTRACT

The precipitation structures and microphysical characteristics of predecessor rain events (PREs) over the Yangtze River Delta area and related tropical cyclones (TCs) from 2014 to 2019 were investigated using Dual-frequency Precipitation radar data from Global Precipitation Measurement (GPM) for drop size distributions (DSDs). Results showed that the total mean rain rate of PREs was larger than that of TCs, primarily due to higher convective and stratiform rain rates, with enhanced fractional coverage of convective rain in PREs. Examination of microphysical characteristics revealed that a greater quantity of small-sized droplets and a smaller quantity of medium- as well as large-sized droplets contributed towards PREs in comparison with TCs. The conclusion still holds when partitioning DSDs based on different precipitation rate categories. Further investigation of DSDs using gamma functions illustrated that precipitation in PREs had lower average mass-weighted diameters (D_m) and enhanced normalized number concentration (N_w) compared with TCs; partitioning precipitation into convective and stratiform components illustrated a larger D_m and lower N_w in TCs than PREs. The analysis of microphysical and thermodynamical processes using the reanalysis data indicates that relatively intense convective activity with drier conditions may be favorable to enhancing raindrop growth through collision-coalescence processes, as a result of larger D_m in TCs than PREs. The empirical relations ($Z-R$ algorithms) applied in different rain regimes (stratiform, convective, and total PREs) revealed significant diversities, relying on weather conditions and geographical locations.

Plain language summary: The Yangtze River Delta area is an important economic belt in China. Under climate change, observed frequent occurrences of weather extremes of heavy rainfall and tropical cyclones (TCs) exert adverse effects on economic development in this region. Thus, a deep understanding of the mechanism of TCs torrential rainfall in the Yangtze River Delta area is urgently necessary. In this study, we investigated the precipitation patterns and microphysical characteristics of predecessor rain events (PREs) in the Yangtze River Delta region, and their association with TCs in the South China Sea-Western North Pacific Ocean (SCS-WNPO) area from 2014 to 2019. We found that PREs had a higher total mean precipitation rate than TCs. Further examination using gamma functions demonstrated that PREs exhibited lower average mass-weighted diameters (D_m) and higher normalized intercept parameters (N_w) than TCs. This pattern persisted when distinguishing between convective and stratiform precipitation components. We believe that our study makes a significant contribution to the literature because these results provide valuable insights into the distinct precipitation characteristics of PREs and TCs in the study region and contribute to a better understanding of tropical cyclone-related rainfall patterns, and act as a scientific basis for disaster mitigation.

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1. Introduction

Observed changes in the weather extremes of heavy rainfall and tropical cyclones (TCs) have strengthened under climate change, and have caused widespread economic losses and significant damage to human society (IPCC, 2023). In China, weather extreme events (e.g. extreme rainfall) are often associated with TCs, and TC heavy precipitation events displayed an increasing trend from 1980 to 2019 (Chien and Kuo, 2011; Henny et al., 2021; Li and Zhao, 2022; Tian et al., 2022; Xu et al., 2022). Although rainfall forecasting has significantly improved over the last several decades, the reliable forecasting of intense rainfall remains challenging (Golding, 2003; Chen et al., 2010; Sene, 2013; Forbes et al., 2015; Chirigati, 2021). Severe rainfall related to TCs is linked to complex thermodynamic and physical processes and even involves the amalgamation of different meteorological systems (Zhang et al., 2000; Chen et al., 2010; Chien and Kuo, 2011; Shu et al., 2020; Xu et al., 2021; Xu et al., 2023).

TCs can result in torrential precipitation in remote regions when they interact with mid-latitude westerly troughs (Chen et al., 2010; Xu et al., 2023). This type of rainfall is called predecessor rain events (PREs) during the advancement of TCs (Cote, 2007) or TC remote precipitation (TRP) in China (Chen, 2007). PREs do not occur frequently and may cause significant damage because accurate prediction of the interaction between TCs and westerly troughs is challenging for numerical models and forecasters (Cote, 2007; Byun and Lee, 2012). Therefore, PREs have the potential to cause torrential rainfall, which may increase flood risks, cause economic losses, and threaten human lives. For example, the far-away influences of TCs Cempaka (2021) and In-fa (2021) were crucial for inducing extreme precipitation events in Henan of China on July 19–20, 2021 (Xu et al., 2022; Xu et al., 2023a).

Numerous studies have investigated the PREs associated with westerly troughs and tropical cyclones, mainly focusing on weather diagnostic analysis of these events. Studies indicate that PREs typically occur on the right side of the entrance region of an upper-level jet stream; At low levels, there is moisture transport from the vicinity of the typhoon, and such rainfall usually happens ahead of an upper-level trough in the baroclinic zone or regions of convective instability (Bosart and Carr, 1978; Cong et al., 2012; Bosart et al., 2012; Moore et al., 2013). The position and intensity of the baroclinic zone and its associated secondary circulation are crucial for the uplift of warm moist air, which is essential for heavy precipitation (Zhu et al., 2000; Byun and Lee, 2012; Galarneau Jr. et al., 2010; Schumacher et al., 2011; Schumacher and Galarneau, 2012). Other studies pointed out that the westerly trough provides dynamic conditions for such rainfall. Positive vorticity advection ahead of the trough favors the development of upward motion, and the frontogenesis resulting from the interaction of cold air behind the trough and warm moist air triggers PREs (Cote, 2007; Cong et al., 2012; Yuan et al., 2018; Xu et al., 2023). PREs occur when moisture-rich air from a TC converges with the mid-latitude troughs, creating an environment conducive to vigorous convective activity. Within this condition, cloud microphysics such as coalescence, and ice-phase interactions significantly influence rainfall. Some studies showed that cloud drop nucleation and the presence of ice crystals can influence rainfall characteristics in TCs (Xu and Li, 2019), and precipitation efficiency is sensitive to the cloud dynamics and the microphysical processes of hydrometeors (Xu et al., 2021). The PREs result from the interactions of clouds from TCs and westerly troughs may show microphysical characteristics of both weather systems.

The Yangtze River Delta area (YRD) is a subtropical monsoon climatic zone and is among the most economically developed regions in China. PREs related to the TCs in the South China Sea and northwestern Pacific Ocean (SCS–WNPO) occur in the YRD every year, and have the potential to cause adverse impacts and economic losses owing to the sudden onset and inaccurate predictions (Duan et al., 2020; Chen et al., 2021; Xu et al., 2023). Configurations of synoptic circulation and TCs in severe precipitation associated with PREs in different climate zones have

been examined, and it has been shown that PREs have frontal precipitation characteristics (Schumacher et al., 2011; Schumacher and Galarneau, 2012; Moore et al., 2013; Yuan et al., 2018; Duan et al., 2020; Xu et al., 2023). Pieces of literature have demonstrated that different types of rainfall at different latitudes exhibit variations in microphysical characteristics. Previous studies showed that convective regions have smaller raindrops than stratiform regions (Rosenfeld and Ulbrich, 2003; Leighton et al., 2022), whereas others illustrated the opposite results (Janapati et al., 2020; Janapati et al., 2021). Another study revealed that maritime-like convective clusters comprise drops characterized by smaller averaged sizes and greater drop concentrations than continental-like clusters (Bringi et al., 2003). Ryu et al. (2021) revealed that continental (oceanic shallow) convective types of precipitation show the largest (lowest) raindrop diameter and lowest (largest) number concentration, whereas oceanic deep convective types show medium values. Numerous other studies have supported these findings (e.g., Thompson et al., 2015; Seela et al., 2017; Dolan et al., 2018; Zeng et al., 2019; Raut et al., 2021; Zhao et al., 2022).

Microphysical features also vary with weather systems and seasons under different climates and topographies. For instance, convective precipitation in squall lines and intense convection in plain regions and during summer generally result in larger raindrop diameters and higher concentrations (Lang et al., 2010; Jung et al., 2012; Luo et al., 2011; Houze Jr., 2012; Chen and Zhao, 2017; Zagrodnik et al., 2019; Seela et al., 2018). Coastal warm-sector heavy rainfall exhibits larger drop sizes than the inland frontal heavy rainfall in South China during the pre-summer rainy season (Han et al., 2021). The microphysical characteristics in different regions of TCs are also different. Bao et al. (2020a) showed that the raindrop concentration parameter (diameter parameter) generally increases (decreases) from the TC center to outer rainbands. Specifically, in the eyewall, the dominant collision-coalescence process corresponds to the presence of large-/mid-size raindrops (Bao et al., 2020b); The dominant collision-coalescence, breakup, and evaporation processes in the inner rainbands lead to larger amounts of mid-/small-sized drop diameters compared to those in the outer rainbands, where dominated by the melting and evaporation processes and small amount of large drops (Wu et al., 2021). Chen et al. (2019a) found that hydrometeors have a low mean diameter (D_m) near the TC center, which increases in the outer TC region; Collision-coalescence dominates in both areas, while breakup processes significantly influence the rainband regions. Other studies have investigated droplet size distributions (DSD) features for tropical and non-TCs and found higher concentrations of smaller raindrops in TCs (Radhakrishna and Rao, 2010; Sharma et al., 2009; Deo and Walsh, 2016; Janapati et al., 2021). Other investigations of RSD characteristics of typhoons and frontal systems revealed that typhoons generally exhibit maritime behavior and frontal systems exhibit continental behavior (Chen and Chen, 2011; Tu and Chou, 2013; Chen and Zhao, 2017; Chen et al., 2019b; Wen et al., 2020). Even within the same TC, the convective outer rainbands could exhibit higher concentrations of raindrops across all sizes compared to the convective frontal rainbands (Bao et al., 2019). PREs are generated by interactions between TCs and mid-latitude systems, which may have characteristics of both maritime and continental weather systems (Chen et al., 2022a). Despite investigations of typhoon systems and mid-latitude systems, their microphysical characteristics, especially the features of PREs, have rarely been examined.

PREs over the YRD areas are mainly associated with the synergism between the westerly trough and TCs. In this study, we examined RSDs to comprehend the microphysics features of PREs. In particular, we aimed to determine (1) how do the drop size distributions (DSDs) of PREs change and (2) how do the precipitation structures in PREs and TCs differ. Given the varying microphysical characteristics of rainfall across different rainfall regions within the same weather system, the DSDs of PREs for convective and stratiform rainfall are also discussed.

2. Data and methodology

In the following research, the datasets in this study incorporated the GPM satellite data (version 6), which is the successor to the TRMM satellite (after February 27, 2014). The GPM satellite contains a dual frequency PR, incorporating Ka-band (35.5 GHz) precipitation radar (KaPR) and Ku-band (13.6 GHz) precipitation radar (KuPR). The scan pattern of KuPR is known as the normal scan (NS), whereas the KaPR contains the matched scan (MS) and high-sensitivity scan (HS) to detect weak rain and snow. This dual-frequency scanning provides information on the DSD parameters. The main DSD parameters applied in this study include the normalized droplet concentration (dBN_w) and mass-weighted averaged droplet diameter (D_m). Detailed information on DSD parameters can refer to Iguchi et al. (2020) and Huffman et al. (2015). The GPM DPR retrieved the parameters, which include attenuation-corrected reflectivity, near-surface rain rate, precipitation type, D_m , and normalized intercept parameters (N_w) at clutter-free bottom-level profiles. Both Ka-band and Ku-band for the above parameters are accessible in the inner swath of NS, whereas only Ku-band datasets are available in the outer swath. To minimize the errors caused by the different scanning methods, and NS datasets were applied. The near-surface rain rate of less than $0.1 \text{ mm} \cdot \text{h}^{-1}$ was excluded, considering the detectable rain rate in Ka-band and Ku-band mode and the contamination from surface clutter (Shimizu et al., 2009; Huang and Chen, 2019). The precipitation type was also from the NS mode, the convective and stratiform type was utilized, and the total rainfall included the convective and stratiform rainfall. The detailed classification method of the precipitation type of GPM was also introduced by Huang and Chen (2019), that of NS mode was specified in detail in Iguchi et al. (2020). The normal scan (NS) datasets in the PRE region ($27\text{--}33^\circ\text{N}$, $117\text{--}124.2^\circ\text{E}$, See Fig. 1) and TC domains (Table 1) were available during the 2014–2019 PRE period, and they were applied in this study. The inner swath NS data in the squall line and TCs in China have been applied and verified by Huang et al. (2022). The GPM NS datasets have been utilized to analyze microphysical characteristics of rainfall in China by Huang and Chen (2019), Zhang et al. (2020), and Wen et al. (2023).

This information from the GPM makes it possible to investigate the spatiotemporal distributions of raindrop microphysics in terrestrial regions and open oceans where ground-based disdrometers or radars cannot be set. It has been reported that the GPM DPR-retrieved D_m and rain rate (R) generally agree well with disdrometer measurements in Italy (Adirosi et al., 2021) and the USA (Liao and Meneghini, 2022). Other studies have shown that radar reflectivity and D_m in the GPM DPR correspond well with ground-based observations in the Yangtze–Huai valley regions as well as South China (Sun et al., 2020; Huang et al., 2022). GPM DPR datasets have been utilized to examine the

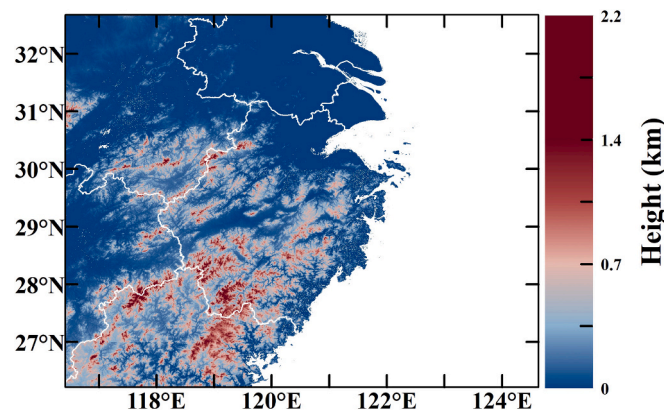


Fig. 1. Map of the Yangtze River Delta area as well as terrain height from the digital elevation model (DEM).

Table 1

Lists of symbols.

Symbol	Description	SI unit
N_w	normalized drop concentration parameter	$\text{mm}^{-1} \text{m}^{-3}$
$N(D)$	number concentration	$\text{mm}^{-1} \text{m}^{-3}$
N_t	number concentration in total	m^{-3}
D_m	mean diameter	mm
R	rain rate	mm h^{-1}
μ	parameter for shape	–

microphysics of TCs in the various Oceans, and found that collision-coalescence is dominant in the eyewalls and the impacts of breakup processes increase in the rainbands in the tropical cyclones over the northwestern Pacific Ocean (Huang and Chen, 2019; Chen et al., 2019a). The storms are more intense with larger drops and higher rain rates in the eyewall than that in the rainbands over the North Indian Ocean (Kumar et al., 2023a). Both collision-coalescence and breaking-up processes are important in stratiform rainfall, and the collision-coalescence process is dominant in the convective rainfall in the tropical cyclone rainfall over the Arabian Sea (Kumar et al., 2023b). GPM datasets have also been applied to investigate different characteristics of DSD over continental and oceanic areas of Southeast Asia, and raindrops in the South China Sea showed smaller sizes than those in the Western Pacific and larger sizes than those in the North Indian Ocean (Radhakrishna et al., 2016; Kumar and Silva, 2019; Radhakrishna et al., 2020; Huang et al., 2023). GPM DSD datasets have also been applied to explore the precipitation structures of Meiyu rainfall, squall lines, and TC rainfall in China (Huang and Chen, 2019; Sun et al., 2020; Huang et al., 2022); and investigate the global distributions of DSD characteristics for heavy rainfall (Ryu et al., 2021). The DSD characteristics derived from the DPR-retrieved data were consistent with those of the ground-based observations, confirming the DPR data quality, as summarized in a previous study (Ryu et al., 2021).

TC centers were from the Japan Meteorological Agency (JMA), which can be accessed at https://www.data.jma.go.jp/multi/cyclone/cyclone_caplink.html?lang=en. PREs and TCs datasets used in this study were constructed as follows: PREs connected to SCS–WNPO TCs in 2014–2019 were detected by Xu et al. (2023). The detailed periods from 2014 to 2019 when PREs occurred can be found in Table 1 with references to Xu et al. (2023). The PREs mainly occurred in a rectangular domain of $27\text{--}33^\circ\text{N}$, $117\text{--}124.2^\circ\text{E}$ (See Fig. 1), and the GPM datasets during the PREs available in this region were used to investigate the DSD characteristics. The TCs associated with PREs during the periods when PREs took place in the YRD areas can also be found in Table 1, referring to Xu et al. (2023b). Using the TC centers and precipitation data from

Table 2

The PREs connected to SCS–WNPO TCs in 2014–2019.

TC (year)	TC number	Initiation time (UTC) and date	TC domain	End time (UTC) and date
Fung-Wong (2014)	1416	0000 UTC 20 Sep	$15\text{--}20^\circ\text{N}$, $113\text{--}118^\circ\text{E}$	0000 UTC 21 Sep
Linfa (2015)	1510	0000 UTC 06 Jul	$15\text{--}20^\circ\text{N}$, $115\text{--}120^\circ\text{E}$	1800 UTC 06 Jul
Goni (2015)	1515	1200 UTC 23 Aug	$15\text{--}20^\circ\text{N}$, $115\text{--}120^\circ\text{E}$	1200 UTC 24 Aug
Meranti (2016)	1614	0600 UTC 13 Sep	$15\text{--}25^\circ\text{N}$, $110\text{--}120^\circ\text{E}$	0000 UTC 14 Sep
Khanun (2017)	1720	1800 UTC 14 Oct	$15\text{--}25^\circ\text{N}$, $110\text{--}120^\circ\text{E}$	0000 UTC 16 Oct
Mangkhot (2018)	1822	0000 UTC 16 Sep	$15\text{--}25^\circ\text{N}$, $110\text{--}120^\circ\text{E}$	0600 UTC 17 Sep
Podul (2019)	1912	1200 UTC 28 Aug	$15\text{--}25^\circ\text{N}$, $105\text{--}115^\circ\text{E}$	0600 UTC 29 Aug
Lingling (2019)	1913	0000 UTC 02 Sep	$10\text{--}20^\circ\text{N}$, $120\text{--}130^\circ\text{E}$	1800 UTC 02 Sep

these periods, TC-affected domains were detected. The TC-affected domains for each TC can be referred to Table 2. The terrain of the YRD region (See Fig. 1) can be obtained using 30 m digital elevation model (DEM) datasets, and the data were obtained from <https://www.earthdata.nasa.gov/vidual-new-aster-gdem>.

Previous studies showed that the gamma distribution was generally appropriate to describe the DSD distributions (Ulbrich, 1983; Testud et al., 2001). Following Ryu et al. (2021), the mathematical formulation related to the DSD function was depicted using the gamma distribution function, and it can be described as follows:

$$N(D) = N_w \frac{6}{4^4} \frac{(4 + \mu)^{4+\mu}}{\Gamma(\mu + 4)} \left(\frac{D}{D_m} \right) \exp \left[-(\mu + 4) \frac{D}{D_m} \right] \quad (1)$$

Where D denotes the droplet diameter (mm), μ is a parameter for shape, $N(D)$ denotes the number concentration ($\text{mm}^{-3} \cdot \text{m}^{-3}$), N_w is the normalized drop concentration parameter (referred to as dBN_w in GPM DPR datasets), and D_m is the mass-weighted mean diameter. The shape parameter μ was set as 3 as in previous studies (Seto et al., 2016; Liao and Meneghini, 2022; Ryu et al., 2021). Applying parameters retrieved from GPM DPR observations, $N(D)$ can be calculated via the formulations listed in Eq. (1).

Following Seela et al. (2017) and Janapati et al. (2021), the number concentration in total (N_t ; m^{-3}) was obtained by the equation:

$$N_t = \sum_{i=1}^n N(D_i) \cdot \Delta D_i \quad (2)$$

where D_i (mm) denotes the drop diameter for the size bin i , ΔD_i is the corresponding diameter interval (mm).

The contributions of different diameter classes to the total number concentration (rainfall rate) for different types of rainfall can be given by Eqs. (3.1)–(3.2) as follows. For the given diameter class (D_k), the contributions of number concentration can be given by the following equations.

$$(C_{PRE}^x)_{D_k} = \frac{[(x)_{PRE}]_{D_k}}{\sum_{k=1}^5 [(x)_{PRE}]_{D_k}} \quad (3.1)$$

$$(C_{TC}^x)_{D_k} = \frac{[(x)_{TC}]_{D_k}}{\sum_{k=1}^5 [(x)_{TC}]_{D_k}} \quad (3.2)$$

where x denotes N_t or R . Namely, $(C_{PRE}^x)_{D_k}$ can be $(C_{PRE}^{N_t})_{D_k}$ or $(C_{PRE}^R)_{D_k}$, which denotes contributions of number concentration of the D_k diameter class to the total number concentration (N_t) and that to the rainfall rate (R) for PREs, respectively. $(C_{TC}^x)_{D_k}$ can be $(C_{TC}^{N_t})_{D_k}$ or $(C_{TC}^R)_{D_k}$, which denotes contributions of the diameter class D_k to the total number concentration (N_t) and that to the rainfall rate (R) for TCs, respectively. D_k ($k = 1, 2, 3, 4, 5$) is denoting different classes with diameters <1 , 1 – 2 , 2 – 3 , 3 – 4 , and 4 – 5 mm.

For each diameter class, the occurrence percentage δ_{N_t} of number concentration in total and that of δ_R for R ($\text{mm} \cdot \text{h}^{-1}$) at different drop diameter sizes can be formulated by Eq. (4.1)–(4.4) as follows:

$$(\delta_x)_{PRE} = \frac{(x)_{PRE}}{(x)_{PRE} + (x)_{TC}} \quad (4.1)$$

$$(\delta_x)_{TC} = \frac{(x)_{TC}}{(x)_{PRE} + (x)_{TC}} \quad (4.2)$$

Where x denote N_t or R . Namely, $(\delta_x)_{PRE}$ can be $(\delta_{N_t})_{PRE}$ and $(\delta_R)_{PRE}$, which respectively represent the occurrence percentage of total number concentration N_t and that of rainfall rate R for PREs; $(\delta_x)_{TC}$ can be $(\delta_{N_t})_{TC}$ or $(\delta_R)_{TC}$, which respectively represent the occurrence percentage of rainfall rate R and that of total number concentration N_t for TCs; $(N_t)_{PRE}$ and $(N_t)_{TC}$ represent the total number concentration in PREs and TCs,

respectively; and $(R)_{PRE}$ and $(R)_{TC}$ represent the R in the PREs and TCs, respectively.

In the same way, the percentage of $N(D)$ for various R categories was given in Eqs. (5.1)–(5.2) as follows:

$$\delta(D, RC_k)_{PRE} = \frac{[N(D)_{PRE}]_{C_k}}{[N(D)_{PRE}]_{C_k} + [N(D)_{TC}]_{C_k}} \quad (5.1)$$

$$\delta(D, RC_k)_{TC} = \frac{[N(D)_{TC}]_{C_k}}{[N(D)_{PRE}]_{C_k} + [N(D)_{TC}]_{C_k}} \quad (5.2)$$

here $[N(D)_{TC}]_{C_k}$ and $[N(D)_{PRE}]_{C_k}$ denote the average $N(D)$ of the PREs or TCs for different R classes C_k ($k = 1, 2, 3, 4, 5, 6, 7$). The R ($\text{mm} \cdot \text{h}^{-1}$) threshold for RC_1 was $0.1 \leq R < 1$, that for RC_2 was $1 \leq R < 2$, that for RC_3 was $2 \leq R < 5$, that for RC_4 was $5 \leq R < 10$, that for RC_5 was $10 \leq R < 30$, that for RC_6 was $30 \leq R < 50$, and that for RC_7 was $R > 50$.

3. Results

3.1. Spatial distributions of precipitation

Before examining the characteristics and vertical structures of different rainfall types, it is necessary to investigate the R characteristics of PREs and TCs, and investigate stratiform and convective precipitation roles in the generation of R s in PREs and TCs, Fig. 2 shows the mean R , fractional coverage, and conditional mean R in terms of stratiform and convective R in PREs and TCs by utilizing similar method as Fritz et al. (2016) and Shu et al. (2021). The total mean R was defined as the sum of convective and stratiform R , whereas the mean R for one rain type was defined as the R for the kind of precipitation divided by the precipitation pixels in total. The fractional coverage of each type of rain was calculated by dividing the pixel number for the rain type by the total number of rain pixels. The conditional mean R for convective (stratiform) rain was the total R of convective (stratiform) rain divided by the pixel numbers of convective (stratiform) precipitation events. The mean R for stratiform rainfall from the TCs to the PREs increased slightly (Fig. 2a), whereas its fractional coverage was reduced (Fig. 2b) because of the increased conditional mean R (Fig. 2c). The enhancement of total mean R from TCs to PREs was mainly attributed to the increased convective R (Fig. 2a), and the enhancement of the convective R from TCs to PREs was mainly associated with the increased occurrence frequency (fractional coverage) rather than the conditional mean R (Fig. 2b–c). This implies that the rain rate in PREs may be more concentrated than that in TCs.

3.2. Contributions of different-diameter raindrops to R

Precipitation characteristics are closely associated with DSD features. To further investigate the reasons for various precipitation characteristics between TCs and PREs, the contributions of raindrop diameters to all types of R (convective, stratiform, and total R s) are analyzed below.

Applying Eqs. (3.1)–(3.4) to calculate the contributions of different diameter classes to the total number concentration (N_t) and rainfall rate (R), and the results can be illustrated in Fig. 3. For convective R in PREs and TCs, the contributions of different-diameter categories to the total number concentration (N_t) decrease as drop sizes increase (Fig. 3a), whereas that of R increases and then decreases (Fig. 3b); raindrops with the sizes of <1 mm contribute to $\sim 58\%$ N_t (Fig. 3a), but contribute to only around 13% R (Fig. 3b). For the stratiform and total R s in PREs and TCs, the contributions of different size raindrops to N_t and R increase with the enhancement of drop diameter size for small- (<1 mm) to medium-sized drops (1 – 2 mm), while diminishing with the enhancement of drop sizes for medium- (1 – 2 mm) to large-size drops (>2 mm) [Fig. 3c–f]. For N_t in TCs and PREs, raindrops with sizes of 1 – 2 mm contribute to approximately 40% – 70% of N_t (Fig. 3a, c, e), but to

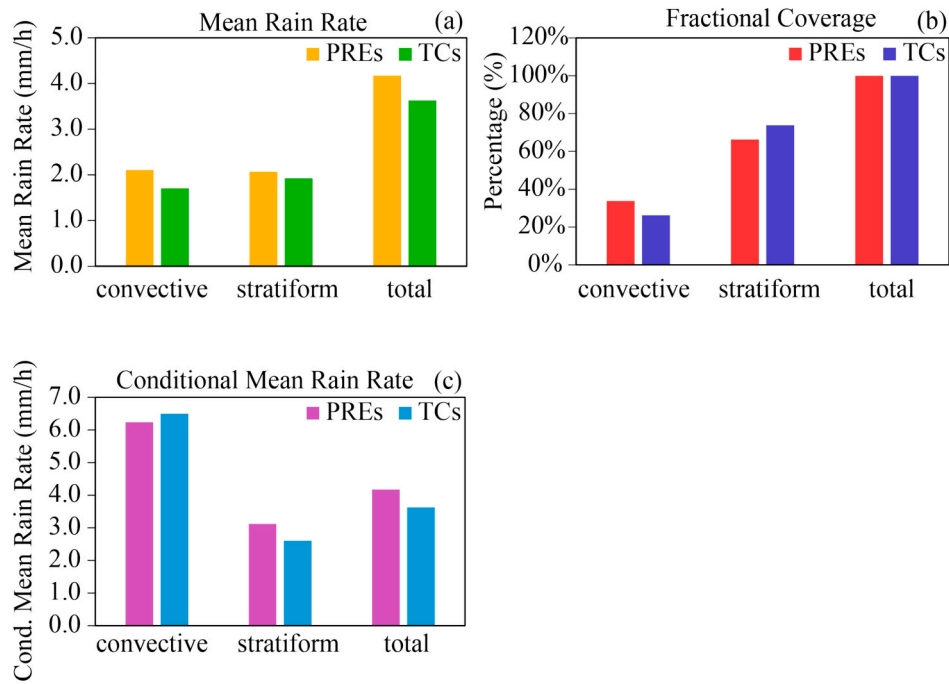


Fig. 2. Total mean rain rates, fractional coverage, conditional mean rain rate in convective (“Con Rain”) and stratiform rainfall (“Stra Rain”), and total rainfall (“Total Rain”) for predecessor rain events (PREs) and tropical cyclones (TCs). The total mean rain rate was calculated as the total amount of one type of rainfall divided by the total number of pixels of the total rainfall; conditional mean rain rate was defined as the total amount of one type of rainfall divided by the total number of pixels of that type.

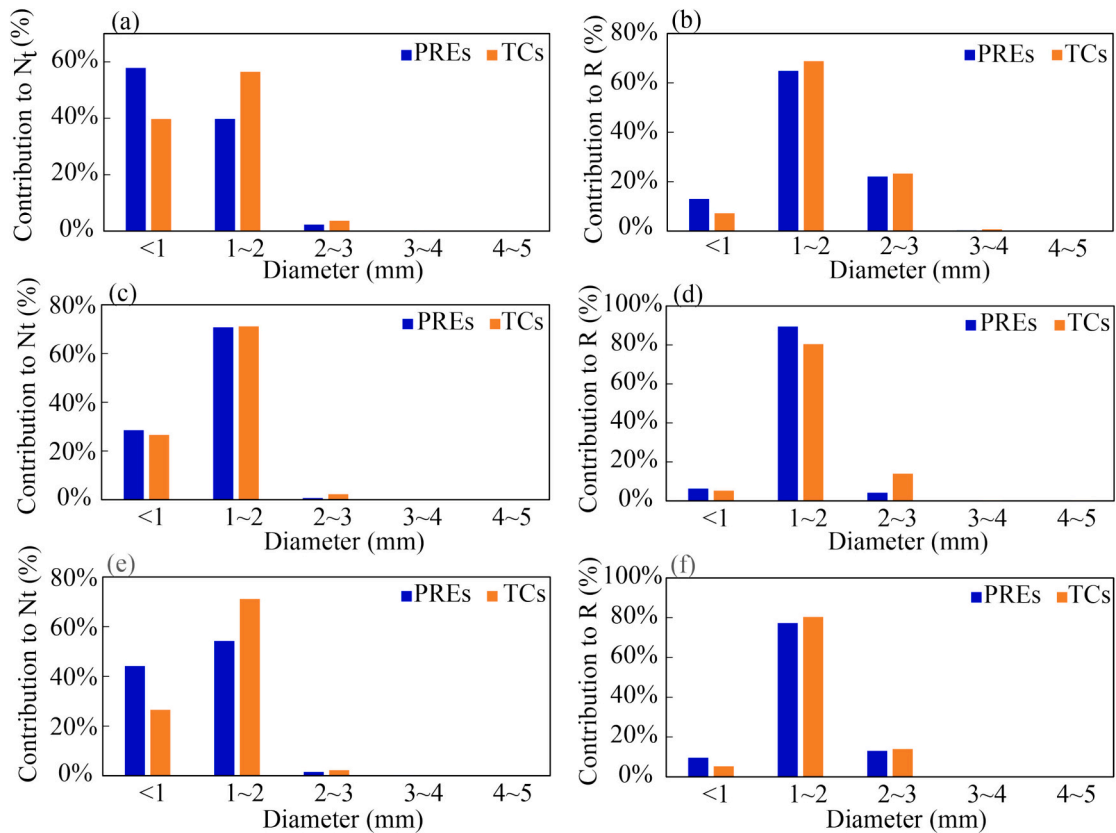


Fig. 3. Contributions of different diameter classes to the total number concentration (N_t) for (a) convective rainfall, (c) stratiform rainfall, and (e) total rainfall during predecessor rainfall events and tropical cyclone rainfall events. Contributions of different diameter classes to the rainfall rate (R) for (b) convective rainfall, (d) stratiform rainfall, and (f) total rainfall for predecessor and tropical cyclone rainfall events.

around 70 %–80 % of R (Fig. 3b, d, f); drops with sizes of 2–3 mm contribute to only 1 %–5 % of N_t , but result in around 10 %–20 % of R , this is similar case as pointed out by Wu et al. (2019) and Janapati et al. (2021). Compared to TCs, the small-size drops (< 1 mm) generally contribute more to N_t and R for convective and total rainfall in PREs, while the medium-sized drops (1–2 mm) contribute less. In summary, it illustrates that small- and medium-sized droplets dominantly promote the N_t , and the small-sized drops in PREs contribute more to N_t than that in TCs; Whereas medium and large drops mainly contribute to R , and those in convective and stratiform PREs contribute less than TCs, indicating the significance of medium and large drop parameterizations in TC rainfall forecasts.

Applying Eqs. (4.1)–(4.4) to calculate the occurrence percentages (OCP) of N_t and R at various diameters for the convective, stratiform, and total R_s , and the results are depicted in Fig. 4a–e. The OCP of N_t and R decreased with increasing drop diameter in PREs, whereas that of N_t and R raised with enhancing droplet diameter in TCs. For drop diameter sizes of <1 mm, the OCP of N_t (R) was more dominant in PREs than in TCs, whereas it was more essential in TCs than in PREs for drop diameter sizes of >1 mm. Fig. 4 highlights that the occurrence percentages of the N_t were higher in PREs than in TCs for small drops, whereas that of the R was higher in TCs than in PREs for medium- and large-sized drops for all types of R_s . Additionally, the occurrence percentages of N_t and R for stratiform rainfall for large drop diameter sizes of >3 mm were 0, indicating no drop diameter sizes of >3 mm contribute to stratiform rainfall both in PREs and TCs.

3.3. DSDs of different precipitation types

Previous studies have illustrated disparities in DSDs between different precipitation types. The scatter densities of the average D_m and $\log_{10}N_w$ for all rainfall types (convective, stratiform, and total) further

emphasize the points. For convective, stratiform, and total rainfall, the averaged ($\pm$ standard deviations) values of D_m in PREs (TCs) were 1.13 ± 0.39 (1.35 ± 0.48), 1.24 ± 0.27 (1.26 ± 0.28), and 1.2 ± 0.32 (1.28 ± 0.35) mm, respectively, and those of $\log_{10}N_w$ were 3.89 ± 0.49 (3.57 ± 0.63), 3.52 ± 0.35 (3.38 ± 0.33), and 3.64 ± 0.44 (3.43 ± 0.44) $m^{-3} mm^{-1}$. The D_m and $\log_{10}N_w$ values for convective and stratiform rainfall in TCs are similar to those in post-monsoon TCs in the Arabian Sea (Kumar et al., 2023b), and the convective rainfall in PREs are similar to those in Meiyu frontal rainbands (Wen et al., 2016). This indicates that D_m increased from the PREs to the TCs for all three types of rainfall, whereas $\log_{10}N_w$ decreased.

Fig. 5 shows the average $\log_{10}N_w$ and D_m for convective rain, stratiform rain, as well as total rain for PREs and TCs. The average D_m and $\log_{10}N_w$ for convective, stratiform, and total rain in the PREs and TCs were compared with the DSD features of previous studies (Fig. 5). The diameter (D_m) and concentration parameters ($\log_{10}N_w$) of precipitation in PREs and TCs were generally different from those of the oceanic shallow/deep convective type and the continental type. D_m in this study for all three types of rainfall in the PREs/TCs were much lower than the continental type, the values of $\log_{10}N_w$ were lower than the shallow oceanic type, and both D_m and $\log_{10}N_w$ were lower than the deep oceanic type. However, the values of D_m and $\log_{10}N_w$ for PREs are generally in agreement with the results obtained for the Pacific Ocean TCs in Janapati et al. (2020) and Meiyu frontal rainfall in the East China (Wen et al., 2016), and those of TCs rainfall is generally in accord with the findings in the post-monsoon TCs (Kumar et al., 2023b), and in the summer rainfall of East China (Wen et al., 2023). This indicates that compared with the typical continental and ocean precipitation, the DSDs of PREs generally share the characteristics of post-monsoon TCs in the Pacific Ocean and Meiyu front rainfall in East China, whereas those of TCs share the characteristics of the post-monsoon TCs. Other literature demonstrated that typhoon DSDs have similar characteristics to shallow

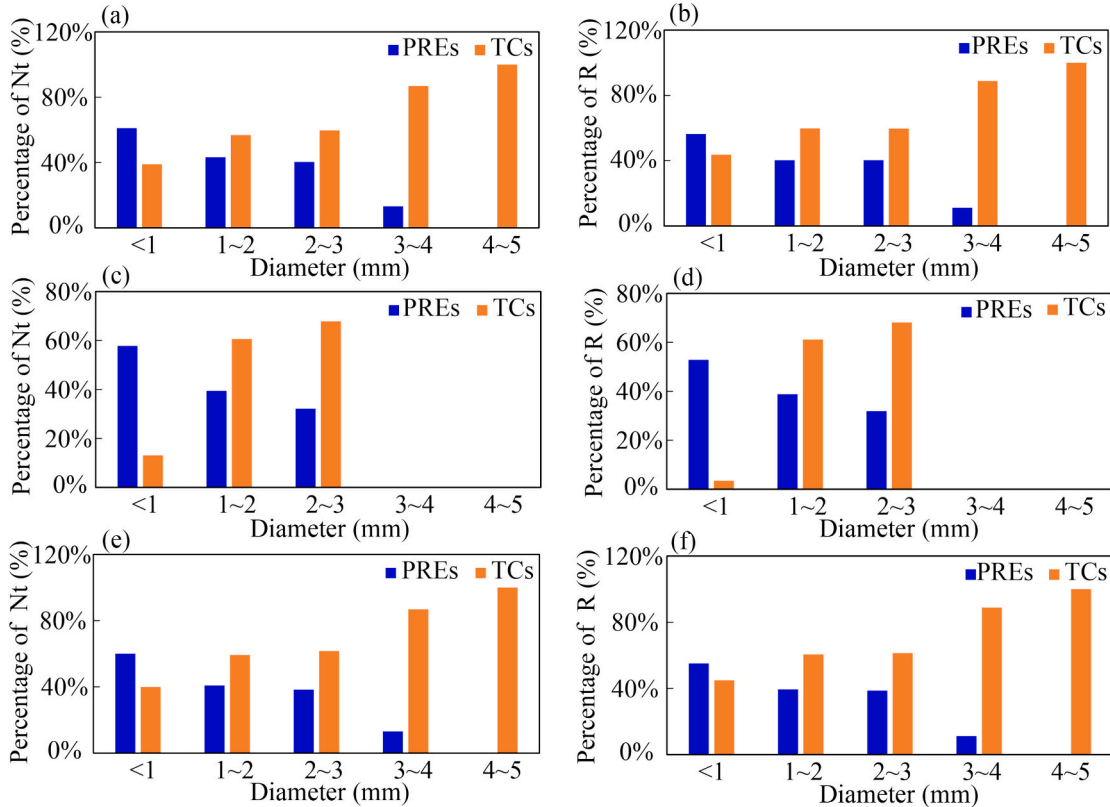


Fig. 4. Occurrence percentages of total number concentration (N_t) for (a) convective rainfall, (c) stratiform rainfall, and (e) total rainfall for predecessor rainfall events and tropical cyclone rainfall events. Occurrence percentages of the rainfall rate (R) for (b) convective, (d) stratiform, and (f) total rain for predecessor rainfall events and tropical cyclone rainfall events.

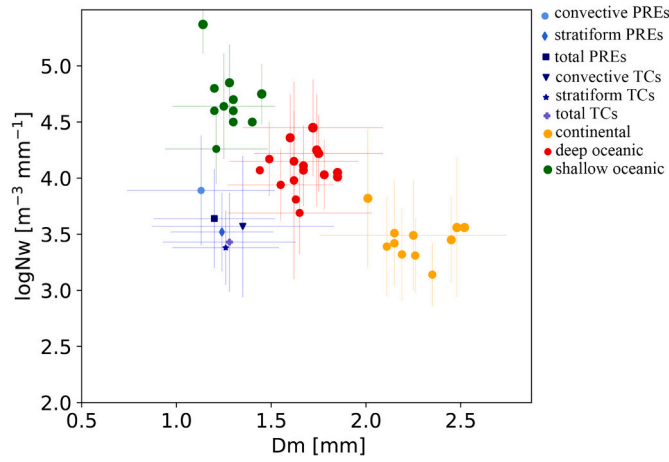


Fig. 5. Averaged $\log_{10}N_w$ ($\text{mm}^{-1} \text{m}^{-3}$) as well as D_m (mm) for convective rainfall, stratiform rainfall, and total rainfall in predecessor rainfall events and tropical cyclone rainfall events in this study (blue markers), and those measured in different areas described in the literature. Orange, red, and green dots denote continental, deep oceanic, and shallow oceanic convective clusters, respectively. The values at the bottom and top of the vertical lines indicate the standard deviations of D_m and the values on the left and right of the horizontal lines denote the standard deviations of $\log_{10}N_w$. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

oceanic convective regimes, but the specific locations and developmental stages also affect typhoon DSD features (Janapati et al., 2020; Ryu et al., 2021; Zhang et al., 2020). D_m and $\log_{10}N_w$ achieved larger values in convective rain than stratiform rain for TCs, whereas D_m showed smaller values and $\log_{10}N_w$ showed higher values for convective precipitation than stratiform one for PREs. Furthermore, there were larger $\log_{10}N_w$ values and smaller D_m values in PREs than in TCs for both convective and stratiform rainfall, as leading to larger $\log_{10}N_w$ values and smaller D_m values in PREs than in TCs for total rainfall. The possible physical reasons for larger D_m in TCs may be attributed to strong updrafts in the eyewall region, which suspends the drops for a longer time

and enhances the drop growth at higher pressure levels and transport of hydrometeors aloft to other regions from the eyewall region.

Substituting the D_m and $\log_{10}N_w$ values into Eq. (1), given $\mu = 3$, the corresponding DSD distributions are given in Fig. 6. Fig. 6 shows that $N(D)$ increases to a certain high value when D_m reaches a certain value (inflection point) and then reduces. The averaged D_m values of inflection points for convective, stratiform, as well as total precipitation in the PREs/TCs were 0.38 (0.45), 0.46 (0.53), and 0.41 (0.48) mm, respectively, whereas those for the number concentration ($N(D)$) were 1729.1 (918.9), 633.7 (378.1), and 982.0 (516.9) $\text{m}^{-3} \cdot \text{mm}^{-1}$, respectively. This illustrated that the diameters for convective precipitation were lower than the stratiform one, whereas the number concentration for convective precipitation was higher than the stratiform one both for PREs and TCs. Additionally, the number concentrations at these inflection points were generally higher for PREs than for TCs, whereas the diameters were lower for PREs than for TCs.

The $N(D)$ distributions for different rainfall diameters show that the drop concentrations for convective precipitation were higher than the stratiform regime for both PREs and TCs. In addition, the $N(D)$ in the convective R was broader than that in the stratiform R (Fig. 6). This may be attributed to large drop breakups resulting from collisions, as implied by other studies (Hu and Srivastava, 1995; Niu et al., 2010; Chen et al., 2013b; Das et al., 2017; Janapati et al., 2021). Those DSD characteristics for stratiform and convective rain were generally consistent with those reported by the previous studies (Jayalakshmi and Reddy, 2014; Krishna et al., 2016; Ryu et al., 2021; Janapati et al., 2021). The concentrations of medium- and large-sized droplets were greater in TCs than in PREs. The higher concentrations of medium- and large-sized droplets in TCs may be attributed to the composition of TCs rainfall, which includes the eyewall, inner rainbands, and outer rainbands, the mean diameters and concentration parameters are quite similar to the post-monsoon TCs as summarized by Kumar et al. (2023b). In contrast, precipitation associated with PREs exhibits DSD characteristics of outer rainbands and Meiyu frontal rainfall by Wen et al. (2016), which generally show smaller diameters and higher concentrations than the eyewall and inner rainbands (Bao et al., 2020a, 2020b; Wu et al., 2021). The mean diameters and concentrations of total rainfall in PREs (1.2 mm, $3.64 \text{ m}^{-3} \cdot \text{mm}^{-1}$) also show similarities with the total one in the western part of monsoon Meiyu frontal rainfall (1.2 mm, $3.6 \text{ m}^{-3} \cdot \text{mm}^{-1}$) in Zhang

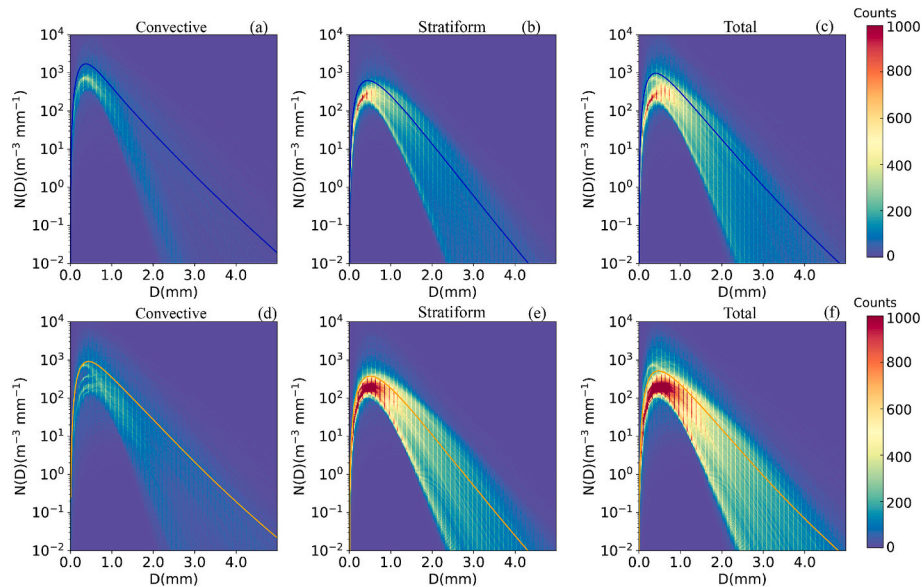


Fig. 6. Histogram of calculated number concentrations $N(D)$ (a) convective (“Convective”), (b) stratiform (“Stratiform”), (c) total (“Total”) rain for predecessor rain events (PREs), and the blue solid line denotes the mean curve for each panel; and those in for (d) convective rainfall, (e) stratiform rainfall, (f) total rainfall for tropical cyclones (TCs), and the orange solid line denotes the mean curve for each panel. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

et al. (2020). The mean diameters and concentrations of convective rainfall in PREs (1.13 mm, $3.89 \text{ m}^{-3} \cdot \text{mm}^{-1}$) also show similarities with the total one in Meiyu frontal rainfall (1.18 mm, $3.99 \text{ m}^{-3} \cdot \text{mm}^{-1}$) in Wen et al. (2016), but show much lower mean diameters and concentrations than the frontal rainfall in Bao et al. (2019). Compared to the eyewall region, processes such as collision-coalescence, breakup, evaporation, and melting dominate in the inner and outer rainbands (Chen et al., 2019a; Bao et al., 2020b; Wu et al., 2021; Huang et al., 2023), which may together contribute to the smaller mean diameters and larger concentrations.

3.4. DSDs partition based on R

To further examine the differences in the number concentration and R between PREs and TCs, the PRE and TC DSDs were partitioned into seven types according to R classes (Table 3). As pointed out in previous studies (Jayalakshmi and Reddy, 2014; Seela et al., 2017; Janapati et al., 2021), to make DSD comparisons meaningful, the data samples for PREs and TCs in each R category ought to be sufficiently great, and the averaged R in PREs need to be close to those in TCs in each category (Deo and Walsh, 2016). Table 3 and Table 4 illustrate the statistical values of the seven R classes for TCs and PREs. The calculated mean as well as standard deviations of Rs values from the first to the sixth category Rs in PREs are close to those in TCs, with a difference of $<0.5 \text{ mm} \cdot \text{h}^{-1}$. For the first, fourth, sixth, and seventh precipitation categories (RC₁, RC₄, RC₆, and RC₇), the TCs achieved larger skewness values than the PREs. The skewness values for all seven R categories were positive, indicating that the Rs were generally distributed below the average values.

The relative contributions of N(D) in the discrepant R categories for convective, stratiform, and total R in PREs and TCs are demonstrated in Fig. 7. The contributions of N(D) in PREs and TCs illustrate that small-sized drops ($<1 \text{ mm}$) display a dominant percentage in PREs compared with the total Rs of TCs, whereas medium and large-sized drops ($>1 \text{ mm}$) show a dominant contribution of N(D) in TCs compared with the total R. Compared TCs to PREs, medium and large-sized drops dominantly contribute to the convective (stratiform) rainfall in TCs, whereas small-sized drops contribute to that in PREs for all R grades. Comparing convective to stratiform rainfall, it corroborated that higher percentages of medium and large drops in convective rainfall compared to stratiform rainfall in TCs, whereas higher percentages of small drops are present in convective rainfall than stratiform rainfall in PREs. In terms of the differences between PREs and TCs for convective (stratiform) rainfall, higher percentages of small drops contribute to convective rainfall in PREs, and the relative contributions generally increased with the increasing of rain rate classes; and higher percentages of medium and large drops contribute to stratiform rainfall in TCs, and

Table 3

Number of samples, skewness, kurtosis, averaged values, and standard deviations for convective precipitation rate for seven rain rate classes during PREs. Unit is mm h^{-1} .

Rain rate class	Rain threshold	PREs				
		Number of samples	Mean	Standard deviation	Skewness	Kurtosis
RC ₁	$0.1 \leq R < 1$	6173	0.52	0.22	0.37	-1.04
RC ₂	$1 \leq R < 2$	2958	1.43	0.28	0.32	-1.11
RC ₃	$2 \leq R < 5$	3148	3.22	0.86	0.38	-1.04
RC ₄	$5 \leq R < 10$	1667	6.95	1.36	0.45	-0.87
RC ₅	$10 \leq R < 30$	877	16.17	5.24	0.78	-0.46
RC ₆	$30 \leq R < 50$	164	38.51	5.88	0.3	-1.16
RC ₇	$R > 50$	141	107.56	74.08	1.72	1.73

Table 4

Number of samples, skewness, kurtosis, averaged values, and standard deviations for convective precipitation rate for seven rain rate classes during TCs. Unit is mm h^{-1} .

Rain rate class	Rain threshold	TCs				
		Number of samples	Mean	Standard deviation	Skewness	Kurtosis
RC ₁	$0.1 \leq R < 1$	13,202	0.48	0.24	0.52	-0.97
RC ₂	$1 \leq R < 2$	5311	1.44	0.28	0.25	-1.13
RC ₃	$2 \leq R < 5$	6357	3.22	0.85	0.38	-1.02
RC ₄	$5 \leq R < 10$	2649	6.77	1.34	0.64	-0.62
RC ₅	$10 \leq R < 30$	1327	16.89	5.46	0.7	-0.59
RC ₆	$30 \leq R < 50$	319	38.08	5.56	0.44	-0.96
RC ₇	$R > 50$	211	92.52	53.51	2.4	5.87

the relative contributions generally reduced with the increasing of rain rate classes.

The $\log_{10}N_w$ ($\text{m}^{-3} \text{mm}^{-1}$) and D_m distributions for various R categories for convective, stratiform, and total Rs in PREs and TCs are illustrated using box plots in Fig. 8. The D_m values enhanced the stratiform rainfall in the PREs as the precipitation R class increased from RC₁ to RC₄. With increased R, the values of D_m generally increased for both convective and total Rs in PREs, as well as for all R types in TCs. This could be attributed to enhanced contributions of concentration by large- and medium-sized drops and reduced contributions of concentration by small-sized drops, as pointed out by Rosenfeld and Ulbrich (2003) or other studies (Rao et al., 2009; Krishna et al., 2016). These characteristics are similar to those reported in Radhakrishna and Rao (2010) or previous studies (Jayalakshmi and Reddy, 2014; Deo and Walsh, 2016; Bao et al., 2020a; Janapati et al., 2021). Moreover, the values for D_m are larger in TCs than in PREs for all seven R categories, which may be associated with the predominant contributions of small drops to PREs and the predominant contributions of droplets with medium and great sizes to TCs concentrations, as shown in Fig. 7. In contrast to the D_m scenario, the values for $\log_{10}N_w$ were larger in the PREs than in the TCs for all seven R categories. For all R classes, the maximum values of raindrop concentrations and diameters are greater in convective rainfall than in stratiform rainfall both for PREs and TCs. This indicates the existence of larger drop diameter and higher concentration in convective rainfall than stratiform rainfall. Similar findings were reported by previous studies in Wen et al. (2016), Janapati et al. (2020), Zhang et al. (2020), Kumar et al. (2023b).

3.5. Z-R relationships in precipitation

The calculation of R from radar reflectivity largely depends on geographic location, weather systems, as well as microphysics of precipitation (Ulbrich and Atlas, 1978; Atlas and Ulbrich, 1999; Steiner et al., 2004; Janapati et al., 2021; Ryu et al., 2021). Accurate radar reflectivity and rain rate (Z-R) formula alleviate uncertainty in the estimation of R from using the formulation $Z = A \cdot R^b$. The values of coefficient A are generally proportional to the mean mass-weighted diameter sizes (Atlas and Williams, 2003), and the values of b are associated with microphysics (Steiner et al., 2004; Janapati et al., 2021). Larger b (>1) indicates the significance of collision and coalescence, while b (~ 1) indicates the prevalence of collision, coalescence, and breakup (Rosenfeld and Ulbrich, 2003; Sharma et al., 2009; Bao et al., 2019). Taking logarithms for the Z-R equation and applying linear regression for $\log_{10}Z$ and $\log_{10}R$, the corresponding Z-R relationships can be derived (Fig. 9).

Fig. 9 shows that the Z-R relationships for PREs and TCs differ from those applied in the 1988 Doppler weather radar (Atlas and Williams,

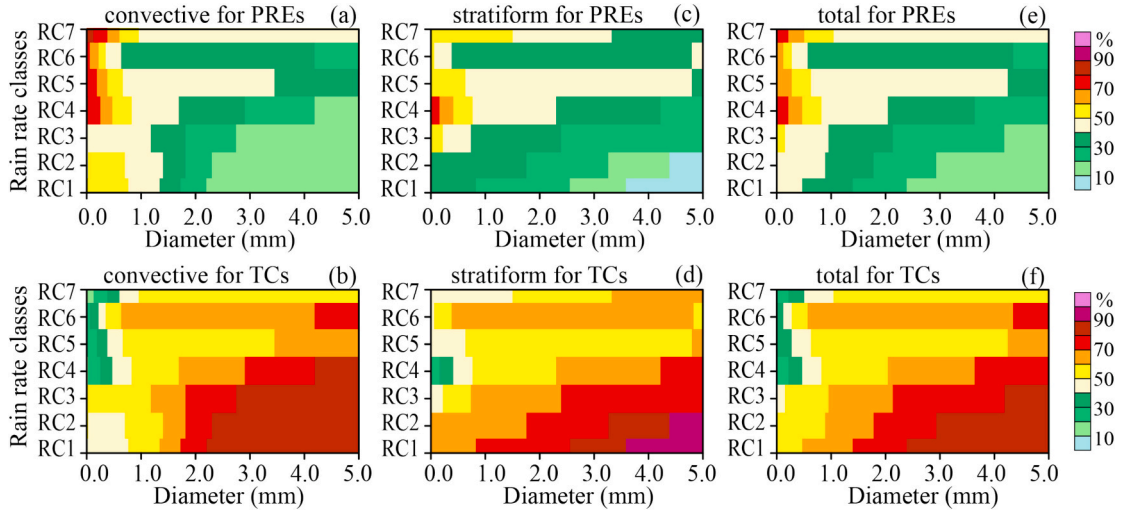


Fig. 7. Relative contributions of $N(D)$ [$\text{mm}^{-1}\cdot\text{m}^{-3}$] in various precipitation categories for (a) convective, (c) stratiform, and (e) total rain in predecessor rainfall events; those for (b) convective, (d) stratiform, and (f) total rain in tropical cyclones.

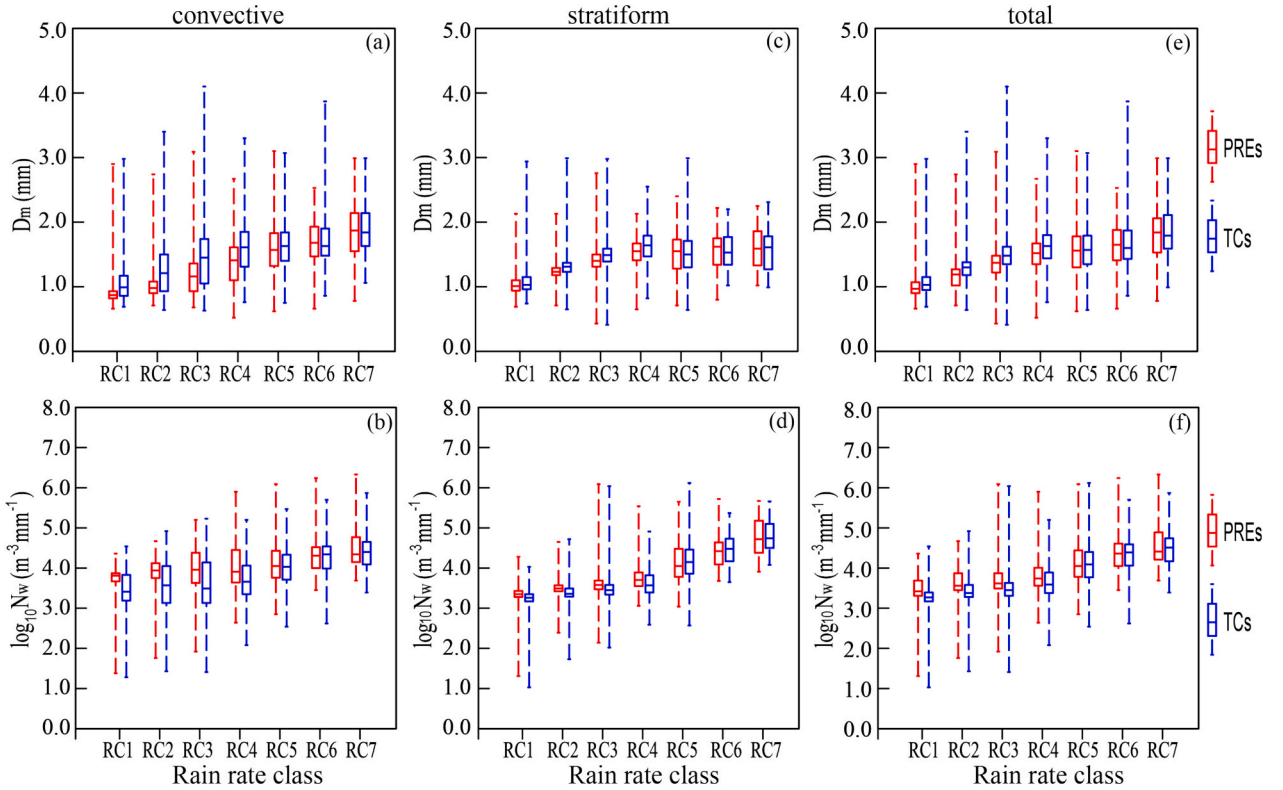


Fig. 8. Box plots of D_m (mm) in different precipitation rate (R) grades for (a) convective rainfall, (c) stratiform rainfall, and (e) total rainfall in predecessor rainfall events (PREs; red) and tropical cyclones rainfall events (TCs; blue); those of $\log_{10}N_w$ ($\text{m}^{-3}\cdot\text{mm}^{-1}$) in various R grades for (b) convective rainfall, (d) stratiform rainfall, and (f) total rainfall in predecessor rainfall events and tropical cyclones rainfall events. The lowest, center and highest lines of the boxes denote the 25th, median, and 75th percentiles, respectively; the lowest and highest dashed lines denote the minima and maxima, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2003), which can be written as $Z = 300R^{1.4}$. In general, the coefficient A of convective (stratiform/total) rainfall in PREs is much smaller than the value of that in TCs in this study, this may be attributed to the higher concentrations of small drops in PREs., as confirmed by Fig. 4 and Fig. 8. The coefficients b range from 1.36 to 1.41 in both TCs and PREs and the ranges of b are generally consistent with those coefficients proposed in Janapati et al. (2021). Though deviations exist, the Z–R formulations of convective, stratiform, as well as total R for TCs are generally close to

those of TCs in the Pacific Ocean in Janapati et al. (2020), with $Z = 328.73R^{1.42}$ for convective rainfall, $Z = 368.28R^{1.49}$ for stratiform rainfall, $Z = 346.03R^{1.42}$ for total rainfall, coefficients A ranging from 316 to 368, and coefficients b ranging from 1.37 to 1.49, possibly because TCs in this study encompassing TCs that occurred in the SCS–WNPO. In contrast, the Z–R equations in terms of convective, stratiform, and total Rs for the PREs were different from those derived in other regions in other studies (Ulbrich and Lee, 2002; Atlas and

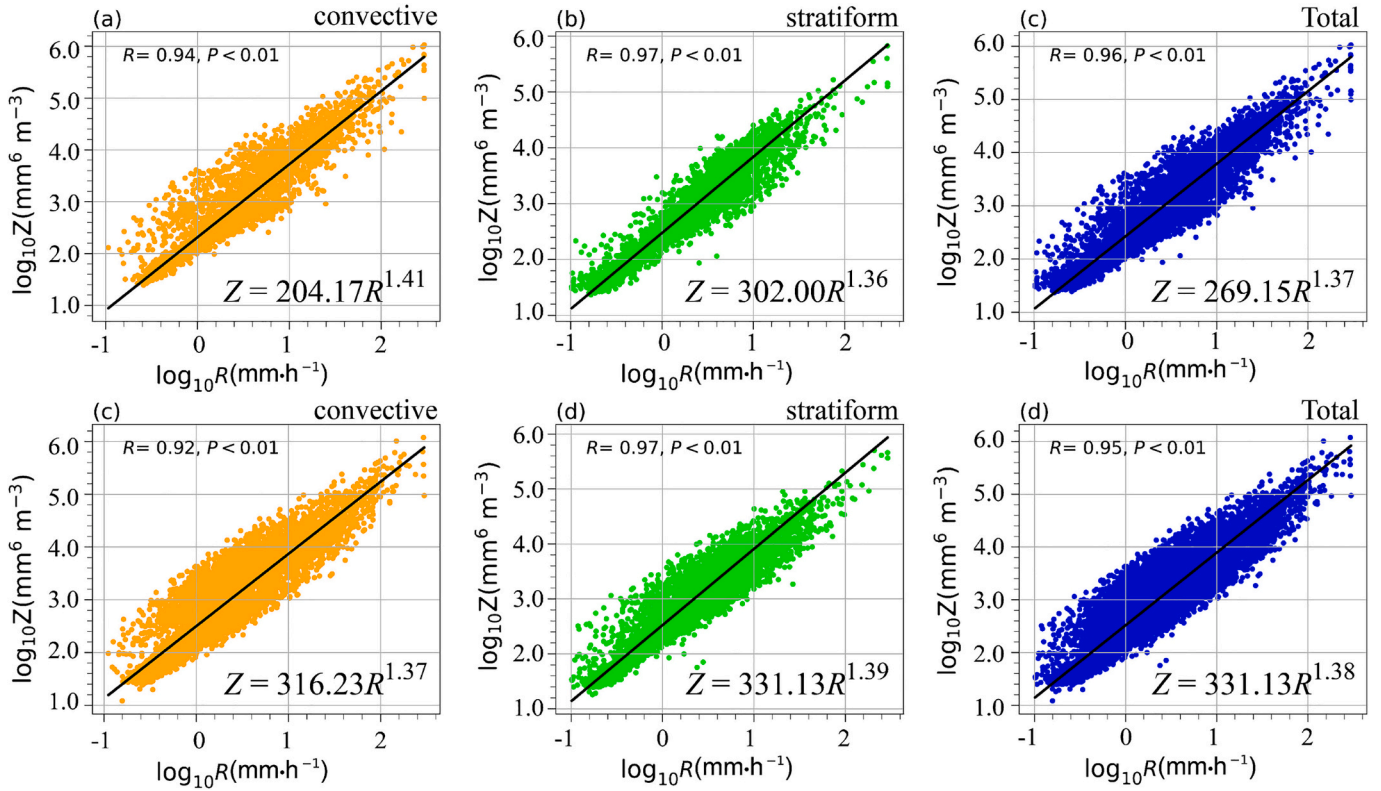


Fig. 9. Z–R plots of (a) convective precipitation (“Convective”), (b) stratiform precipitation (“Stratiform”), and (c) total precipitation (“Total”) for predecessor rain events (PREs) for samples at an altitude of 125 m; and those in for (d) convective and (e) stratiform rainfall, and (f) total rainfall for tropical cyclones (TCs). The line of the best fit deduced from the linear least-squares algorithm is drawn through the points, and the corresponding equations are given.

Williams, 2003; Jayalakshmi and Reddy, 2014; Seela et al., 2017; Seela et al., 2018; Wen and Zhao, 2018; Wen and Zhao, 2019; Bao et al., 2020b; Janapati et al., 2020). Different from the TCs, the coefficient A of total rainfall in PREs ($Z = 269.15R^{1.37}$) is highly consistent with the non-typhoon rainfall in Taiwan of China in the Northwest Pacific Ocean ($Z = 264.58R^{1.36}$) reported by Janapati et al. (2021) and that of summer rainfall in the North Taiwan of China ($Z = 266.42R^{1.38}$) reported by Seela et al. (2018), whereas it is much smaller than the convective rainfall related to the cold front in the Atlantic Basin ($Z = 365.05R^{1.38}$) found by Ulbrich and Lee (2002), coastal frontal rainfall ($Z = 354.05R^{1.22}$) in Bao et al. (2019) and the Meiyu convective rainfall ($Z = 368.0R^{1.21}$) in Eastern China reported by Chen et al. (2013a). This may be attributed to large amounts of small drops in total PREs than the coastal convective frontal rainfall and the Meiyu convective rainfall. Note that the frontal rainfall in Bao et al. (2019) and Meiyu rainfall in Chen et al. (2013b) are convective, not total rainfall.

Total in all, the Z–R equations for PREs differ from the default ones in the Doppler weather radar 1988 and tropical weather radar ($Z = 250R^{1.2}$), indicating that specific Z–R relationships may be necessary for a specific weather system in a given geographic location, which has been emphasized by other researchers (Ulbrich and Lee, 2002; Atlas and Williams, 2003; Jayalakshmi and Reddy, 2014; Seela et al., 2017; Seela et al., 2018; Wen and Zhao, 2018; Wen and Zhao, 2019; Bao et al., 2020a; Janapati et al., 2020; Janapati et al., 2021). The estimations of Z–R relationships are favorable for enhancing the quantitative estimation of precipitation from radar reflectivity for PREs over the YRD as well as for TCs in the SCS–WNPO.

4. Discussions

To investigate the possible mechanisms contributing to the differences in DSDs between PREs and TCs, reanalysis data from the National

Centers for Environmental Prediction (NCEP) Final Analysis (FNL) datasets on $1^\circ \times 1^\circ$ were applied. Fig. 10 shows that precipitable water and water vapor were less abundant in PREs than in TCs, and the storm height was slightly lower in PREs than in TCs. The convective available potential energy (CAPE) was lower in the PREs than in the TCs. This indicates more intense convection related to stronger upward and downward motions in TCs than in PREs, making it possible to elevate small drops to higher levels in TCs than in PREs as a result of larger drops reaching the ground, as illustrated in Steiner et al. (2004) and Janapati et al. (2020, 2021). Additionally, the environmental fields were warmer and drier in the TCs than in the PREs in the lower troposphere below 700 hPa (Fig. 11a–b), and the small drops generated by collision breakup were more likely to evaporate, leading to relatively lower number concentrations of small drops reaching the ground.

Meanwhile, the contributions of small raindrops to R or concentrations in PREs are larger than those in TCs, which implies the pronounced impacts of small drops on the precipitation in PREs. This may be partly due to the stronger raindrop breakup in the PREs induced by the larger mid-latitude environmental wind shear on the PREs rainbands as Fig. 11c showed, which was reported by other studies (Steiner et al., 2004; Zhang et al., 2020; Shu et al., 2021). This phenomenon was also observed in the eastern part of the East Asian summer monsoon (EASM) rainbands as pointed out by Zhang et al. (2020), who found stronger baroclinicity on the eastern side of the EASM rainband, leading to larger environmental wind shear, which may be more favorable for raindrop breakup.

Tropical precipitation systems are generally characterized by warm temperatures and high humidity, which favor the formation of numerous small hydrometeors primarily through warm rain processes where collision and coalescence are dominant. Tropical cyclones generally exhibit a large number of cloud droplets and substantial mixed-phase regions where ice and liquid water coexist, corresponding

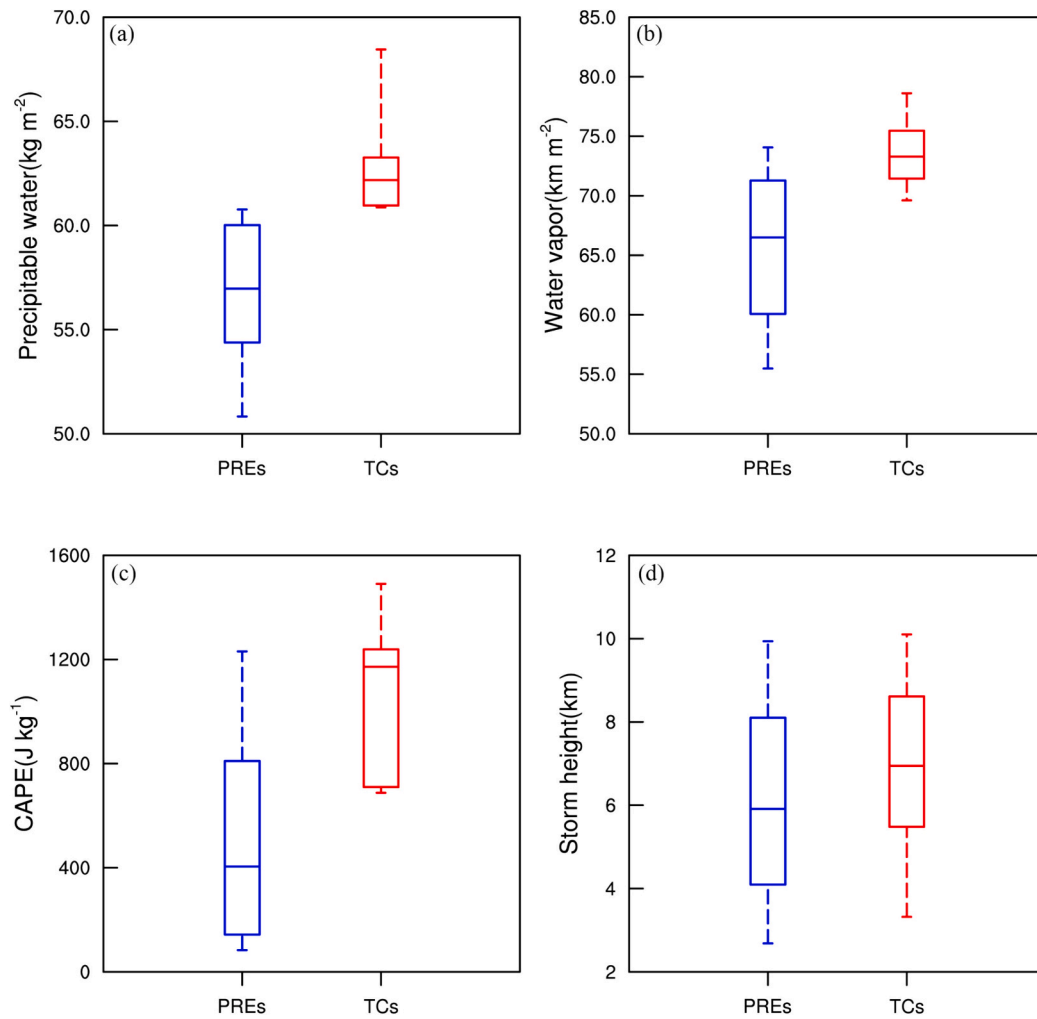


Fig. 10. The box-plots of (a) precipitable water ($\text{kg}\cdot\text{m}^{-2}$), (b) integrated water vapor in vertical, (c) convective available potential energy ($\text{J}\cdot\text{kg}^{-1}$), and (d) storm height for predecessor rain events (PREs), and tropical cyclones (TCs). The blue box on the left denotes PREs and the red box on the right denotes TCs. Center lines indicate median values, the lowest and highest lines of the boxes denote the 25 % and 75 %, respectively. The top and bottom vertical lines indicate 92 % and 8 %, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

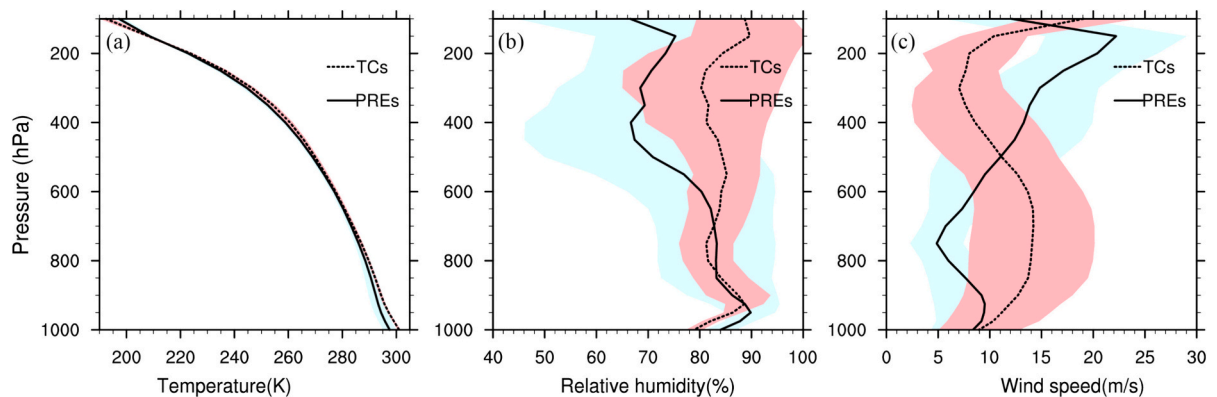


Fig. 11. The averaged temperature (K), relative humidity (%), and wind speed profiles for predecessor rain events (PREs) and tropical cyclones (TCs).

to higher concentrations of small to medium drops and lower concentrations of larger drops compared to nontropical cyclones (Janapati et al., 2021; Chen et al., 2022b; Radhakrishna and Rao, 2010; Deo and Walsh, 2016). In contrast, mid-latitude systems generally encounter colder temperatures and are characterized by mixed-phased stratocumulus or cold clouds, and precipitation may be associated with the

melting of snow or ice crystals as they fall into warmer layers. Accordingly, precipitation associated with mid-latitude systems may display higher concentrations of small drops due to larger wind speeds and wind shear, and they may also exhibit a small number of large drops due to the dominance of aggregation and riming processes (Fu and Lei, 2017; Lee et al., 2021; Wu et al., 2022).

PREs are generated due to the interactions of mid-latitude troughs and tropical cyclones, as a result of complex microphysical characteristics from both systems. The number concentrations for PREs are lower than the shallow oceanic clusters and larger than the continental clusters, which are more similar to those from tropical cyclones compared to the continental and oceanic clusters; the mean diameters are much smaller than the continental clusters, which are more similar to those from tropical cyclones compared to the continental and oceanic clusters. Though the number concentrations and drop diameters of PREs show Meiyu frontal rainfall characteristics reported in Wen et al. (2016), they are within similar magnitudes as TCs and summer rainfall observed in the Pacific Ocean in previous studies (Janapati et al., 2020, 2021).

While this study mainly discussed the precipitation and DSD characteristics of PREs and TCs, the obtained Z–R relationships could be applied to improve cloud microphysics and interpret disparities between simulated radar reflectivity and observations. Other literature (Rogers et al., 2007; Yang et al., 2008; Xu and Li, 2017) showed that simulated radar reflectivity tends to be larger than that from observations, which may further improve the understanding of DSD features for different types of rainfall associated with specific clouds and precipitation in a given region. In addition, it may be applied to validate weather model results in terms of precipitation structures and DSD features. The specified Z–R relationship may help quantify the detailed contributions of stratiform and convective rainfall to the total rainfall by using specified empirical formulas suited for each type of precipitation.

5. Summary and conclusions

This research examines the rainfall and associated DSD features of rainfall from GPM DPR observations during PREs and associated TCs in the South China Sea and northwestern Pacific Ocean. The analysis of different types of precipitation rates to total precipitation rates showed that the total mean R in the PREs was larger than that in the TCs, which was mainly attributed to the higher mean stratiform and convective rain rates. The higher mean stratiform rain rate was related to the enhanced conditional mean rain rate of stratiform regime in PREs than in TCs, and the higher convective mean rain rate was associated with the enhanced fractional coverage of convective rainfall in PREs than in TCs.

For the DSD features for different rainfall types, the PREs exhibited smaller droplets and a greater number of small-sized droplets, resulting in a lower average D_m and higher N_w compared to TCs. The segregation of DSDs into different Rs for stratiform and convective precipitation illustrated smaller N_w and larger D_m for TCs than for PREs. The small (medium and large) droplets mainly contributed to R and N_t were higher (lower) in PREs (TCs) than in TCs (PREs) precipitation. In TCs, the N_w and D_m values of convective precipitation are larger than those of stratiform one; In PREs, the N_w values are larger in convective precipitation, while the D_m values are smaller than the stratiform one. Overall, the ranges of D_m and N_w for PREs and TCs in this study generally comply with those for TCs and summer rainfall observed in the Pacific Ocean in previous studies (Janapati et al., 2020, 2021). The D_m and N_w for PREs also show Meiyu frontal rainfall characteristics reported in Wen et al. (2016).

In summary, this study implied that the rainfall structures together with DSD characteristics are different, indicating that the microphysics connected to PRE and TC precipitation are disparate. Compared with PREs, TCs may show more intense convective activity with higher storm height, higher precipitable water, and higher convective available potential energy (CAPE) values with cold cloud tops, which also illustrated by Janapati et al. (2020) and Janapati et al. (2021). The Z–R algorithms in the research may contribute to the improvement of rainfall estimation from radar reflectivity and cloud simulations in weather models for PREs over the YRD area and related TCs over the northwestern Pacific Ocean and South China Sea.

Despite detailed examinations of rainfall structures as well as DSD features of different kinds of rainfall for PREs and TCs, the results are

based on GPM observations. Further studies applying measurements from ground-based disdrometers and dual-polarimetric radars are necessary to better understand microphysical processes (e.g., collision, breakup, and coalescence) and to use simulations to analyze the dominant physical processes (e.g., water vapor convergence) responsible for different types of rainfall in PREs and TCs.

CRedit authorship contribution statement

Huiyan Xu: Conceptualization, Methodology, Software, Investigation, Formal analysis, Writing – original draft. **Bin Xie:** Data curation, Conceptualization. **Xiaofan Li:** Investigation, Writing – review & editing. **Ben Wang:** Writing – review & editing, Supervision. **Lingyun Lou:** Resources. **Zhifeng Yu:** Validation. **Jiaxi Wu:** Software. **Dengrong Zhang:** Supervision. **Feng Zhang:** Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The Global Precipitation Measurement (GPM) data applied in this study can be accessed via the NASA Goddard Earth Sciences Data and Information Services Center at https://gpm1.gesdisc.eosdis.nasa.gov/data/GPM_L2/GPM_2ADPR.06/, which are freely available online as described by Ryu et al. (2021). The NCEP FNL data with $1^\circ \times 1^\circ$ horizontal resolution can be freely obtained from the NCAR Center (<https://rda.ucar.edu/>). The other data processing tools including Python and NCL used for the data processing are freely available online though <https://www.python.org/> and <https://www.ncl.ucar.edu/>.

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