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Comparison of Monsoon Raindrop Size Distribution Between Inland and Coastal in South China

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Abstract: The raindrop size distribution (DSD) is a significant characteristic of precipitation physics, which plays a crucial role in improving the accuracy of radar quantitative precipitation estimation and prediction. There is an effect of atmospheric circulation and weather systems in South China, with frequent precipitation and differences in regional features, resulting in a limited understanding of the DSD characteristics and their impact mechanisms in the region. In this study, six ground-based two-dimensional video disdrometers (2DVDs) were used to analyze the DSD of inland and coastal in South China during the five-year (2016–2020) monsoon seasons (April to September), ERA5 reanalysis data and MODIS cloud property products were also used to investigate the dynamics and microphysical characteristics of monsoon precipitation. Compared to inland rainfall, coastal rainfall has a higher concentration of small, medium, and diameter of less than 4.7 mm large raindrops. Considering the contributions to precipitation, the inland and coastal rainfall are dominated by convective rain, accounting for 74.8% and 84.7% of the total rainfall, respectively. The coastal rainfall has a higher the mass-weighted mean diameter (D_m) value than the inland rainfall D_m for both the stratiform and convective rainfall. The logarithmic mean of the generalized intercept parameter ($\log_{10}N_w$) in inland stratiform rain is greater than that in coastal areas, while convective rain is relatively small. Due to the impact of precipitation types and climate conditions, The Z-R relationship between inland and coastal rainfall also shows obvious differences. Compared to inland areas, there is more frequent convective activity, relatively moist near-surface conditions, and lower cloud droplet number concentrations, which contribute to larger D_m of raindrops in coastal areas. This study deepens the understanding of changes in South China's coastal and inland DSD and provides support for improving numerical weather forecasting in the region.

Key words: raindrop size distribution; monsoon rainfall; regional variability; South China

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1 INTRODUCTION

Raindrop size distribution (DSD), a fundamental characteristic of precipitation, describes the size distribution of raindrops and their concentration per unit volume. It reflects the changing trend of precipitation cloud clusters during their formation under the combined effects of cloud dynamics, thermodynamics, and microphysical processes (Rosenfeld and Ulbrich, 2003; Bringi et al. 2009; Mudlar et al. 2018). Therefore, studying DSD characteristics enhances our understanding of key precipitation processes such as evaporation, collision, and coalescence (Tang et al. 2014; Huang and Chen 2019; Bao, 2020). It holds significant importance for optimizing precipitation parameterization schemes in numerical

weather forecasting models (Tokay and Short, 1996; Zhang et al. 2006; McFarquhar et al. 2015).

The variations in DSD characteristics mainly depend on factors such as geographical location, seasons, weather system, and rainfall type (Tokay and Short 1996; Krishna et al. 2016; Lee et al. 2019; Chen et al. 2019). To explore the impact of topographies on DSD, Suh et al. (2020) found that the DSD of convective precipitation in South Korea varies with the distance from the coastline. This variation is evident in both the relationship of higher mass-weighted mean diameter (D_m) and normalized intercept parameter ($\log_{10}N_w$), and radar reflectivity (Z) and rain rate (R). Through the investigation of the characteristics of DSD from ten observation stations in Beijing, it was found that the raindrop spectra in Beijing present strong geographical dependence. The shape parameter and slope parameter values are relatively higher in the northern mountainous areas, while the values of D_m and N_w are relatively larger in the southern areas (Han et al. 2021). A comparison study of DSD between Taiwan and Palau is performed by Seela et al. (2017), and they report that Taiwan has a higher D_m and lower $\log_{10}N_w$, slope parameter, and shape parameter than Palau. The North Indian Ocean tropical cyclones exhibit more mesoscale and large raindrops along the coast than inland, with higher D_m values and smaller $\log_{10}N_w$ values (Seela et al.

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2021). Wu et al. (2019) demonstrated the characteristics of DSD in different regions of the Pacific Ocean and compared the results with those in other regions. They also observed variations in D_m and N_w across different regions. Kozu et al. (2006) investigated the seasonal and diurnal differences of DSD at Gadanki, Singapore, and Kototabang in Asia areas. The seasonal difference is most significant at the tropical station (Gadanki) in eastern East India, and the D_m in the southwest monsoon is greater than that in the northeast monsoon. In addition, monsoon changes have a significant impact on precipitation in southeastern India, particularly in terms of D_m and rain droplet concentration (Radhakrishna, 2009). By discussing the characteristics of raindrops in summer and winter precipitation over northern Taiwan, it was found that the concentration of small raindrops in winter is higher compared with those in summer, while the concentration of medium and large raindrops is lower. Summer has a large D_m and a small $\log_{10}N_w$ (Seela et al. 2018). Zeng et al. (2019) collected precipitation data in the South China Sea from 2012 to 2016 and exhibited the differences in the DSD for different periods in summer monsoon. For different types of precipitation, there are obvious differences in DSD between convective precipitation and stratiform precipitation on the mainland, among which convective precipitation has the characteristics of a higher concentration, large scale, and wide spectrum type (Chen et al. 2016; Zhang et al. 2017).

South China is situated in the south-central region of mainland China. Under the influence of East Asian summer monsoon system, frequent heavy rainfall events result in serious flood disasters in this region. Precipitation demonstrates pronounced seasonal variability and distinct regional characteristics (Cheng et al. 2005; Luo et al. 2017). The primary rainfall period in South China spans from April to September annually, marking the onset of the rainy season in China (Luo et al. 2017; Liu et al. 2005; Luo et al. 2008). Therefore, analyzing the precipitation patterns in South China is crucial for predicting the migration of the Chinese rain belt. Extensive research has been conducted on South China's precipitation characteristics. For instance, Lai et al. (2022) analyzed 2DVD data from South China between 2016 and 2019, demonstrating that dry-season precipitation is predominantly stratiform precipitation with lower intensity and smaller droplets, while wet-season precipitation is mainly convective precipitation, characterized by a broader raindrop spectrum. Utilizing a PARSIVEL laser raindrop spectrometer and radar data, Huo et al. (2019) conducted a comparative analysis of DSD characteristics across four precipitation types (convective, stratiform, hybrid, and shallow-cloud precipitation) during summer observations at Longmen Station. Their results demonstrated that convective precipitation exhibited markedly higher rain intensity and mass-weighted mean diameter (D_m) values compared to other precipitation categories, along with broader spectral

widths. Most studies on raindrop size distributions in South China concentrate on specific events (e.g., typhoons and storm systems) or seasonal changes, neglecting the pronounced regional variability of precipitation patterns (Lai et al. 2022; Feng et al. 2020; Feng et al. 2021). Therefore, it is necessary to study the DSD characteristics of different terrains in South China. This study analyzed 2DVD data collected in South China during the flooding seasons of 2016–2020 to investigate precipitation characteristics across both coastal and inland regions. The details of the data and methods are introduced in section 2. The differences between coastal and inland DSD are discussed in section 3. Potential impact factors of DSD variations are discussed in Section 4, while the study's conclusions are presented in Section 5.

2 DATA AND METHODS

The DSD data sets are collected by Two-dimensional video disdrometer (2DVD) from six stations at Longmen Field Experimental Base of China Meteorological Administration (Liu et al. 2023), and the observation areas are divided into inland areas (Longmen, Fogang, Heyuan, and Xinfeng) and coastal areas (Bohe and Hailingdao) according to topographic characteristics of South China. The location of each station is shown in Fig.1, and the stations in inland and coastal areas are distinguished by color, where red represents inland stations and blue represents coastal stations. The focus of this study is to analyze the precipitation during the monsoon season (April to September) from 2016 to 2020. It is noticed that since 2DVD starts observations at different times at each site, the periods of the observations collected may vary from site to site. Due to the significant difference between the DSD of typhoon precipitation and the DSD of monsoon precipitation, typhoon precipitation directly affects the characteristic analysis of summer precipitation (Janapati et al. 2020; Liu et al. 2018). The purpose of this study is to investigate the regional variations in

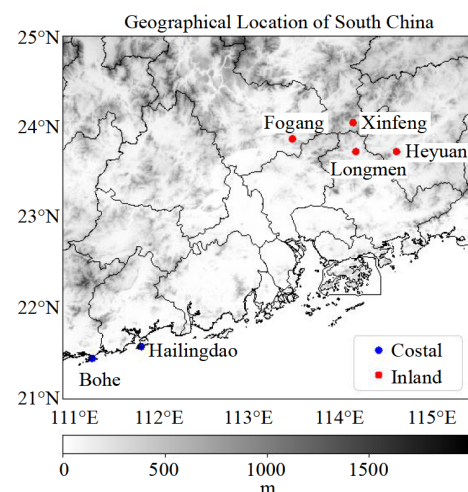


Figure 1. Locations of two-dimensional video disdrometers, including Longmen (LM), Fogang (FG), Heyuan (HY), Xinfeng (XF), Hailingdao (HLD) and Bohe (BH).

monsoon precipitation in this region. Therefore, to eliminate the influence of typhoon DSD, the precipitation during typhoon occurrences is excluded. Details of each site, including location information, altitude, and observation duration, are given in Table 1.

2.1 Two-dimensional video disdrometer data

The 2DVD used for observation in the South China region is the third-generation version produced by Joanneum Research in Graz, Austria (for more details, please visit [www.distrometer.at]). Two orthogonal high-speed scanning cameras at different heights accurately observe the entire falling process of raindrops within the observation area (the intersection cross-section of two optical paths), thereby obtaining information such as the front and side contours, falling speed, and rainfall parameters of raindrops (Schnhuber et al. 2007; Kruger and Krajewski, 2002). To enhance the observation quality of 2DVD and minimize the impact of invalid data on the results, it is necessary to implement a quality control process for the observed data. This study excluded observational results with total droplet counts less than 10 and rain rates smaller than 0.1mm h⁻¹ to ensure the reliability and accuracy of the analysis (Tokay et al. 2013).

The DSD measured by 2DVD is calculated with the following formula:

$$N(D_i) = \sum_{i=1}^{41} \sum_{j=1}^{n(i)} \frac{1}{A \cdot \Delta t \cdot V_{i,j} \cdot \Delta D_i} \quad (1)$$

where $n(i)$ is the number of drops in i^{th} bin, A (10×10 cm²) is the sensing area, Δt (1min) is an interval time, $V_{i,j}$ (m s⁻¹) is the drop fall speed. D_i (mm) is the equivalent raindrop diameter. ΔD_i (mm) is the bin interval.

The radar reflectivity factor Z (mm⁶ mm⁻³), rain rate R (mm h⁻¹), Liquid water content W (g m⁻³), total raindrop concentration N_t (m⁻³), and other integrated rainfall parameters are derived:

$$Z = \sum_{i=1}^L D_i^6 N(D_i) \Delta D_i \quad (2)$$

$$R = \frac{6\pi}{10^4} \sum_{i=1}^L D_i^3 V_i N(D_i) \Delta D_i \quad (3)$$

$$LWC = \frac{\pi}{6000} \sum_{i=1}^L D_i^3 N(D_i) \Delta D_i \quad (4)$$

$$N_t = \sum_{i=1}^L N(D_i) \Delta D_i \quad (5)$$

where L represents the total number of size bins.

The n^{th} -order moment of gamma DSD is represented by the following formula:

$$M_n = \int_0^{D_{max}} N(D) D^n dD \quad (6)$$

The mass-weighted mean diameter D_m (mm) is calculated using the third and fourth moments of DSD:

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

The generalized intercept parameter N_w (m⁻³ mm⁻¹) is calculated using W and D_m as shown below:

$$N_w = \frac{4^4}{\pi \rho_w} \left(\frac{10^3 W}{D_m^4} \right) \quad (8)$$

where ρ_w (g cm⁻³) represents the density of water. Some investigations have compared and evaluated the accuracy of 2DVD observations in South China using rain gauges at automatic weather stations, and the results of 2DVD observations are basically consistent with those of rain gauges. As a result, the observation dataset collected by 2DVD in the region can effectively provide a precise depiction of the precipitation characteristics over South China.

2.2 ERA5 reanalysis data and MODIS cloud properties

The fifth-generation reanalysis (ERA5) data from the European Centre for Medium-Range Weather Forecasts (ECMWF) is recognized as one of the most reliable global reanalysis datasets. It offers real-time data spanning from 1979 to the present, with a temporal resolution of 1 hour and a spatial resolution of 0.25°×0.25° (Hoffmann et al. 2019; Hersbach and Dee, 2016). The convective available potential energy (CAPE), total column water vapor (WV), and the profiles of atmospheric temperature and relative humidity at 2DVD stations in inland and coastal areas of South China are used to illustrate the atmospheric characteristics of this region. The cloud properties

Table 1. The locations, observation periods and total number of 1-min DSD of six stations

Station		Observation period	Total number of 1-min DSD
Inland	Longmen	2016–2020	45,033
	Fogang	2017–2019	27,743
	Xinfeng	2017–2019	21,818
	Heyuan	2019–2020	19,013
Coastal	Hailingdao	2017–2018	16,638
	Bohe	2020	3395
Total			133,640

products of the Moderate Resolution Imaging Spectroradiometer (MODIS) have undergone multiple improvements, with the current version capable of accurately characterizing the optical and microphysical properties of both ice and water clouds (Platnick et al. 2017). In this study, the MODIS level-3 daily mean cloud product (effective particle radius of ice and water clouds), with a spatial resolution of $1^\circ \times 1^\circ$, is used (Remer et al. 2005; Hubanks and Platnick 2008; Platnick et al. 2003). Due to the differing temporal resolutions of ERA5 and MODIS, the hourly ERA5 data were processed via daily averaging to align with MODIS temporal resolution. Moreover, the cloud effect of aerosols in the atmosphere is significantly influenced by cloud condensation nuclei (CCN) within clouds. Although aerosol optical depth (AOD) serves as a metric to describe aerosol concentration, its correlation with the formation of CCN and cloud droplet number concentration (CDNC) remains relatively weak (Bennartz. 2007; Bennartz and Rausch. 2017). To delve deeper into the characteristics of cloud particles during precipitation in coastal and inland regions, we incorporate CDNC into our analysis to elucidate the underlying microphysical processes. The relevant formula is as follows:

$$CDNC = \frac{\tau^3}{k} (2W)^{-\frac{5}{2}} \left(\frac{3}{5} \pi Q \right)^{-3} \left(\frac{3}{4\pi\rho_w} \right)^{-2} c_w^{\frac{1}{2}} \quad (9)$$

$$W = \frac{5}{9} \rho_w \tau r_e \quad (10)$$

where k (0.8) is the dispersion of the assumed cloud droplet size distribution. Q , the Mie scattering efficiency, is 2.0. In general, $C_w (2 \times 10^{-6} \text{ km m}^{-4})$ is the condensation rate, $\rho_w (10^3 \text{ kg m}^{-3})$ is the density of liquid water, τ and $r_e (\mu\text{m})$ represent liquid cloud optical thickness and effective radius, respectively.

It should be noted that only ERA5 and MODIS pixels closest to the 2DVD stations are considered. For ERA5 pixels, the closest distance to the 2DVD observation site is about 3.0 km, and the farthest distance is 14.4 km. Since the spatial resolution of MODIS is relatively low, the closest (farthest) distance to the 2DVD site is about 19.4 (58) km.

3 RESULTS

During the monsoon season observation spanning nearly four years (2016–2020), this study records a total of 113,607 mins of inland rainfall and 20,033 mins of coastal rainfall in South China. Fig. 2 illustrates the variations of the raindrop diameter and $N(D)$ for monsoon precipitation in both inland and coastal areas. It is observed that the DSD for both inland and coastal precipitation follows a gamma distribution. The DSD of small raindrops (with raindrop diameters less than 1 mm) exhibits an upward concave pattern. The peak value of $N(D)$ for small raindrops occurs at approximately 0.3 mm. For small raindrops with a diameter of less than 0.3 mm, it can be found that the concentration is significantly greater in the

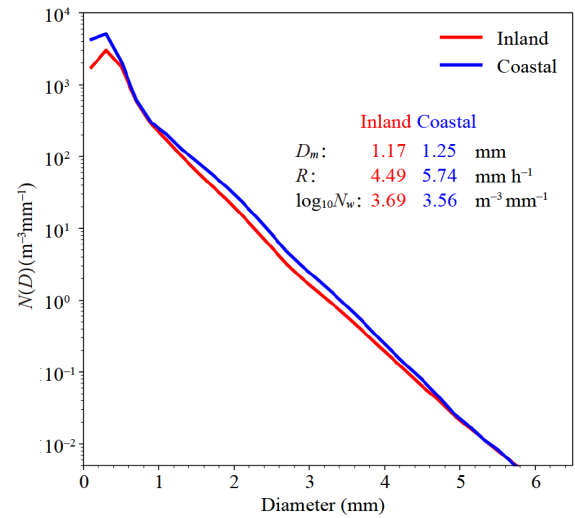


Figure 2. The mean raindrop size distribution for inland (solid red line) and coastal (solid blue line) areas. The mean values of D_m (mm), R (mm h^{-1}), and $\log_{10}N_w$ ($\text{m}^{-3} \text{ mm}^{-1}$) in inland (red) and coastal (blue) areas are all plotted in the figure.

coastal, while the size distribution of small raindrops between 0.3 and 1 mm is similar in both regions. For medium raindrops (with diameters ranging from 1 to 3 mm) and large raindrops (with raindrops exceeding 3 mm) of diameter less than 5.2 mm, the raindrop concentration in inland areas is significantly lower than that in coastal areas. For large raindrops with a diameter exceeding 5.2 mm, there is little difference in the number concentration of raindrops between the two areas. In addition, Fig. 2 indicates the mean values of D_m , R , and $\log_{10}N_w$. The D_m value is greater in coastal areas (1.25 mm) than that in inland (1.17 mm). The mean value of R increases from 4.49 mm h^{-1} inland to 5.74 mm h^{-1} in coastal. In contrast, the mean value of $\log_{10}N_w$ in inland areas ($3.69 \text{ m}^{-3} \text{ mm}^{-1}$) is greater than that in coastal counterparts ($3.56 \text{ m}^{-3} \text{ mm}^{-1}$).

To elucidate the DSD characteristics between inland and coastal, the probability density functions (PDFs) of DSD parameters ($\log_{10}R$, $\log_{10}W$, D_m , $\log_{10}N_w$, $\log_{10}N_t$, and Z) for both regions are presented in Fig. 3. When $\log_{10}R$ exceeds 0.6 mm h^{-1} , the PDF of $\log_{10}R$ (Fig. 3a) shows that the frequency of inland regions is higher than that of coastal regions. In terms of liquid water content (Fig. 3b), the values for both regions are concentrated within a range of -1.8 g m^{-3} to -0.4 g m^{-3} , with coastal areas showing smaller values. The PDF of D_m for coastal areas becomes significantly larger than that for inland areas when values exceed 0.95 mm , with peaks at approximately 1.25 mm and 1.15 mm for coastal and inland, respectively (Fig. 3c). This finding aligns with the previous results shown in Fig. 2. When $\log_{10}N_w$ is less than $3.9 \text{ m}^{-3} \text{ mm}^{-1}$, the probability density function for coastal areas is notably higher (Fig. 3d). The PDF of the total raindrop concentration indicates that inland areas have a higher distribution frequency within the range of 1.9 to 3.4 m^{-3} , with a peak near 2.6 m^{-3} (Fig. 3e). The radar reflection

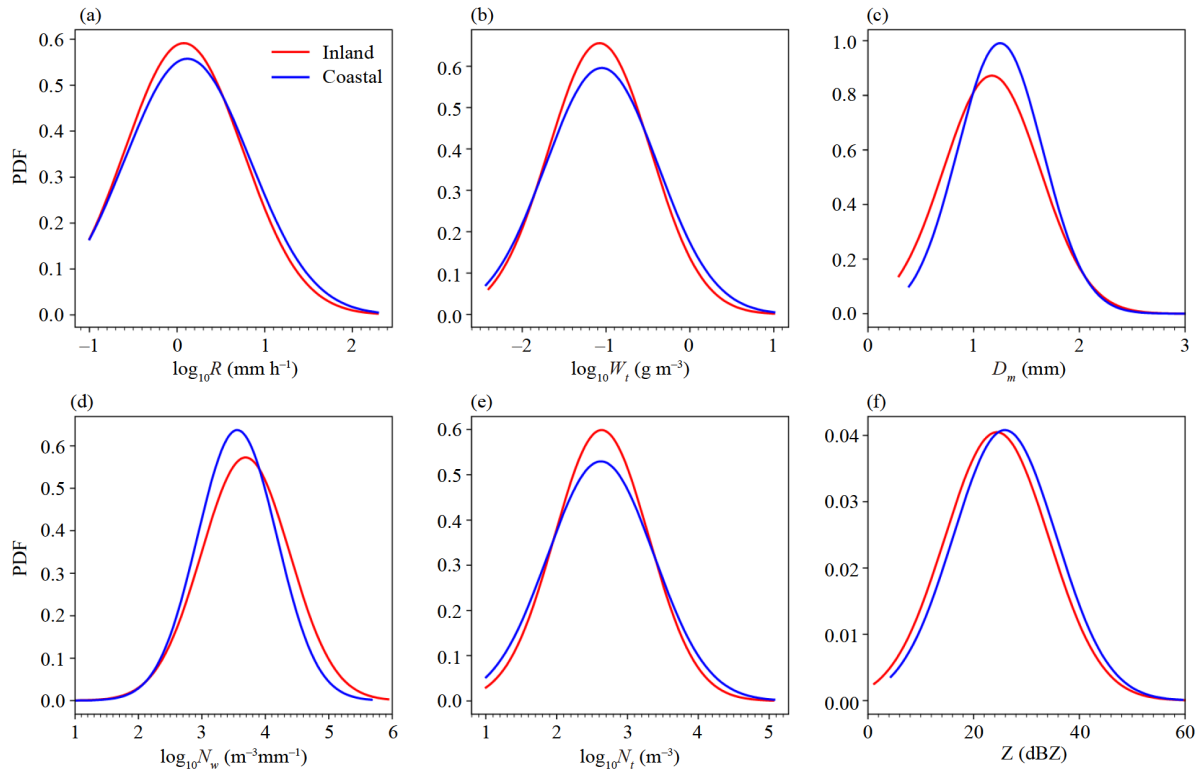


Figure 3. The probability distribution functions (PDFs) of the (a) $\log_{10}R$ (mm h^{-1}), (b) $\log_{10}W$ (g m^{-3}), (c) D_m (mm), (d) $\log_{10}N_w$ ($\text{m}^{-3} \text{mm}^{-1}$), (e) $\log_{10}N_t$ (m^{-3}), and (f) Z (dBZ) for raindrops over inland and coastal areas.

factor (Z) curves for both regions exhibit comparable distribution patterns. Compared to coastal areas, the distribution for inland areas is narrower, with the PDF peak of Z occurring near 23 dBZ (Fig. 3f).

3.1 Raindrop size distribution at different rain rate classes

This section provides a detailed discussion on the DSD of different rain rate classes, aiming to better understand the precipitation differences between inland and coastal areas in South China. Nzeukou et al. (2004) divided DSD into eight levels according to precipitation rate for discussion. They found that the slope of the DSDs tends toward a constant value when rain rates R are higher than about 20 mm h^{-1} . Therefore, this study adopts a simplified classification for precipitation with R greater than 20 mm h^{-1} . The six levels of precipitation (C1: $0.1-1$, C2: $1-5$, C3: $5-10$, C4: $10-20$, C5: $20-50$ and C6: $\geq 50 \text{ mm h}^{-1}$) are discussed. Fig. 4 illustrates the probability of occurrence for each rain rate class. It is observed that precipitation in both coastal and inland areas is primarily concentrated in classes C1 and C2. Specifically, the probability of C1 class occurring is similar in coastal and inland areas, with values of 49.1% and 49.3%, respectively. The frequency of C2 class precipitation occurring inland is 32.4%, which is higher than the result in coastal (29.5%). Compared to coastal areas, inland areas exhibit a lower occurrence probability of rainfall with rain rates exceeding 5 mm h^{-1} .

The distributions of DSD for different rain rate classes of inland and coastal rainfall over South China are

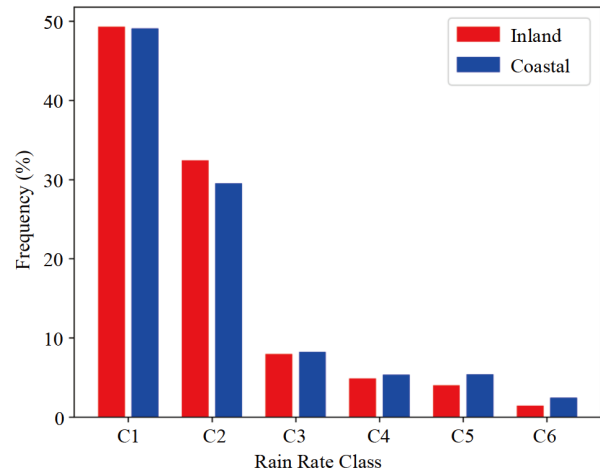


Figure 4. The occurrence frequencies at different rain rate classes in inland and coastal areas.

depicted in Fig. 5. For six classes of precipitation (C1–C6), the spectral width of raindrops and the $N(D)$ of small raindrops increase with the increase of rain rate. In C1 (Fig. 5a), the results of small raindrops in inland areas are larger than those in coastal areas. The $N(D)$ of medium-sized raindrops shows the opposite trend, with relatively lower number concentrations observed in inland areas. In the case of C2 precipitation (Fig. 5b), the $N(D)$ of inland small and larger raindrops is slightly higher and the $N(D)$ of medium raindrops in coastal and inland is similar. It is observed that when R exceeds 5 mm h^{-1} , the number concentration of raindrops with a diameter less than

0.4 mm in coastal is significantly larger than that inland. Furthermore, the DSD changes in inland and coastal areas at the C3–C4 precipitation level are similar. Compared to inland regions, the $N(D)$ of large raindrops is comparatively lower in coastal areas during C5 and C6 rainfall events.

Figure 6 illustrates the changes of the inland and coastal D_m , $\log_{10}N_w$, μ , and Λ with rainfall rate classes. Table 2 displays the average and standard deviation of D_m , $\log_{10}N_w$, μ , and Λ of inland and coastal precipitation at

each rain rate class. Notably, both inland and coastal precipitation exhibit an upward trend in the mean value of D_m as the rain rate increases (Fig. 6a). In the first three precipitation classes (C1–C3), the mean D_m values in coastal exhibit higher compared to those inland. However, for rain rates exceeding 20 mm h^{-1} , inland areas show larger D_m values. Compared with coastal areas, the range of mean D_m values in inland areas is greater. The mean D_m values in inland areas range from 0.95 to 1.97 mm, while those in coastal areas range from 1.07 to 1.86 mm. The

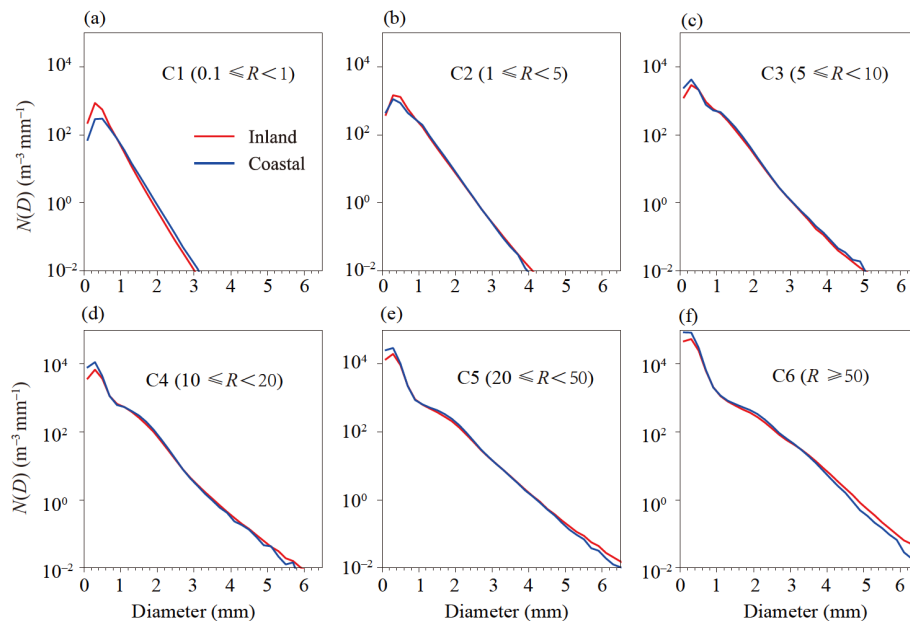


Figure 5. The mean raindrop size distribution for inland (solid red line) and coastal (solid blue line) areas for six rain rate classes.

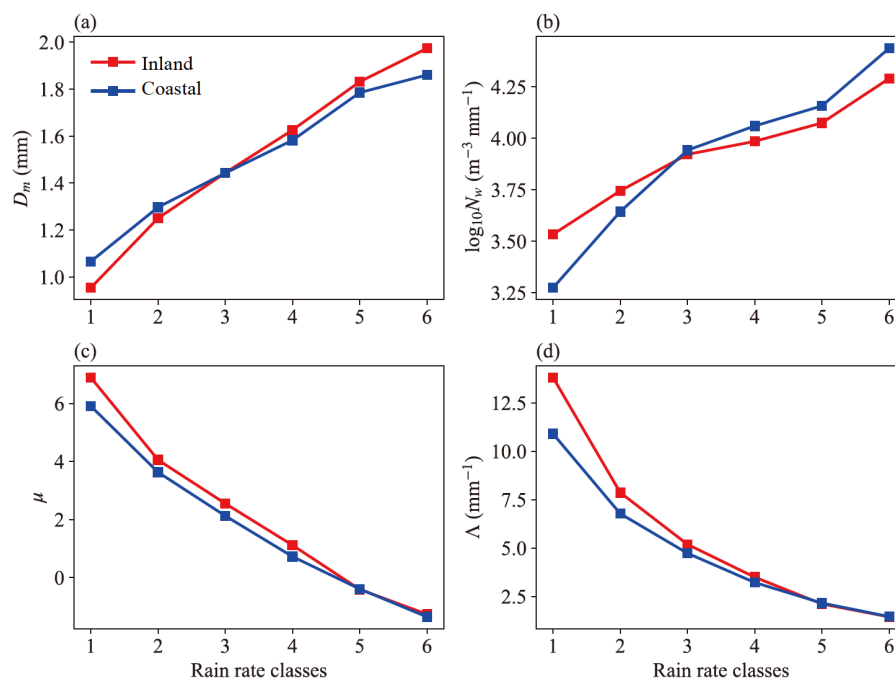


Figure 6. The variations of (a) D_m (mm), (b) $\log_{10}N_w$ ($\text{m}^{-3} \text{ mm}^{-1}$), (c) μ , and (d) Λ (mm^{-1}) of inland (red) and coastal (blue) rainfall classified by rate classes.

Table 2. The average and standard deviation of D_m , $\log_{10}N_w$, μ , and λ of inland and coastal precipitation at each rain rate class

Class	Inland								Coastal							
	D_m		$\log_{10}N_w$		μ		λ		D_m		$\log_{10}N_w$		μ		λ	
	Ave	Std	Ave	Std	Ave	Std	Ave	Std	Ave	Std	Ave	Std	Ave	Std	Ave	Std
C1	0.95	0.35	3.53	0.75	6.89	4.47	13.80	9.16	1.07	0.32	3.27	0.60	5.91	4.18	10.89	7.27
C2	1.25	0.39	3.74	0.64	4.05	3.71	7.86	6.16	1.30	0.33	3.64	0.52	3.63	3.45	6.77	4.73
C3	1.44	0.40	3.92	0.50	2.55	2.93	5.19	3.54	1.44	0.34	3.94	0.41	2.13	2.79	4.73	3.00
C4	1.63	0.46	3.98	0.46	1.11	1.96	3.49	1.96	1.58	0.39	4.06	0.40	0.72	2.12	3.22	1.81
C5	1.83	0.47	4.07	0.42	-0.41	1.04	2.11	0.89	1.78	0.42	4.16	0.39	-0.39	1.50	2.16	1.10
C6	1.97	0.39	4.29	0.35	-1.26	0.40	1.44	0.35	1.86	0.29	4.44	0.30	-1.35	0.49	1.46	0.34

average $\log_{10}N_w$ of inland and coastal rainfall also increases with rain rate, as shown in Fig. 6b. In the first two rain rate classes ($0.1-10 \text{ mm h}^{-1}$), the mean $\log_{10}N_w$ values in inland areas are higher compared to the values of coastal areas, while lower values are in the last four classes (C3–C6). The shape parameters (μ) and slope parameters (λ) of inland and coastal areas exhibit a decreasing trend with increasing rain rates (Figs. 6c and 6d). The range of μ mean values range from 6.89 to 1.26 for inland and 5.91 to 1.35 for coastal areas. For λ , the mean values inland range from 13.81 to 1.44 m^{-1} , whereas those in coastal areas range from 10.89 to 1.46 m^{-1} in coastal.

3.2 Raindrop size distribution in stratiform and convective precipitation

In addition to precipitation intensity, the raindrop spectral characteristics of different precipitation types exhibit discernible distinctions (Tokay et al. 2008; Sharma et al. 2008; Thurai et al. 2017). This investigation divides precipitation events in inland and coastal areas of South China into two categories: stratiform and convective rainfall. The specific discrimination method is similar to

that proposed by Bringi et al. (2009). The analysis focuses on the R and its standard deviation (σR). If the R consistently exceeds 0.5 mm h^{-1} and σR remains below 1.5 mm h^{-1} during a continuous ten-minute period of precipitation data, then the precipitation data during that period is classified as stratiform precipitation. On the other hand, if R exceeds 5 mm h^{-1} and the σR is larger than 1.5 mm h^{-1} , the precipitation data during that period is classified as convective precipitation. The remaining samples that do not meet these criteria are regarded as mixed precipitation and are excluded from further analysis in this study.

Figure 7a presents the proportion of different precipitation types in coastal and inland areas. Stratiform precipitation demonstrates a higher propensity to occur in inland and coastal areas, representing 80.1% and 74.9% of the total precipitation time, respectively. In contrast, convective precipitation displays a comparatively lower probability of 19.9% in inland areas, compared to 25.1% in coastal areas. Furthermore, considering their contribution to the overall precipitation (Fig. 7b), stratiform and

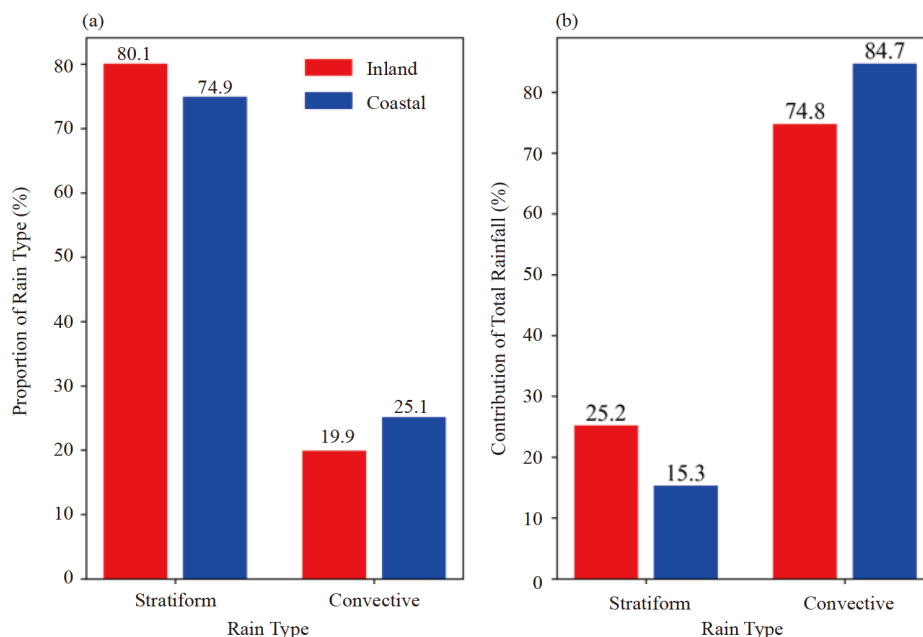


Figure 7. The probability of different precipitation types (stratiform and convective) (a) and their contribution to total rainfall (b) in inland and coastal areas.

convective precipitation contribute 25.2% and 74.8% respectively to the total inland precipitation. In terms of coastal precipitation, convective precipitation dominates, accounting for 84.7% of the total rainfall. This is consistent with previous studies. To investigate the DSD of different rainfall types in inland and coastal areas of South China, Fig. 8 illustrates the variation in the DSDs of stratiform and convective rain in inland and coastal areas. It is observed that $N(D)$ for stratiform precipitation is significantly lower than that of convective precipitation in both inland and coastal areas. The droplet size distribution for stratiform rain is narrower compared to that of convective rain. For stratiform rain, the concentration of raindrops with a diameter of less than 1.1 mm inland is greater than that in coastal. Convective precipitation shows a lower $N(D)$ in inland areas, especially for small and medium-sized droplets, compared to coastal regions. Compared to stratiform $N(D)$ s, the convective $N(D)$ s over both inland and coastal show a slight concavity near a droplet diameter of approximately 1.0 mm. A primary factor contributing to these differences is the intense convective motions in convective precipitation, which lead to collisions and breakups of larger droplets. In contrast, stratiform precipitation has less vertical development, leading to less upward transport of water vapor (Hu et al. 1995).

The variations in the D_m and $\log_{10}N_w$ values for stratiform and convective rain in inland and coastal areas are illustrated in Fig. 9. In general, convective rain shows significantly higher mean D_m and $\log_{10}N_w$ values compared to stratiform rain. One of the factors causing this phenomenon is the occurrence of collision-coalescence and breakup processes that are more prevalent in convective rain, while stratiform precipitation tends to occur in relatively stable conditions (Jiang, 2003; Lin et al. 2006). On the other hand, the coastal rainfall has a higher D_m value than the inland rainfall D_m for both the rainfall regimes (stratiform and convective). Changes in the surface (coastal and inland areas) may be one of the reasons for the above-mentioned regional differences in DSD. Furthermore, the mean $\log_{10}N_w$ of inland stratiform rain is greater compared to coastal areas, while convective rain is relatively small. An important factor contributing to this difference is the water vapor supply in coastal areas is much greater than that in inland areas. During convective precipitation, water vapor in coastal areas is more likely to condense into droplets and undergo collision and fragmentation, thereby increasing the concentration of raindrops (Martinez and Gori, 1999; Feng and Wang, 2011). Bringi et al. (2003) measured the relationship between D_m and $\log_{10}N_w$ of convective rainfall over continents and maritime, and their results are represented by a gray rectangle in Fig. 9. The maritime rain D_m ($\log_{10}N_w$) value ranges from 1.5 to 1.75 mm (4 to 4.5 $\text{m}^{-3} \text{mm}^{-1}$) and the continental rain D_m ($\log_{10}N_w$) value ranges from 2 to 2.75 mm (3 to 3.5 $\text{m}^{-3} \text{mm}^{-1}$), it can be seen that the convection and stratiform precipitation in coastal and

inland areas of South China conform to their classification. In addition, the DSD parameters of convective precipitation in coastal and inland areas are similar to those of maritime convective precipitation.

3.3 Radar reflectivity (Z)-rain rate (R) relations

The relationship between radar reflectivity (Z) and rain rate (R) obtained from the radar equation can be expressed as $Z=AR^b$ (Ulbrich C. 1983). The existence of unique characteristics in the Z - R relations is attributed to variations in geographical regions and precipitation types. By establishing a Z - R relation based on precise location, season, and rain type, the uncertainty in quantitative precipitation estimation by weather radar can be minimized to the greatest extent possible (Rosenfeld and Ulbrich 2003; Seela et al. 2017). For example, Wen et al. (2016) provided a QPE algorithm for precipitation in East China ($Z=232.44R^{1.34}$). Han et al. (2022) investigated

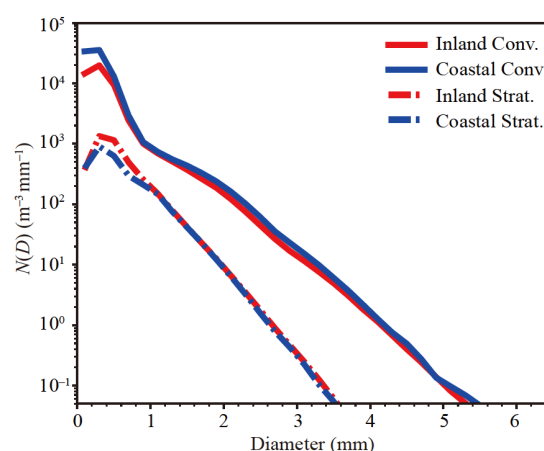


Figure 8. The mean raindrop size distributions of different precipitation types (stratiform and convective) in coastal and inland areas.

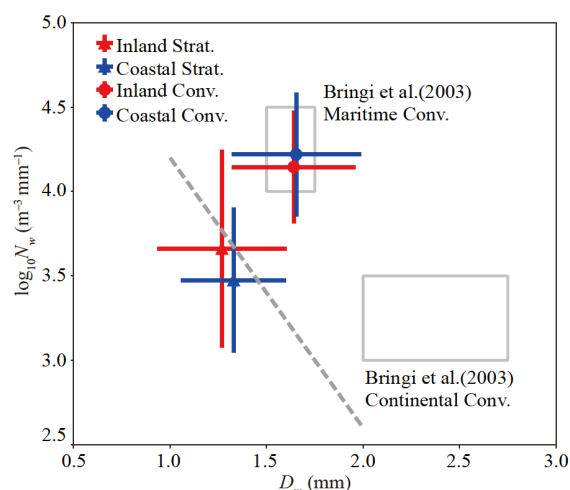


Figure 9. The error bar of the mean D_m versus $\log_{10}N_w$ for convective (circles) and stratiform (triangles) rain types over inland (red) and coastal (blue) areas. The two rectangles represent the extent of maritime and continental convective precipitation, respectively. The grey dotted line represents the stratiform-convective separation line.

the Z - R relationship under different precipitation types in six regions of China and found significant differences. These established relationships provide valuable guidance for enhancing the accuracy of radar-based precipitation estimation under specific conditions.

The size of raindrops can be deduced from the coefficient A in the Z - R equation, while the index b represents physical processes. If index b is greater than 1, it is mainly controlled by size or mixing (collision-coalescence). If index b is equal to 1, it is mainly controlled by quantity and is related to uniform rainfall (Seela et al. 2017; Atlas et al. 1999; Steiner et al. 2004). This study discusses the Z - R relationship between the two rainfall regimes (stratiform and convective) in inland and coastal areas of South China, as shown in Fig. 10. To facilitate comparative analysis, the results are displayed on a logarithmic scale. It is observed that Z generally increases with an increase in R . The Z - R relationship for convective rain closely resembles to the overall pattern, indicating that convective precipitation in both coastal and inland regions of South China plays a significant role in total precipitation. This finding aligns with those reported by Lai et al. (2022) and Huo et al. (2019). The indexes b for both coastal and inland rainfall regimes exceed 1, indicating that the size-controlled microphysical process primarily influences the precipitation in these regions. The A values for convective and stratiform precipitation in inland areas are higher than those in coastal areas, while the b values are correspondingly lower. This finding is consistent with the conclusions of Suh et al. (2021), who demonstrated that A values increase while b values

decrease as distance from the coastline increases. According to the classification proposed by Fujiwara (1965), precipitation events are classified into thunderstorms and continuous precipitation. Thunderstorms are typically characterized by A values ranging from 300 to 1000 and b values between 1.25 and 1.65, whereas continuous precipitation is associated with A values below 300 and b values ranging from 1.2 to 2.0. It is observed that precipitation in inland regions is predominantly of thunderstorm type, whereas coastal rainfall tends to be more continuous in nature.

4 DISCUSSION

To elucidate the potential factors contributing to the variations of DSD between the inland and coastal precipitation, ERA5 reanalysis data (CAPE, water vapor, the vertical profiles of atmospheric temperature and relative humidity) and MODIS cloud properties (cloud effective radius and aerosol optical depth) collected during the 2DVD observation period are used to analyze the atmospheric environmental characteristics in South China. As shown in Figs. 11a and 11b, CAPE and water vapor levels are significantly higher in coastal areas compared to inland regions. Coastal regions thus have a higher likelihood of convective activity than inland areas. In other words, the relatively higher water vapor and stronger updrafts and downdrafts cause cloud particle (liquid and solid) growth in coastal areas (by aggregation, condensation, and collision-coalescence processes) much larger than in inland areas (Rosenfeld and Ulbrich 2003; Tokay and Short 1996; Kozu 2006; Suh et al. 2016). In

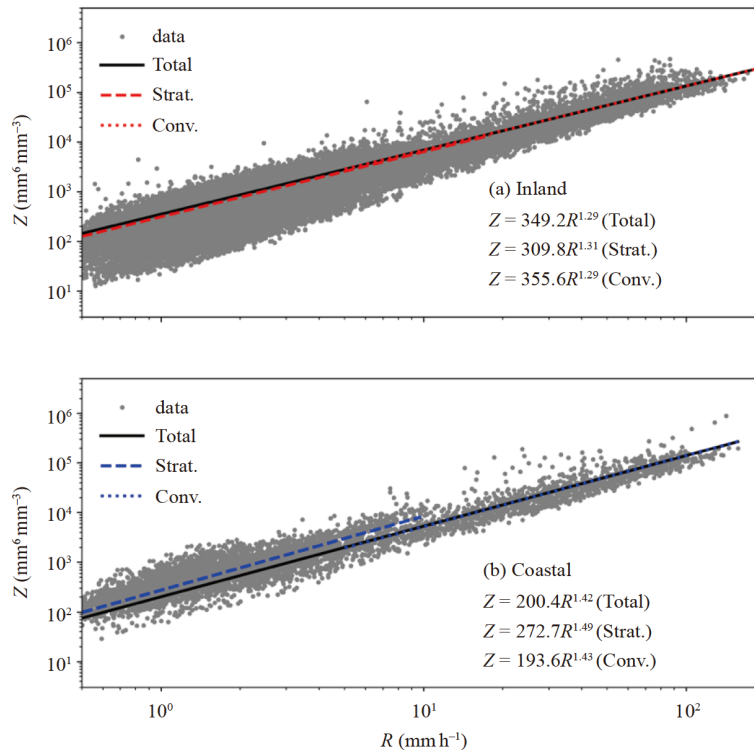


Figure 10. The radar reflectivity-rain rate (Z - R) relations for stratiform and convective rainfall in inland (upper) and coastal (lower) areas.

contrast to coastal, inland is characterized by relatively drier near-surface conditions (similar temperatures, lower relative humidity), in Figs. 11c and 11d. Consequently, raindrops evaporate and diminish in volume before reaching the ground in inland regions. However, at pressures above 930 hPa, coastal area precipitation experiences more arid conditions.

The cloud effective radius (CER) of liquid and ice clouds at inland and coastal stations are derived from the MODIS level-3 data product (MOD08_D3), and the corresponding results are presented in Fig. 12. The results indicate that both liquid water clouds (Fig. 12a) and ice clouds (Fig. 12b) have higher CER values in coastal regions compared to inland regions. The median CER of ice clouds exhibits an increase from 29 μm (inland

areas) to 32 μm (coastal areas). For liquid water clouds, the CER in inland areas is predominantly concentrated within the range of 12.5 μm to 17.52 μm , while the CER range in coastal areas is relatively larger, mainly concentrated between 12.6 μm and 17.8 μm . In other words, cloud droplets with a larger size in coastal areas promote the collision and coalescence of cloud droplets and raindrops, resulting in the formation of more medium and small-sized raindrops.

Comparing the cloud droplet number concentration between the two areas, as illustrated in Fig. 12c, the median of CDNC increases from about 51 cm^{-3} in coastal to about 60 cm^{-3} inland. In the case of less water vapor and smaller CAPE inland (Fig. 11), as the cloud droplet number concentration increases, the cloud-water mixing

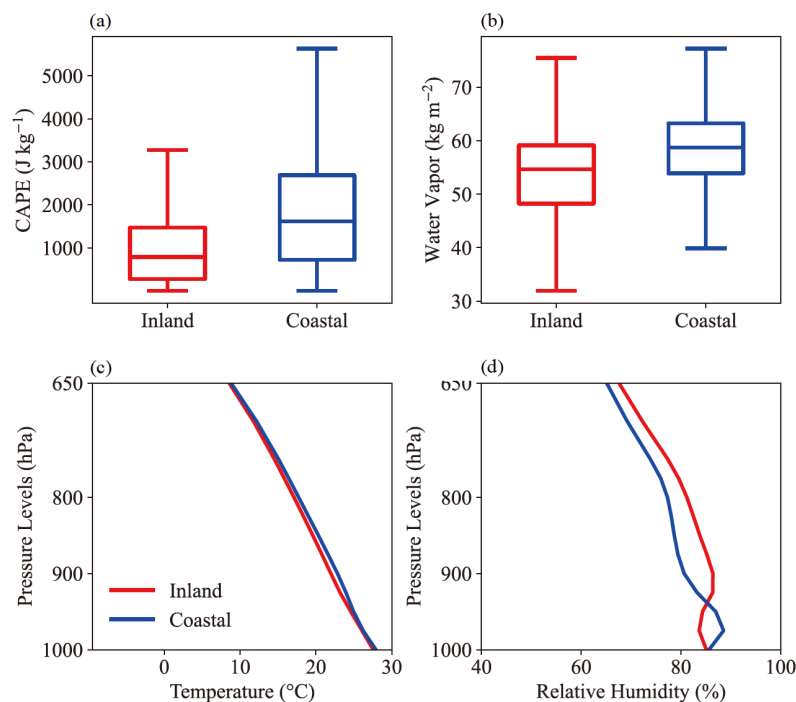


Figure 11. The box and whisker plot of (a) convective available potential energy (CAPE, J kg^{-1}), (b) total column water vapor (WV, kg m^{-2}). The vertical profiles of (c) atmospheric temperature ($^{\circ}\text{C}$) and (d) relative humidity (%) for inland (red) and coastal (blue) areas.

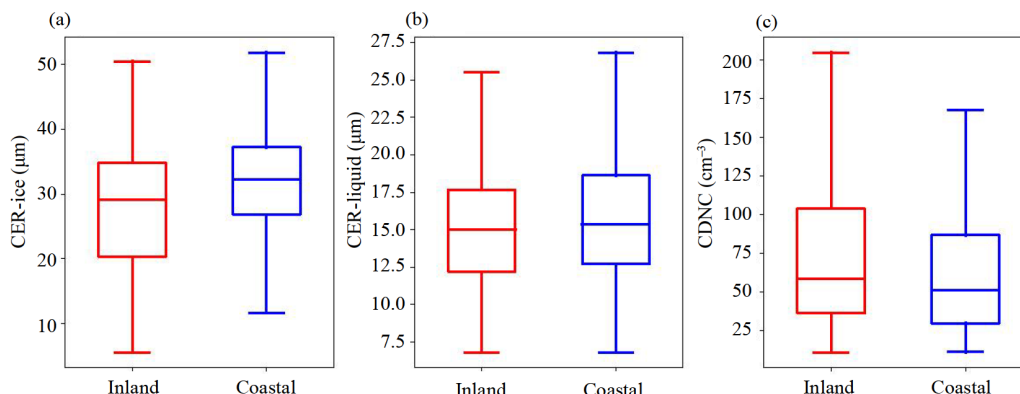


Figure 12. Box and whisker plot of (a) ice cloud effective radius (μm), (b) liquid water cloud effective radius (μm), (c) cloud droplet number concentration (cm^{-3}) for inland (red color box) and coastal (blue color box) areas.

ratio decreases and the cloud droplet size decreases accordingly (Fig. 12b). In other words, an increase in cloud droplet concentration leads to a decrease in raindrop collision efficiency and the conversion rate of cloud droplets into precipitation particles (Suh et al. 2016; Breon et al. 2002; Rosenfeld et al. 2008). Therefore, the residence time of cloud droplets in the cloud increases, and the formation of raindrops may be inhibited. The above thermodynamic and microphysical processes result in smaller raindrops in inland precipitation than in coastal areas.

5 SUMMARY

The raindrop size distributions over South China inland and coastal are analyzed, using two-dimensional video disdrometer observations from six sites in Guangdong Province from 2016 to 2020. The analysis reveals that inland rainfall is predominantly thunderstorm precipitation, while coastal precipitation mainly occurs as continuous precipitation. Additionally, the DSDs in inland and coastal areas of South China exhibit a unimodal distribution. Compared to inland rainfall, coastal rainfall exhibits a higher concentration of small, medium, and diameters less than 4.7 mm large raindrops. Furthermore, the coastal rainfall displays a larger R and D_m compared to inland rainfall. To further investigate the characteristics of the DSDs, we performed an analysis of six different classes of DSDs categorized based on the rain rates. It is noticed that a clear distinction in D_m , N_w , μ , and A is found between inland and coastal rainfall. From the perspective of summer stratiform and convective precipitation in South China, although the duration of stratiform precipitation is long, the contribution to total rainfall dominates convective precipitation. The $N(D)$ of convective rain is significantly larger than that of stratiform rainfall. For stratiform rainfall, $N(D)$ of small raindrops inland is greater than that over coastal, and those of midsize and large raindrops are similar. The D_m and $\log_{10}N_w$ values of convective rainfall in inland and coastal areas align with the characteristics of maritime convective rainfall of Bringi et al (2003). There are significant differences in the Z - R relations between inland and coastal rainfall. This indicates that the Z - R relationship is greatly affected by precipitation types and climate conditions. In addition to 2DVD measurements, the ERA5 and MODIS data are employed to elucidate the dynamics and microphysical processes occurring in these two distinct areas. Coastal areas exhibit higher values of convective available potential energy and total column water vapor compared to inland areas. This indicates a higher probability of convective motion occurring in coastal areas. In addition, increased aerosol concentrations in inland areas act as cloud condensation nuclei, leading to reduced effective sizes of cloud particles and higher cloud droplet number concentrations. This is evident from the cloud effective radius, coastal areas show higher mean CER values for both liquid water and ice clouds compared to inland

regions. Based on vertical profiles of atmospheric temperature and relative humidity, the drier near-surface conditions in inland areas enhance raindrop evaporation compared to coastal regions.

In this study, the differences in DSD between inland and coastal areas in South China are discussed in detail. We found that the observed variations can be primarily attributed to the topography, vertical atmospheric motion and, aerosols. The results of this research provide a physical basis for improving radar precipitation retrieval algorithms as well as refining cloud microphysical parameters within numerical models

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